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IDENTIFYING THE NEUROCOGNITIVE BASES OF CREATIVITY TO INCREASE HUMAN AND COMPUTATIONAL CREATIVITY

DOCTORAL THESIS

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RESUMEN

Resumen

En la presente Tesis Doctoral se ha identificado la estructura neurocognitiva que sustenta la creatividad humana en base al análisis conjunto de más de 800 referencias bibliográficas que muestran las investigaciones más importantes realizadas hasta el momento. En base a dicha estructura se ha descrito un paradigma neurocognitivo de la creatividad humana, y un paradigma computacional de la creatividad. Finalmente se ha propuesto la estructura de un sistema computacional creativo, basado en un sistema multiagente, basado en la estructura neurocognitiva de la creatividad humana.

Las investigaciones que se han realizado sobre el tema son muy especializadas y se centran en aspectos muy concretos de la creatividad, y en muchos casos tienen poca relación entre sí. Por ello, y para tener una idea conjunta y holística de los procesos neurocognitivos de la creatividad humana es necesario estudiar de forma interconectada todas estas investigaciones. Esta idea conjunta permitiría redireccionar investigaciones más específicas con la finalidad de ser más efectivas. Por ello, lo primero que se ha hecho ha sido clasificar, agrupar, analizar, entrelazar y estructurar, de forma ordenada, las investigaciones más importantes que se han realizado hasta el momento.

No obstante, el trabajo realizado va mucho más allá, ya que al estructurar y entrelazar las investigaciones existentes se han podido identificar determinados patrones, correlaciones y paralelismos, y realizar ciertas deducciones, que en su conjunto, han permitido identificar las bases neurocognitivas fundamentales de la creatividad humana. Y en base a ello se ha podido modelar un paradigma neurocognitivo de la creatividad humana y un paradigma computacional de la creatividad.

Para lograr los objetivos planteados, la presente Tesis doctoral se ha estructurado en 8 capítulos, cuyos resultados se resumen a continuación.

Capítulo 1.

Introducción

En el primer capítulo se establecen los objetivos principales y secundarios de la tesis, se muestra el estado del arte de las investigaciones previas, se establece la metodología seguida, y se muestran las aportaciones más importantes.

Capítulo 2.

Creatividad.

Análisis de los principales métodos para estimular la creatividad

En este capítulo, en primer lugar se ha reflexionado sobre el concepto de creatividad, mostrando algunas de las definiciones más representativas que se han realizado a lo largo de la historia. Al analizar estas definiciones se constata que se trata de un concepto muy ambiguo y lleno de matices, aunque en esencia es un proceso complejo de generación y de evaluación de ideas. Todas las definiciones recopiladas son diferentes entre sí, y recogen tan solo algunos aspectos del proceso creativo. No obstante, de entre todas ellas, destacan dos que son especialmente ilustrativas. Una afirma que el componente más importante de la creatividad es el descubrimiento de nuevas relaciones entre diferentes conceptos, con el fin de transformar las normas establecidas, siempre que se resuelva un determinado problema. Otra es mucho más completa, ya que propone que la creatividad es un proceso por el cual el ser humano puede alterar voluntariamente el funcionamiento de su sistema cognitivo, y por tanto cambiar la forma habitual de percibir e interactuar con el entorno, y la forma habitual de establecer conceptos y procesos.

Por tanto, la definición más correcta y completa del proceso creativo sería aquella que pudiera incluir todas las definiciones recopiladas, así como las que se pudieran recopilar en un futuro.

Se hace necesario abordar la definición y análisis de la creatividad de un modo diferente. Lo más adecuado sería identificar un marco taxonómico adecuado que contenga la mayor cantidad de matices en la definición del concepto de creatividad, y que al mismo tiempo, permita analizarlo con rigor y detalle. Por ello, y como resultado de analizar todas las taxonomías propuestas hasta el momento se ha elegido la más completa y adecuada: la *taxonomía 4-P* (*Person, Process, Product, Press*), ideada en los años 60, y recuperada en la actualidad por los investigadores de inteligencia artificial.

Person. Lo que hace que el agente sea creativo.

Process. Las acciones realizadas por el agente para generar resultados creativos.

Product. El resultado creativo (objeto, entidad o proceso).

Press. El entorno cultural en el que evalúa el resultado.

Esta taxonomía proporciona el marco más adecuado y completo para definir y analizar la creatividad humana, y proporciona la referencia más adecuada para dirigir el resto de investigaciones.

Dentro de esta taxonomía, los principales criterios para evaluar el nivel de creatividad de los resultados obtenidos son la novedad, el valor y la sorpresa, aunque también existen otros criterios como la eficacia, la elegancia, la generalización, la imaginación, la apreciación, etc.

No obstante, por muy bien que se elijan los criterios, el proceso de evaluación siempre será un problema, ya que si se reduce su número, algunas ideas no creativas podrían catalogarse como tales. En cambio, si se amplía la cantidad de criterios de evaluación algunas ideas creativas podrían quedar descartadas. Además, dependiendo de cómo se elijan los criterios de evaluación, se pueden premiar determinadas ideas en detrimento de otras. Finalmente, las ideas también pueden ser más o menos creativas dependiendo de cuál sea su entorno conceptual o temporal. Pongamos un ejemplo ilustrativo: la idea de asar la carne (para proteger su interior) no es una idea creativa ya que se realiza de forma habitual, en cambio la idea de asar la madera (para proteger su interior) podría considerarse como muy creativa. Por otro lado, los cuadros de Van Gogh no fueron valorados en el tiempo en el cual fueron realizados, en cambio, hoy en día se les otorga un gran valor creativo.

Teniendo en cuenta el marco taxonómico elegido, se ha realizado una recopilación y un análisis de los métodos más efectivos que estimulan creatividad humana. Del mismo modo, se han mostrado las ventajas e inconvenientes de cada uno, así como los entornos más adecuados para utilizarlos.

La elección de los métodos se ha realizado por su carácter diferenciador, y por su eficacia (número de ideas generadas, y novedad de las mismas), bajo la *taxonomía 4-P*. Cabe decir que todos estos métodos se han diseñado siguiendo pautas metodológicas identificadas al analizar los resultados creativos del cerebro humano, como si fuera una caja negra, y sin conocer su estructura neurocognitiva.

El hecho de que, a lo largo de la historia, se hayan creado estos métodos para estimular la creatividad humana demuestra que el cerebro humano tiene ciertas limitaciones neurocognitivas, y que su funcionalidad debe ser reconducida con la finalidad de que pueda obtener resultados creativos.

En general, los métodos implementados para potenciar la creatividad humana lo que hacen es obligar que el árbol de búsqueda de soluciones se recorra por caminos distintos a los habituales. Solemos resolver los problemas más o menos de la misma forma, ya que solemos utilizar los mismos procedimientos. Por ello, los métodos antes mencionados nos obligan a realizar procesos cognitivos distintos a los habituales, cuando es evidente que estos son estériles. Esto demuestra que el proceso creativo es mucho más flexible y complejo de lo que podría derivarse del análisis de los modelos conceptuales sobre la estructura del proceso creativo propuestos hasta la fecha.

El análisis de estos métodos proporciona una idea general sobre las fortalezas y las deficiencias del cerebro humano para resolver problemas de forma creativa. Además plantea interrogantes que tan solo se pueden resolver investigando la actividad neurocognitiva del cerebro humano. Los métodos para estimular la creatividad se han ido diseñando y modificando, a lo largo de la historia, mediante una metodología de prueba-y-error. Se han ido proponiendo nuevos métodos, y mejorando los existentes, dando palos de ciego, realizando propuestas continuadas y observando posteriormente su efectividad. Y ello ha supuesto un proceso muy lento, y en muchos casos ineficaz.

Cuando se consigue un método eficaz se intentan identificar, de forma especulativa, las razones del éxito, aunque nunca se tenga la certeza. Por ello, muchas veces, cuando en base a estas especulaciones se intenta mejorar un método, lo que se hace es empeorarlo (como ha ocurrido de forma recurrente con las diferentes propuestas de Brainstorming). Por tanto se necesitan otras razones que expliquen y justifiquen el éxito de algunas metodologías para amplificar la creatividad humana, con la finalidad de mejorarlas, o de proponer otras más eficaces. Estas razones podrían provenir del conocimiento de los factores neurocognitivos de la creatividad.

A partir del análisis del comportamiento de las personas creativas, y a partir del análisis de los métodos para estimular la creatividad, se han identificado diferentes modelos conceptuales sobre la estructura del proceso creativo. De hecho, en la presente Tesis se han descrito algunos, y en base a ellos se ha propuesto un nuevo modelo conceptual más completo. Según este modelo, el proceso creativo es un proceso complejo de generación y evaluación de ideas. Este proceso tiene un componente secuencial, y también un componente transversal, y en todo momento se toman decisiones de arriba hacia abajo y de abajo hacia arriba. El proceso creativo se desarrolla en varios niveles de abstracción en cada una de sus etapas, tomándose decisiones de todo tipo, desde las más abstractas y generales, hasta las más concretas y detalladas. Desde el inicio del proceso creativo se proponen ideas, por lo que el proceso de imaginación es fundamental, y sobre todo se basa en la asociación sorprendente de conceptos e ideas previamente conocidas. El proceso creativo también es muy flexible, y en muchos casos es indeterminado, lo que significa que pequeños cambios en la información de entrada pueden generar ideas muy diferentes.

Tanto este modelo, como los propuestos con anterioridad, se están utilizando para encauzar los diferentes investigaciones sobre las bases neurocognitivas de la creatividad. Y del mismo modo, los descubrimientos que se están obteniendo en estas investigaciones se están utilizando para completar y detallar dichos modelos conceptuales.

Capítulo 3.

Estructura funcional del cerebro humano y su relación con el proceso creativo

En este capítulo se ha identificado la estructura neurocognitiva general del cerebro humano que permite la generación de los procesos fundamentales y básicos de su actividad creativa.

Los *factores neurocognitivos fundamentales* que se han identificado son los siguientes:

- Capacidad del cerebro humano para generar procesos neurocognitivos en serie y en paralelo. La actividad creativa requiere recorrer el árbol de búsqueda de soluciones en serie y en paralelo, en diferentes niveles de abstracción, para poder llegar a soluciones sorprendentes y creativas, y el cerebro humano tiene una enorme facilidad para realizarlo. Hemos identificado que los procesos cognitivos en paralelo se desarrollan fundamentalmente por medio de redes de gran escala (*large-scale networks*), que integran diferentes regiones corticales con funcionalidad variada. Los procesos cognitivos en serie se fundamentan por los gradientes de actividad neuronal, desde los nodos sensorimotores, hasta las redes de alto nivel cognitivo.
- Estructura funcional del cerebro humano basada en la activación de redes neuronales de gran escala, que integran diferentes zonas especializadas distribuidas topográficamente de un modo estratégico. El funcionamiento en base a redes a gran escala permite la generación de procesos cognitivos de alto nivel y varios niveles de abstracción. De este modo las mismas redes se activan para resolver problemas aparentemente distintos, y cada vez que se activan no involucran exactamente las mismas zonas especializadas del cerebro. Ello permite la creación de analogías de alto nivel semántico, y la generación de procesos generales de alto nivel de abstracción, que tienen una estructura común, pero con detalles diferentes para cada actividad concreta. Para comprender la actividad cognitiva general del cerebro humano, en este capítulo han especificado y se han analizado las redes y subredes más importantes que se han identificado hasta la fecha, y se han identificado las más relevantes en la generación de procesos creativos.

- Existencia de una *red de integración multimodal* (MIN), que integra el flujo jerárquico de información entre las diferentes *large-scale networks*, a diferentes niveles de abstracción, desde las regiones sensorimotoras a las redes asociativas multimodales de alto nivel cognitivo. La generación de ideas creativas requiere que se puedan realizar paralelismos y procesos cognitivos en diferentes niveles de abstracción, y la estructura multimodal del cerebro lo permite de un modo natural.

- Existencia de una determinada estructura topográfica del córtex. Según la *hipótesis Tethering*, el cerebro humano se ha expandido de forma evolutiva como resultado de la necesidad de una mayor capacidad neurocognitiva para manejar información cada vez más compleja, en entornos sociales cada vez más complejos. La expansión se hizo de tal manera que las diferentes regiones sensorimotoras se separaron entre sí y se desarrollaron nuevas áreas corticales a su alrededor de forma incremental. De este modo, las nuevas áreas, conforme se alejaban de las regiones sensorimotoras podían involucrase paulatinamente en actividades con cada mayor nivel cognitivo, ya que se liberaban de las restricciones de los sistemas sensorimotores. Esto permitió el desarrollo de redes neuronales de gran escala de alto nivel cognitivo, integrando las áreas perimetrales más adecuadas de los diferentes nodos sensorimotores. Como resultado, se producen gradientes de información y la información procesada por los nodos sensorimotores se va transformando paulatinamente, conforme se aleja de los mismos. La información se va haciendo cada vez más abstracta, y se va estructurando por niveles. Por tanto, la estructura evolutiva topográfica del cerebro humano permite la generación de pensamientos abstractos, algo fundamental para la generación de ideas creativas.

- Existencia de las estructuras neurocognitivas básicas para sustentar las componentes fundamentales de la creatividad: generación y evaluación de ideas, imaginación, y manipulación semántica. A continuación se especifican las más importantes:

- Existencia de una estructura neurocognitiva básica (*Triple network model*) para generar y evaluar ideas basado fundamentalmente en la interrelación de tres large-scale networks: la *Executive control network* (ECN), la *Default mode network* (DMN), y la *Salience network* (SN). Dentro de este modelo la ECN se activa cuando la SN detecta un evento relevante externo que requiere atención cognitiva para realizar una tarea concreta orientada a objetivos. En cambio, cuando no existen tareas externas (o cuando las tareas son triviales o requieren experiencia previa) se activa de

DMN. Esta estructura creativa básica justifica muchas pautas tradicionalmente observadas en el proceso de generación de ideas creativas, y quizás el más conocido de todos es el que se conoce como “eureka”. En esta pauta las ideas geniales parecen que surgen de la nada, sin haber realizado un mayor esfuerzo. Sin embargo está sustentado en el modelo neurocognitivo del triple network model.

Cuando el problema está muy bien definido, o es sencillo, generalmente la ECN se activa y suele resolver el problema. En cambio, si el problema está poco definido, o es especialmente difícil, y al mismo tiempo se es muy exigente, la ECN no suele resolver el problema. En este caso por medio de los procesos cognitivos analíticos de la ECN se intenta resolver, una y otra vez, un determinado problema, pero las soluciones obtenidas no son satisfactorias. El proceso infructuoso parece no tener fin, y finalmente se suelen tomar ciertos recesos, intentando “desconectar” con el problema. Y justo en ese momento, en medio del descanso, es cuando una idea aparece en la mente, como si surgiera de la nada.

Lo que ha ocurrido en realidad es que, la SN identifica eventos externos orientados a objetivos durante un periodo largo de tiempo. En este caso se activa la ECN (y se deactiva la DMN) e intenta buscar una solución. Si la solución es insatisfactoria, la ECN intenta buscar otra, mediante un proceso reiterativo y continuado en el tiempo. El proceso se suele prolongar infructuosamente en el tiempo, y finalmente se debe tomar un receso. En este caso, la SN detecta que no hay eventos externos, por lo que se activa la DMN y se deactiva la ECN. La DMN intenta resolver el problema, de forma inconsciente, manipulando tanto la información de entrada, como la información parcial generada con la ECN. La DMN provoca igualmente la mezcla de la información disponible con información personal y sensorial, por lo que es capaz de recorrer el árbol de búsqueda por otro camino, y de este modo se puede llegar a una solución creativa inusual, difícil de alcanzar por caminos convencionales. La SN detecta ahora un nuevo evento saliente (una posible solución generada internamente) y se activa la ECN para poder evaluarla convenientemente de forma consciente, y con la ayuda eventual de la DMN. Es posible que la ECN nunca pudiera dar con esta solución, ya que utiliza estrategias rígidas y más convencionales. En cambio la DMN utiliza estrategias más flexibles, modificando sutilmente la información en curso, y mezclándola con información personal almacenada en memoria, y con información sensorial y cognitiva en curso.

En este proceso la corteza dorsolateral prefrontal izquierda (DLPFC) juega un papel fundamental ya que es responsable de priorizar los pensamientos autogenerados en situaciones de baja demanda (*context-dependent prioritization of off-task thoughts*). La MTL (componente de la DMN) contribuye también en los procesos asociativos permitiendo la generación de ideas creativas.

La DMN tiene una doble funcionalidad, ya que contribuye a la generación de ideas creativas (por su bajo nivel de control de la información), y también contribuye a la evaluación de ideas (ya que está involucrada en el proceso de evaluación afectiva y visceral). De forma alternativa, la ECN contribuye al proceso de evaluación analítica de la actividad creativa. La DMN también está involucrada en lo que se denomina "evaluación del yo interior", es decir, en la evaluación de un problema tomando como base la información más interna y personal. Igualmente se involucra en el placer profundo generado en la contemplación y evaluación de las obras de arte que conectan directamente con lo más profundo de nuestro ser (catarsis estética), lo cual es un ingrediente fundamental para la capacidad creativa humana.

- Existencia de una estructura neurocognitiva básica para imaginar cosas y planear el futuro. La creatividad implica la visualización futura de algo que aún no existe. Por tanto, en el proceso creativo, aunque de forma borrosa y ambigua, se deben hacer planes, del mismo modo que las personas proyectan sus metas personales. Al imaginar y planificar para el futuro, se deben llevar a cabo dos procesos diferentes:

    - *Simulación de procesos*. Es el proceso de visualizar los pasos que se deben dar para obtener una determinada meta.
    - *Simulación de resultados*. Es el proceso de visualizar los efectos que se obtienen cuando se ha logrado una determinada meta.

Como se ha dicho, la actividad creativa es muy compleja y es el resultado de varios procesos diferentes. Uno de estos procesos consiste en la visualización de los pasos a seguir, y en la visualización de los resultados que se pretenden alcanzar. Por un lado, se deben visualizar los pasos necesarios que se deben realizar para lograr un determinado objetivo, y por otro lado, se debe visualizar el resultado deseado, con la finalidad de experimentar el placer de las posibles recompensas asociadas (reconocimiento, logro personal, dinero, etc.). El cerebro dispone de procesos neurocogntivos muy poderosos para entrelazar información, e imaginar eventos y escenarios inexistentes, lo que le permite una enorme capacidad creativa.

- Existencia de una estructura neurocognitiva básica para realizar procesos semánticos a diferentes niveles de abstracción. Como se ha visto, a lo largo del proceso creativo se debe manipular la información con diferentes niveles de abstracción, desde aspectos más generales, hasta aspectos más concretos. Los aspectos más generales pueden ser compartidos por mayor cantidad de entes, objetos o ideas, lo que permite recorrer el árbol de búsqueda de soluciones por caminos más variados. Por tanto se necesita una correcta estructura semántica de la información y un correcto sistema de procesado de la misma.

  Según estudios recientes, la memoria semántica se genera en el cerebro por medio de un centro transmodal. Los paradigmas neurocognitivos clásicos asumían que las regiones de modalidad específica interactúan directamente para generar conceptos multimodales. No obstante se ha descubierto que el cerebro dispone de un *centro semántico intermodal* en el cual se llevan a cabo las funciones semánticas. En base a esto, los conceptos se crean en base a una combinación de representaciones transmodales y de modalidad específica. Por supuesto, la información de la modalidad específica es una fuente básica para la construcción de conceptos, pero es insuficiente, ya que los diferentes “atributos” (características de los objetos) se combinan de manera compleja y no lineal al formar un concepto. En este contexto, el *centro semántico intermodal* puede proporcionar dos importantes "funciones semánticas":

    - Permite mapeos correctos entre los "atributos" de la modalidad específica y un determinado concepto relevante.
    - Permite representaciones transmodales que proporcionan la base para hacer generalizaciones semánticas teniendo en cuenta las similitudes conceptuales, en lugar de las similitudes superficiales.

Capítulo 4.

El papel fundamental de la DMN en el proceso creativo

En el capítulo anterior se han analizado los *factores neurocognitivos fundamentales* de la creatividad humana, y se ha observado que la *Default mode network* (DMN) tiene un protagonismo indiscutible. Por ello, se ha dedicado un capítulo completo a su estudio, y se han identificado varios factores que la involucran directamente en la actividad creativa del cerebro humano. Entre estos factores, se destacan los siguientes:

- La DMN está directamente involucrada tanto en la generación de ideas (a través de su gestión de los pensamientos autogenerados), como en la evaluación afectiva y visceroceptiva de las ideas (por su capacidad de gestión de la memoria, en tareas relacionadas con la memoria autobiográfica, episódica y semántica, divagaciones mentales, toma de perspectiva o pensamiento futuro).
- La DMN se encuentra al final del gradiente principal, por lo que manipula información abstracta, que puede estar compartida por varias tareas diferentes en las cuales pueda estar involucrada, y que tan solo difieren entre sí en detalles específicos. Ello le permite involucrarse también en procesos cognitivos de alto nivel, que aparentemente no están relacionados entre sí, pero que comparten una estructura abstracta común. Igualmente le permite involucrarse en procesos cognitivos autobiográficos y relacionados con la imaginación de situaciones y escenarios ficticios. Esta característica proporciona a la DMN un papel protagónico en los procesos creativos.
- Los nodos DMN se ubican topográficamente a la máxima distancia posible de las regiones sensoriomotoras unimodales. Ello permite que la DMN manipule información con el mayor nivel de abstracción posible, con poca o ninguna relación con la información sensoriomotora. Igualmente, permite que pueda realizar funciones de alto nivel cognitivo, alejadas del "aquí y ahora". Entre estas funciones, destaca su capacidad de crear pensamientos autogenerados, que es la actividad natural prioritaria del cerebro (en ausencia de tareas externas), y que son la base para la generación de ideas en los procesos creativos. Por otro lado, la estratégica ubicación topográfica de la DMN, permite que se pueda involucrar con una gran variedad de tareas, que aparentemente tienen poco en común.
- La DMN tiene una funcionalidad muy compleja y de alto nivel cognitivo. Inicialmente, tras su descubrimiento, se sabía comúnmente que el DMN se desactivaba al realizar tareas orientadas a objetivos, y también que su actividad se incrementaba cuando no se realizan tareas. Sin embargo, estudios recientes muestran que DMN aumenta su actividad al realizar tareas en las que la cognición y el comportamiento deben utilizar la memoria de experiencias previas relacionadas. De hecho, se ha comprobado que la DMN aumenta su actividad (en condiciones en las que debería permanecer desactivada) al menos en las siguientes ocasiones:
    - Cuando las decisiones a tomar dependen de la información que se haya generado en decisiones previas.

- Cuando los estímulos relevantes para la tarea deben hacer uso de la memoria a largo plazo.
- Cuando se recupera de la memoria el contexto de una determinada tarea.
- Cuando ya se ha codificado una determinada regla de actuación que puede ser utilizada en acciones posteriores.
- Al realizar tareas de memoria semántica, o memoria de trabajo, muy exigentes.

Todas estas circunstancias acontecen continuamente, y de forma entrelazada, a lo largo del proceso creativo.

- La DMN colabora estrechamente con la ECN, y en conjunto tienen contribuciones diferenciales durante las diferentes etapas del proceso de diseño. La DMN se activa más intensamente durante la etapa de generación de ideas y, en cambio, la ECN se activa más intensamente durante la etapa de evaluación de ideas. La DMN participa en una amplia variedad de procesos imaginativos, como por ejemplo los que comúnmente se denominan como: *mente errante*, *simulación mental* y *pensamiento futuro episódico*, que tienen una gran relevancia durante el proceso creativo. En consecuencia, la conectividad funcional entre la corteza prefrontal inferior (IPFC) (región de ECN) y la DMN puede reflejar un control top-down de los procesos bottom-up. En otras palabras, los mecanismos de control cognitivo de la IPFC se encargan de dirigir y monitorear la actividad espontánea de la DMN.

- La DMN tiene patrones de meta-funcionalidad. DMN participa en patrones de actividad genéricos, de alto nivel cognitivo, que pueden ser compartidos por una gran variedad de actividades diferentes y heterogéneas. Entre estas meta-funcionalidades observadas en las investigaciones destacan las siguientes:
  - *Delayed matching*, según la cual la funcionalidad de la DMN puede variar según la forma en que los procesos cognitivos emergen dentro de la estructura temporal de la tarea actual.
  - *Contextual modulation*, según la cual la DMN puede variar su patrón de actividad neuronal en función de la experiencia previa.
  - *Rule-based decision making*, según la cual la DMN aumenta su actividad cuando se utilizan reglas internas para realizar tareas

Estas meta-funcionalidades son esenciales en el proceso creativo.

- La DMN colabora en la elaboración de representaciones cognitivas detalladas durante la realización de tareas. La DMN integra información de regiones inferiores en la jerarquía cortical para formar una representación del contexto neurocognitivo en curso.

Como se ha dicho, la corteza cerebral está estructurada en un espectro específico de regiones que van desde las unimodales hasta las transmodales. En este espectro, a medida que nos alejamos de la corteza unimodal, la actividad neuronal codifica patrones de pensamiento detallados durante los períodos de mantenimiento de la memoria de trabajo. Esto sugiere que la DMN participa en la elaboración de representaciones cognitivas detalladas a través de interacciones con regiones inferiores de la jerarquía cortical. Además, la DMN juega un papel fundamental en las experiencias detalladas en los procesos de la memoria de trabajo durante la recuperación de la memoria, y está involucrado en el nivel de especificidad de la información, o en el nivel de detalle de la información. Todas estas características son fundamentales para el proceso creativo.

- La DMN integra ciertos componentes subcorticales que le permiten desarrollar una actividad muy especial y compleja. Recientemente se ha descubierto que la DMN integra el prosencéfalo basal (BF) y el tálamo dorsal anterior y medio, y ello le otorga ciertas características funcionales adicionales:

  - Permite que se involucre en procesos de memoria, ya que tanto el tálamo anterior y mediodorsal como el prosencéfalo basal constituyen puntos de conexión del sistema límbico
  - El prosencéfalo basal produce acetilcolina, que tiene un importante efecto neurofarmacológico en los procesos de memoria.
  - DMN se asocia con la vía dopaminérgica mesolímbica a través de su conexión con la corteza prefrontal ventromedial (VMPFC) y el mesencéfalo (MidB), lo que le permite involucrarse en la modulación emocional.
  - El prosencéfalo basal y el tálamo pueden actuar como un relevo a nivel subcortical, integrando las redes funcionales primarias y las entradas del tronco encefálico con las redes asociativas de alto nivel. Esto explica por qué la actividad de la DMN “parece surgir de nuestro interior”, ya que está relacionada con la actividad autorreferencial más íntima de nuestro yo (específicamente la MPFC).

- Finalmente, se ha descubierto que DMN colabora con otras regiones del cerebro, habilitando varias funciones cognitivas que son básicas para la creatividad. Entre estas estructuras cognitivas destacan:

  - La *teoría de la variación ciega y la retención selectiva* (BVSR), que indica que la DMN podría generar un proceso descontrolado de generación de información (*variación ciega*) basado en combinaciones conceptuales aleatorias, y la ECN podría realizar un proceso controlado de evaluación de la información generada (*retención selectiva*).

- La hipótesis del *fallo en la desactivación*, que sugiere que una alta capacidad creativa puede estar basada en un "fallo en la desactivación" de ciertas regiones de la DMN durante tareas que requieren atención enfocada externa. Se ha demostrado que las personas muy creativas no son capaces de suprimir la actividad en el precuneus (región de DMN) cuando realizan tareas de memoria de trabajo (en la que interviene el ECN). Esto sugiere que la capacidad creativa, como se ha dicho previamente, se beneficia de la coactivación de regiones de la ECN y la DMN.
- La *hipótesis del control flexible*, que sugiere la existencia de un mayor acoplamiento entre la ECN y la DMN a lo largo del proceso creativo, reforzando la idea de que el proceso creativo requiere un control cognitivo flexible.

En resumen, la DMN juega un papel fundamental en los procesos cognitivos de alto nivel y especialmente en la creatividad humana. Por ello, y en base al nuevo paradigma funcional de la DMN, apoyado en los nuevos descubrimientos experimentales, se ha propuesto cambiar su nombre por DCN (*Deep cognitive network*).

Capítulo 5.

Identificación y análisis de las bases neurocognitivas de la creatividad humana

En este capítulo, y complementando los *factores neurocognitivos fundamentales* previamente identificados, se ha identificado el conjunto general de factores neurocognitivos que sustentan los procesos creativos en el cerebro humano.

Estos factores se han identificado utilizando tres estrategias diferentes y complementarias:

- Análisis de los recientes descubrimientos sobre la estructura y funcionalidad del cerebro humano.
- Resultados de experimentos concretos relativos a la identificación de la actividad cerebral cuando se realizan actividades creativas (habitualmente actividades de pensamiento divergente). En estos estudios se han detectado ciertas pautas neurocognitivas en el momento de realizar actividades creativas (por ejemplo, la activación de determinadas zonas cerebrales, como pueden ser la ínsula o el giro angular, o de ciertas redes a gran escala, como pueden ser la DMN o la ECN).
- Resultados de experimentos concretos no relacionados directamente con la creatividad, pero que tienen una relación directa con ella (por ejemplo, los receptores

de dopamina D2 en el tálamo se han estudiado de forma muy específica, sin sospechar que pudieran estar relacionados con la creatividad humana).

- Paralelismos detectados entre investigaciones neurocognitivas de carácter general, con el comportamiento observado en personas muy creativas, o con la estructura conceptual y metodológica de los procesos creativos (por ejemplo, la estructura jerárquica del cerebro, basada en secuencias vinculadas de procesos de top-down y bottom up, facilita el control top-down de los pensamientos emergentes bottom-up, al realizar tareas creativas).

Como resultado de estas estrategias se han identificado 17 factores neurocognitivos que sustentan la creatividad humana:

- La estructura del sistema cognitivo humano se sustenta en un conjunto de redes neuronales a gran escala, que integran diferentes regiones (especializadas en ciertos procesos cognitivos de alto nivel) ubicadas de modo estratégico a lo largo del cortex.
- Organización multimodal del cerebro que permite flujos de información, transformándola en varios niveles de abstracción.
- Distribución topográfica estratégica de redes de gran escala y sus nodos constituyentes (ubicados a la máxima distancia de los nodos sensoriomotores), permitiendo la existencia de pensamientos abstractos y la creación de pensamientos autogenerados.
- Colaboración estratégica entre la *Executive control network* (ECN), la *Salience network* (SN) y la *Default mode network* (DMN), creando el mecanismo central de la creatividad humana (*Triple network model*).
- La DMN se ubica en un extremo del gradiente principal, manipula la información de mayor nivel de abstracción, tiene un patrón funcional muy complejo. La DMN está involucrada en una gran cantidad de procesos cognitivos relacionados con la creatividad, y juega un papel fundamental en los procesos de generación y evaluación de ideas.
- El lóbulo temporal medial (MTL) juega un papel fundamental en la creación de pensamientos autogenerados.
- El mecanismo de *Desactivación inducida por tareas* (TID) puede tener fallos operativos, y esto permite la mezcla de información no controlada que es manipulada por separado por el ECN y el DMN. La variabilidad de este mecanismo está directamente relacionada con la *capacidad de memoria de trabajo* (WMC).

- La ínsula (y la SN en general) controlan en parte la funcionalidad de la DMN y la ECN, cuando se realizan tareas creativas.
- El giro angular está directamente implicado en la integración de algunos procesos neurocognitivos relacionados con la creatividad. El AG izquierdo juega un papel importante en la creatividad humana porque forma parte de dos redes relacionadas con la creatividad humana (red semántica y DMN). Las personas creativas también tienen una alta conectividad entre la DMN y el giro frontal inferior, lo que se interpreta como una alta capacidad para ejercer un control de top-down sobre los procesos imaginativos generados DMN.
- Los mecanismos de la memoria son borrosos, y no permiten que la información se recupere con exactitud. La información generada en una determinada experiencia se almacena de forma filtrada en la memoria, y además, cuando se desea recuperarla se ha transformado, y ello ayuda a la generación de procesos creativos.
- La memoria episódica facilita los procesos creativos, ya que sustenta la memoria semántica, y se ha comprobado que bajo un proceso de inducción específica episódica se incrementa la actividad creativa, ya que facilita que se recorra el árbol de búsqueda de soluciones por caminos alternativos.
- La memoria semántica es fundamental para el proceso creativo. Los conceptos se crean a través de una estructura transmodal que integra y refina la "información en bruto" generada por las regiones sensoriomotoras y verbales, y la transforma en representaciones semánticas transmodales coherentes, completas y refinadas. De esta manera, la información se estructura en varios niveles de abstracción y con una gran cantidad de atributos, y esta es una condición básica para permitir el proceso creativo.
- Los mecanismos emocionales del cerebro son capaces de representar y almacenar entes, objetos o conceptos de forma más rica y detallada. La disponibilidad de una mayor cantidad de información estructurada en varios niveles de abstracción, y con una mayor cantidad de relaciones permite recorrer el árbol de búsqueda de soluciones por caminos más variados, pudiendo alcanzar soluciones muy creativas.
- La motivación incrementa la robustez, integridad y eficiencia global de las redes neuronales de gran escala, y por tanto también potenciar los procesos neurocognitivos involucrados en la creatividad humana.
- Los cambios en el sistema neuronal de filtrado de información del tálamo, basados en la alteración de los receptores D2, permiten procesar una mayor cantidad de

información. La disponibilidad de mayor cantidad de información (en algunos casos de relevancia media o baja) para ser procesada posibilita que se recorra el árbol de búsqueda de soluciones por caminos menos usuales.

- Las redes a gran escala pueden cooperar, superponerse y reconfigurarse dinámicamente, lo que permite atravesar el árbol de búsqueda por caminos inesperados.
- La estructura jerárquica del cerebro, basada en secuencias vinculadas de procesos top-down y bottom-up, facilita el control top-down de los pensamientos emergentes bottom-up, al realizar tareas creativas.

Capítulo 6.

Paradigma neurocognitivo de la creatividad humana

El conjunto ordenado y entrelazado de las bases neurocognitivas de la creatividad humana permite definir un paradigma neurocognitivo de la creatividad humana. Este paradigma evidencia que el proceso creativo es mucho más complejo, flexible y eficaz de lo que se puede desprender al analizar los actuales modelos conceptuales del proceso creativo. De hecho en la presente Tesis doctoral, y en base dicho paradigma, se ha propuesto un modelo neurocognitivo del proceso creativo, que reestructura, completa y detalla todos los modelos conceptuales propuestos hasta ahora.

Este modelo neurocogntivo del proceso creativo tiene una gran utilidad en cuatro campos de investigación complementarios:

1. Proporciona un marco general dentro del cual se pueden centrar las investigaciones futuras sobre los fundamentos neurocognitivos de la creatividad humana. Este marco muestra tanto los factores neurocognitivos más importantes, como las relaciones existentes entre ellos. De hecho se han sugerido ciertos experimentos concretos, que permitirían completar y detallar el modelo neurocognitivo propuesto.
2. Permite mejorar y complementar los modelos conceptuales sobre el proceso creativo realizados hasta el momento.
3. Proporciona un marco conceptual en el que se pueden evaluar y mejorar las metodologías actuales para ampliar la creatividad humana, así como diseñar nuevas metodologías más eficientes. De hecho se han propuesto nuevas metodologías para amplificar la creatividad humana.

4. Permite implementar estrategias educativas con la finalidad de incrementar la creatividad humana. De hecho se han propuesto algunas, entre las cuales destacan las siguientes:

- Promover el conocimiento general de cualquier disciplina y el conocimiento profundo de las disciplinas preferidas.
- Aprender a detectar paralelismos y patrones comunes entre los diferentes campos del conocimiento.
- Evitar la especialización prematura, antes de tener una adecuada formación generalizada.
- Promover el aprendizaje abstracto sobre los componentes comunes entre los diferentes campos del conocimiento.
- Fomentar el trabajo duro y la documentación exhaustiva sobre el problema a resolver.
- Fomentar la motivación, incluso la obsesión, por resolver un problema.
- Aumentar el nivel de auto-exigencia.
- Forzar períodos de relajación mental después de largos períodos de trabajo duro y obsesivo.
- Aumentar el número de experiencias personales.
- No aceptar ninguna regla social.
- Cuestionar y analizar cualquier tipo de información.
- Tener fuertes experiencias emocionales (tanto positivas como negativas).
- Mezclar la información del problema con la información sensorial del entorno.
- Evitar tomar fármacos que inhiban algún proceso neurocognitivo creativos (por ejemplo, evitar tomar Ritalin, ya que al potenciar atención, se incrementa la capacidad de la memoria de trabajo, y ello induce una disminución de la actividad de los procesos neurocognitivos creativos).

En la presente Tesis Doctoral se han propuesto diferentes ejercicios prácticos para estimular la capacidad creativa de los niños.

5. Finalmente, el conocimiento de las bases neurocognitivas de la creatividad humana abre nuevos caminos para estimularla con la ayuda de sustancias químicas, sistemas biónicos, y sobre todo de la inteligencia artificial.

Se han realizado varias propuestas, y entre ellas destaca la creación de “sistemas de creatividad aumentada”, que son dispositivos electrónicos conectados mediante sensores al cerebro humano, que permiten la excitación de ciertas áreas cerebrales y la inhibición de otras, con la finalidad de estimular la creatividad creativa del cerebro. Estos sistemas estarían igualmente conectados a sistemas informáticos para aumentar la eficacia en la generación y evaluación de ideas, disponiendo en cada momento de una gigantesca cantidad de información relevante.

Capítulo 7.

Paradigma computacional de la creatividad basado en la estructura neurocognitiva humana

Analizando las diferentes bases neurocognitivas que sustentan la creatividad humana se han establecido paralelismos computacionales y se han realizado diferentes sugerencias para el diseño de un sistema computacional creativo. Al agrupar estas sugerencias se puede hacer una estimación adecuada de la importancia comparativa de cada una, y de su aportación particular relativa en el diseño conjunto del sistema computacional. Las sugerencias son de varios tipos, y corresponden a diferentes aspectos del sistema computacional (estructura del sistema, funcionamiento, limitaciones, estructura de la información, estrategias de manipulación de la información, etc.).

Como resultado se ha diseñado conceptualmente un sistema computacional multi-agente (MAS). Este sistema se basa en tres conjuntos de agentes que interrelacionan entre sí de formas variadas, en base al tipo de problema a resolver. Los diferentes agentes de cada grupo pueden asumir roles diferentes, dependiendo de la etapa de diseño en la que se encuentre el sistema. El sistema incluye un sistema de evaluación, con criterios variables, inicialmente establecidos por los usuarios, pero que el sistema puede cambiar, por sí mismo, a lo largo de su funcionamiento. Del mismo modo, se ha propuesto un sistema de representación del conocimiento que facilita la generación de ideas creativas.

Hay que señalar que el sistema multiagente diseñado no pretende emular la capacidad creativa humana. En su lugar, lo que se ha realizado es el diseño de un sistema computacional creativo basado en la estructura neurocognitiva humana. El funcionamiento de este sistema podrá proporcionar resultados similares al cerebro humano en alunas ocasiones, aunque en otras ocasiones podría dar lugar a resultados muy diferentes. En todo caso el diseño de este sistema computacional es tan solo un punto de partida, capaz de inspirar la realización de nuevos sistemas futuros más evolucionados, con una estructura computacional capaz de evolucionar por sí misma, alejándose de la estructura nurocognitiva creativa humana.

Los resultados y el contenido de la presente Tesis doctoral pueden tener especial importancia para los neurobiólogos, ya que les permite tener una visión global de las bases neuronales de la creatividad humana, y ello les permite establecer nuevas estrategias de investigación con la finalidad de completar el paradigma neurocognitivo de la creatividad humana. También es importante para psicólogos y educadores ya que permite la implementación de diversos tipos de estrategias para el desarrollo de la capacidad creativa humana. Es importante para los ingenieros biónicos, ya que proporciona las bases para la implementación de nuevas tecnologías biónicas, capaces de incrementar la creatividad humana. Es importante para la industria farmacológica, ya que da pistas importantes para la creación de sustancias químicas capaces de incrementar la creatividad humana. Finalmente, también es importante para los investigadores de inteligencia artificial, ya que les permite desarrollar nuevos caminos de investigación e implementación de nuevos sistemas creativos computacionales.

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CHAPTER 1

Introduction

1.1. Context

Creativity is the strange ability human beings have to solve problems in a novel and effective way. However, creativity remains to this day a strange and ambiguous concept, since it has a huge number of nuances and variations.

Throughout history, human beings have shown creative behavior that has allowed them to perform all kinds of actions and solve all kinds of problems in a new and surprising way. Initially, it was not known where this strange quality came from, and it was associated with a power lent by superior beings, which varied according to different religious and spiritual beliefs (spirits, groups of gods, a single god). Very recently, in the Renaissance, it was suspected that creativity came from human beings, and specifically from their brain. However, there was no way to know for sure.

As it was not known where creativity came from, they began to design all kinds of methods to stimulate human creativity, based on the analysis of creative manifestations, and the comparison of results. These methods have evolved and improved based on trial-and-error methodology. Until recently, the maximum that could be advanced was in the identification of a set of patterns, which has made it possible to formulate all kinds of conjectures about creativity and how to expand it.

However, completing the accumulated experience, in recent years new techniques have been developed that have made it possible to know a little more about the functioning of the human brain. These techniques also allow us to know a little more about the activity of the human brain when it is performing a creative activity. Consequently, a considerable number of experiments and measurements have been carried out, identifying different types of neural activity when creative activity is taking place. These experiments and measurements are being carried out very carefully and have allowed few specific ideas about the neurocognitive bases of human creative behavior.

However, at the moment a compilation of all these methods and measurements has not been made in order to create a neural-cognitive paradigm of human creativity. This is the main objective of this Doctoral Thesis.

Identifying the neurocognitive bases of human creativity would allow one to grasp the origin of human creative behavior. In the same way, it would allow one to understand the reasons why behind the methods designed to stimulate human creativity work, and therefore to improve the existing methods, and to create new, and more effective ones.

Knowledge of the neurocognitive bases of human creativity would also facilitate the design of cognitive strategies to increase human creativity. In the same way, it would allow the design of artificial intelligence computational systems, capable of emulating, and maybe surpassing, the human creative capacity. These are the secondary objectives of this Doctoral Thesis.

1.2. Objectives

The main objective of this Doctoral Thesis is to identify the neurocognitive bases of human creativity, that is, the differential characteristics of the brain structure and functioning that allow human beings to be creative.

The doctoral thesis has other secondary objectives.

1. Delimit the concept of "creativity" as much as possible, since it is much more ambiguous than it may initially seem. For this, an exhaustive list of definitions of creativity has been compiled, both from a human point of view and from a more general computational point of view.

2. Make a compilation of the most effective methods to improve human creativity. An analysis of each method is carried out, providing reasons for its effectiveness and areas of applicability.

3. Compile and classify the most recent publications on the structure and functionality of the human brain, in order to conveniently frame the neurocognitive mechanisms of human creativity. The human neurocognitive structure based on the interrelation of large-scale neural networks will be analyzed with special care. In the same way, the topographic distribution of the different regions of the different large-scale networks will be analyzed, as well as their position within the multimodal integration network. Finally, the position of the different neural networks, specially the DMN, in the main connectivity gradient is especially analyzed.

4. Based on the conceptual framework established in the previous point, a compilation and classification of the most recent publications on the neurocognitive processes of human creativity is made. This classification is carried out in order to delimit differential aspects of these neurocognitive processes, based on the different methodological aspects of the conceptual creative process.

5. Given that most of the investigations carried out have a specific and specialized nature, a cross comparison of information is done between all the publications collected. In this way, conceptual frameworks can be created that can identify differently, and with as much detail as possible, the different neurocognitive bases of human creativity. These neurocognitive bases, together, provide a neurocognitive paradigm for human

creativity, which provide a suitable general framework to focus future research on creativity. Also, they can provide an answer to the effectiveness, or failure, of the methodologies to stimulate human creativity that have been designed throughout history.

6. Carry out a cross comparison of information between the previously identified neuronal bases of human creativity, with the different methodological studies on the creative process and with the different methodologies to amplify human creativity. In this way, a set of cause-effect relationships can be identified between the different neurocognitive bases, creative behavior, and the effectiveness of the different methodologies.

7. Establishment of a human paradigm of creativity, based on its neurocognitive bases. By analyzing and integrating the major neurocognitive factors that underpin human creativity, a global paradigm of human creativity can be created. To identify this paradigm, we want to create a complete account that describes the structure and functioning of different brain mechanisms, which together allow the human brain to have a great creative capacity. Based on this general paradigm, a set of different strategies can be designed to increase human creativity: education, choice of lifestyle, choice of environment, attitude and behavior. In addition, a set of technological strategies can be provided to increase human creative capacity: pharmacology, biotechnology and artificial intelligence.

8. Establishment of a computational paradigm of creativity, based on its neurocognitive bases. Analyzing of the neurocognitive basis of the human brain, the architecture of a creative computational system can also be designed. This computational system can function under intrinsically human parameters (that is, to satisfy human desires), but it can transcend and can function under broader parameters (not necessarily satisfying human needs).

1.3. Research challenges

To carry out this research work there are several difficulties that must be considered in order to achieve the identified objectives.

- *The need to define the human creativity*

There is a huge variety of definitions of creativity. These definitions show the most important component of creativity according to the author of each definition. Therefore, it can be concluded that there is no complete definition of the concept creativity, and if there were, it would be an enormously extensive definition.

In general, researchers define creativity in a simplified way when generating novel and valuable results, although this definition is obviously very poor. Therefore, to have a complete and accurate idea about the meaning of creativity, the maximum possible number of definitions that are substantially different from each other should be collected.

Based on these definitions, a more comprehensive definition should be proposed that includes all of them and that is complete, general, and accurate.

- *The need to identify all methods to stimulate human creativity*

Throughout history, a multitude of techniques have been implemented in order to stimulate human creativity. Some of these techniques have been shown to be extremely useful, while other techniques are hardly anecdotal. Many of them are very similar to each other and hardly differ in name, while other techniques group several simpler techniques. Therefore, we have first to collect as many techniques as possible and group them into categories. Subsequently, repetitive techniques and those that do not have proven efficacy should be eliminated.

- *The need to identify the neural-cognitive bases of human creativity*

The establishment of methods to stimulate human creativity, and the design of creative computational systems has been based on an analysis of the structure of the methodological problem-solving systems that have been proposed throughout history. These methods have been refined through trial-and-error strategies, and their evolution has been very slow. Some methods have proven to be very effective, while others have not.

To improve the effectiveness of methods for stimulating and amplifying human creativity, and to establish new and more effective methods, it can be very useful to know the mechanisms by which the human brain is creative.

Knowledge of the neurocognitive bases of human creativity would allow us to go straight to the point and establish more efficient methodologies through more accurate trial and error systems. In the same way, it would make the establishment of new educational and behavioral systems that stimulate human creativity possible.

Finally, the knowledge of the neurocognitive bases of human creativity should allow the formalization of a paradigm of computational creativity that emulates human activity, as a previous step to the establishment of a computational paradigm of creativity, which will transcend the human paradigm.

It is often said that to design a flying craft it is not necessary to imitate the beating of the wings of flying animals. And it is true. However, emulating nature is usually a preliminary step to creating more effective artifacts. If you hadn't started by imitating the beating of the wings, you might not have been able to design the propeller. Therefore, emulating brain activity is not the final purpose of computational creativity research, but an intermediate step. The knowledge of the creative capacity of the human brain will undoubtedly allow the design of computer systems that exceed the human creative capacity.

Until a very few years ago it was not possible to visualize the functioning of our brain. Thanks to new technologies, such as *diffusion tensor imaging* (DTI) and *functional magnetic resonance imaging* (fMRI), and new technologies for analyzing the data obtained, it is possible to know a little more about the brain's cognitive structure and functioning. In the same way, it is possible to identify the brain activity when a creative task is carried out. Consequently, the neurocognitive bases of human creativity can be identified. This is the main contribution of this thesis, as up until now there is not a compilation of the main neurocognitive bases of human creativity.

- *The need to establish a neural-based human creativity paradigm*

Based on the analysis of the main known neurocognitive factors that support human creativity, certain directive suggestions can be deduced to create a neurocognitive paradigm of human creativity. In the same way, a set of strategies can be implemented in order to maximize human creative potential.

- *The need to establish a neural-based human creativity paradigm*

Based on the analysis of the main known neurocognitive factors that support human creativity, certain directive suggestions can be deduced to create a neurocognitive paradigm of human creativity. In the same way, a set of strategies can be implemented in order to maximize human creative potential.

- *The need to establish a neural-based computational creativity paradigm*

Based on the analysis of the main known neurocognitive factors that support human creativity, certain directive suggestions can be deduced for the design of a computational system. The total set of suggestions supports the design of a creative computational system. The most suitable general structure is based on a multi-agent system (MAS) composed of three groups of agents.

As a consequence of these experiences, a competitive paradigm of general creativity can be designed.

1.4. Methodology

The methodology followed to achieve the objectives of this Doctoral Thesis is based on the completion of the following points:

1. Compilation and classification of definitions on creativity.
2. Compilation and evaluation of the most effective methods that stimulate human creativity, based on the most representative definitions.
3. Compilation of the bibliographic references related to the analysis of the brain activity when a creative task is being carried out. That is, compilation of information about the neurocognitive creative capacity of the human brain.
4. Classification and synthesis of the different studies that explain the different aspects of the high human creative capacity.
5. Crossing comparing the information and identification of the different neurocognitive factors of human creativity
6. Proposal of a general paradigm for human creativity and computational creativity
7. Based on the analysis of the neurocognitive factors of human creativity, certain strategies are suggested to amplify its creative capacity: education, environment, way of life, attitude, behavior, drugs, biotechnology, artificial intelligence.
8. Based on the analysis of the neurocognitive factors of human creativity, the design of a computational system that emulates, and where appropriate amplifies, human creativity is suggested.

1.5. Structure of the Doctoral Thesis

The research work of this Doctoral Thesis is organized 3 parts, and 7 chapters:

First part. Methodological proposals to stimulate creativity

Chapter 2. Creativity. Analysis of the main methods to stimulate creativity

The objective of this chapter is to provide a definition of creativity, and to analyze the most effective methods to stimulate human creativity.

Creativity is often defined as the ability to solve a problem in a novel and valuable way. That definition can make researchers happy, and gives them a feeling of having the problem under control, but it does not have much to do with reality (e.g., How could the novelty of Van Gogh's paintings be quantified? How could they be valued?).

It is very likely that there is never a complete and seamless definition of creativity (in the same way that there is not one to define the concept of the soul). Therefore, trying to limit creativity, and what is worse, trying to measure it, would be the best way to get away from it.

Therefore, at the beginning of this chapter a compilation and an analysis of the best definitions of creativity has been done, both from a human point of view, and from a more general computational point of view.

Once defined, this chapter compiles and describes the main methods for stimulating creativity. Hence, an exhaustive compilation of all known methods has been made, and a list of the most effective ones has been provided. The functionality of each of the methods is described, and the fields of knowledge for which they are most suitable are indicated.

Usually when analyzing the methods that stimulate human creativity, all kinds of speculation and reasoning can be used to explain their effectiveness. These methods have been used and gradually improved throughout history, by trial and error. As a result, all methods have proven their effectiveness, although it varies for each particular method.

However, while they are known to work, the exact reasons why they work are not known. For this reason, it is essential to analyze in depth the neurocognitive bases of human creativity.

Second part. Neurocognitive bases of Creativity

Chapter 3. Functional structure of the human brain, and its relationship with the creative process

The methods described in the previous chapter, have proven their usefulness throughout history, although in some cases the reasons are not known. These techniques have been designed using trial and error techniques, analyzing the strategies followed in the realization of works that have been considered "creative" throughout history.

Alternatively, the human brain can generate direct paths and achieving creative solutions to a given problem by generating a limited number of possible solutions. In other words, the human brain, in order to guarantee our survival, has evolved over time and has achieved a certain cognitive structure to be able to find “creative” solutions to any new problem that we may face.

Therefore, it is important to analyze why the human brain has such creative potential by focusing on the neural bases of human creativity.

Knowledge of these bases offers three great advantages:

- It explains and justifies the success of the different techniques.
- It allows improving existing techniques and design new techniques and strategies that stimulate human creativity, and
- It allows the design of a computational system that emulates the creative activity of the human brain.

In order to identify the neurocognitive bases of human creativity, it is first necessary to understand in detail the human brain structure and especially its functional structure.

In this chapter a bibliographic compilation of the latest discoveries of the human functional structure is provided. They have been identified through the most recent and advanced technologies of acquisition and processing of information. The latest discoveries on functional gradients, the topography of functional networks (especially from the DMN), and the identification of multimodal systems are also particularly important.

The networks involved in human creativity are described in detail below: Default mode network (DMN), Executive control network (ECN) and Salience network (SN). The general functionality of these networks and especially their connection with creativity is described.

Chapter 4. The fundamental role of the DMN in the creative process

As a result of the analysis of the different large-scale functional networks, it has recently been observed that one of them -which has been erroneously labeled as “Default mode network” - not only has special importance in human cognitive functioning, but also, has a fundamental role in the creative potential of the human brain.

For this reason, this chapter analyzes in depth the functional structure of the Default mode network, and its relationship with human creativity.

Chapter 5. Identification and analysis of the neurocognitive bases of human creativity

In this chapter, and as a result of the analysis of all the experimental studies carried out, the known neural factors of human creativity are identified and classified.

Several types of neurocognitive factors of human creativity have been identified:

- Some factors have been directly identified as a consequence of analyzing the neural activity of creative people, or people not especially creative, performing creative activities. In these cases, certain conclusions have been reached, according to the analyzes carried out.
- Other factors have been identified by analyzing the functional structure of the human brain, which has some specific characteristics that allow creative activity.
- Other factors have been identified by crossing the existing information resulting from the different analyses of brain activity and comparing it at all times with the most important methodological factors of the creative process, from a point of view of the conceptual theory of information.

The set of identified factors provides a general idea of why the human brain has a high creative capacity.

Once the neurocognitive bases of human creativity have been identified, known methods to stimulate human creativity can be improved, and new methods can be implemented. In the same way, human creative capacity can be directly enhanced (through educational, psychological, pharmacological, bionic and artificial intelligence strategies), and a computational paradigm can be implemented.

Third part. Proposal for a human and computational paradigms of creativity

Chapter 6. Neurocognitive-based human creativity paradigm

The objective of this chapter is to provide a set of suggestions for enhancing human creativity. These suggestions are derived from the analysis of known neural factors of human creativity. The analysis of each factor allows us to know its limits, and therefore it allows us to know how to maximize each one, and thus improve human creative capacity.

To enhance the main factors of human creativity, a set of psychological suggestions are provided: education, way of life, assessment of norms, choice of environment, attitude and behavior.

In the same way, a set of suggestions of a technological nature are provided: drugs, biotechnology and artificial intelligence.

Chapter 7. Neurocognitive-based computational creativity paradigm

The objective of this chapter is to make a conceptual model of a creative artificial intelligence system based on the neural factors of human creativity.

In recent years, many computer techniques have been developed under the name of "computational creativity". These computational creativity techniques are based on the analysis of the performance of certain human activities, and they are considered "creative" because they are based on complex algorithms, and they generate valuable and surprising results. In any case, these techniques take advantage above all of the high speeds of computer systems and generate a huge number of alternatives that can be quickly evaluated.

However, up to now, a computational system that emulates human creativity has not been created since the neural bases that may sustain it were not known. Therefore, in this chapter we will propose a computational system based on the neurocognitive structure of the human brain.

Once the different neuronal factors that support the enormous creative capacity of the human brain have been identified, they must be analyzed one by one. The analysis of each factor allows extracting parallels and suggestions for the design of a computational system. In turn, the set of suggestions makes it possible to design the architecture of a computational system that emulates the enormous creative capacity of the human brain.

The most suitable resulting structure is based on a multi-agent system composed of three groups of agents. One set of agents emulates the operation of the ECN, another group of agents emulates the DMN, and the third one emulates the SN.

Once a computational system that emulates human activity has been designed, a computational model of general creativity can be created.

Many factors that sustain creativity are constrained by the human neurocognitive structure, and by the social structure of human communities. Therefore, the concept of general creativity is limited by our personal and social needs. If these constraints are eliminated, a computational model of general creativity can be created, free of human prejudices, and with a much higher creative capacity.

CHAPTER 2

Creativity. Analysis of the main methods to stimulate creativity

Chapter 2. Creativity. Analysis of the main methods to stimulate creativity

In this chapter, the concept of "creativity" will be analyzed, showing that it is a complex and valuable cognitive process, but difficult to define. Creativity has been considered throughout history as a divine gift, or a high-level human quality, capable of solving problems in surprising, novel and valuable ways. In addition, it has been observed that some people have greater creative capacity than others, and based on the analysis of their activity and the results obtained, a set of methodologies have been designed capable of amplifying human creativity, both individually and in groups. In this chapter, an analysis of the main methods designed so far has been done, and an explanation of their effectiveness is provided.

2.1. Analysis and definitions of creativity

The definition of creativity is very ambiguous [1], and initially it can be defined as the ability to create, innovate, generate new ideas or concepts, or new associations between known ideas and concepts, which usually lead to new conclusions, they solve problems and produce original and valuable solutions [2].

The ambiguity of the concept has generated an enormous multitude of definitions about what creativity is throughout history, and all of them are valid and at yet very incomplete [3].

Below, and just to illustrate the above, a small set of definitions of creativity is provided in order to illustrate the difficulty of expressing the concept. All these definitions are valid and of course they are insufficient, however together they provide a valid idea of the concept of creativity:

"It is a process of creating ideas or hypotheses, verifying them and communicating the results, assuming that the product created is something new" [4].

"Ability to represent, anticipate and produce ideas. Conversion of known elements into something new, thanks to a powerful imagination" [5].

"Creativity shows itself by bringing something new into existence. The essential here is in the novelty and the prior non-existence of the idea or product. Creativity is demonstrated by inventing or discovering a solution to a problem and by demonstrating exceptional qualities in solving it" [6].

"Creativity is an emergence in action of a new relational product, manifesting on the one hand the uniqueness of the individual and on the other the materials, facts, people or circumstances of her life" [7].

"Creativity is the ability to produce, form new and restructure stereotyped situations" [8].

"Ability to find relationships between ideas that were previously unrelated, and which manifest themselves in the form of new schemes, experiences or new products" [9].

"Creativity is not a kind of fluid that can flow in any direction. The life of the mind is divided into different regions, which I call 'intelligences', such as mathematics, language or music. And a certain person can be very original and inventive, even iconoclastically imaginative, in one of those areas without being particularly creative in any of the others" [10].

"Creativity is the human capacity to produce mental content of any kind, which can essentially be considered as new and unknown to those who produce it" [11].

"Creative thinking consists in the formation of new combinations of associative elements. The more remote these combinations are, the more creative the process or the solution" [12].

"Creativity is a process that makes someone sensitive to problems, deficiencies, cracks or gaps in knowledge and leads him to identify difficulties, seek solutions, speculate or formulate hypotheses, approve and test these hypotheses, and modify them if necessary, in addition to communicating the results" [13].

"Creative behavior consists of an activity by which man creates a new order on the contour" [14].

"Creativity designates the ability to produce new solutions, without following a logical process, but establishing distant relationships between the facts" [15].

"Creativity is the process of being sensitive to problems, deficiencies, gaps in knowledge, overlooked elements, disharmony, etc.; to summarize valid information; to define the difficulties and identify the invalid element; to seek solutions; to make assumptions or hypothesize about deficiencies; to examine and test these hypotheses and modify them if necessary, perfecting them and communicating the results" [16].

"Creativity is a complex mental process, which involves: attitudes, experiences, combinatorics, originality and play, to achieve a different production or contribution to what already existed" [17].

"Creativity can be considered a way of solving problems, through intuitions or a combination of ideas from very different fields of knowledge" [18].

“Brain capacity to reach new conclusions and solve problems in an original way. It is related to the effective integration of both cerebral hemispheres” [19].

"Process that compromises the totality of the psychological behavior of a subject and its correlation with the world, to conclude in a certain product, which can be considered new, valuable and appropriate to a context of reality, fiction or identity" [20].

“Creativity is like the ability to illuminate new relationships, to transform the given norms in such a way that they serve for the general solution of the problems given in a social reality” [21].

"Creative thinking can be defined as a metacognitive process of self-regulation, in the sense of the human ability to voluntarily modify its own psychological activity and its behavior or self-monitoring process" [22].

The first conclusion of such a high number of definitions is that the concept "creativity" may never be defined with exactitude, since it encompasses many different manifestations, contains a certain degree of ambiguity, and has an important subjective component.

The term also has an important cultural and social component, which changes with the passage of time, and what for some may seem very creative and ingenious, for others it may be something without merit, or even stupid. As if that were not enough, creativity has often been related to certain mental disorders and illnesses, or certain personal peculiarities, which compounds the problem of proposing an enlightening definition.

Of all the definitions shown, the most important are the last two. *Wollschalager* [21] believes that the most important component of creativity is the discovery of new relationships between different concepts, in order to transform established norms, as long as a certain problem is solved.

On the other hand, *Pesut*'s definition [22] is much more complete since it proposes that creativity is a process by which humans can alter the functioning of their cognitive system voluntarily, and therefore change the usual way of perceiving and interacting with the environment, and the usual way of establishing concepts and processes. Despite the fact that their cognitive systems have been shaped in their first years of life, humans are capable of altering their functioning and looking for new cognitive functionalities. In this way, humans can solve problems by traveling search paths, the existence of which was unknown a priori.

This creative ability of human beings to self-regulate their own cognitive system makes them unpredictable, it has been one of the fundamental components that has allowed us to evolve so much since our origin, manipulating our environment at all times, adapting it to our needs.

In any case, creativity is one of the most important and valued characteristics of human beings, since it allows them to solve problems in surprising and novel ways, which guarantees their happiness and survival. And for this reason, throughout history, innumerable methods have been developed to stimulate it.

2.2. Universal, computational and human creativity

In the previous sections, an attempt has been made to define human creativity, and until recently it was thought that it was the only possible type of creativity. However, with the development of computers, capable of performing increasingly complex tasks, the issue has radically changed.

The first question that is usually addressed when analyzing creativity is whether it is a uniquely human process, or whether on the contrary it can be carried out by machines, and ultimately whether there is a universal concept that can define it in a general way.

Some thinkers and philosophers initially thought that creativity only makes sense in human beings, and that it could not be emulated by machines, although this has recently been refuted by several researchers by the following arguments [23]:

1. Creativity is simply a combination of cognitive processes, and therefore simply must be identified, and later it could be emulated using machines. Even social factors and luck could be emulated by computers [24].

2. Complex life experiences are undoubtedly impossible to implement using computer systems at this time, but they can be provided with framing information to create the illusion of a human-like experience [25].

3. It has been argued that computers cannot emulate "real" consciousness, the "real" understanding, or the "real" creativity. But in reality, what happens is that there is a lack of definition of these concepts, and this does not imply that they cannot be emulated by means of computers. In fact, it is known that human processes of a high cognitive level, such as common sense, consist of a set of concepts defined imprecisely, and induced by sensory perception, and as a consequence can be emulated by means of computers. Even consciousness is a complex mode of self-monitoring and therefore could also be emulated by means of computers [26]. All that is required is to define these terms in detail, as well as the neurocognitive mechanisms that support them.

Therefore, it is possible that in the more or less near future computational systems may be able to imitate complex human cognitive processes, and among them the human creative process.

However, when implementing a creative computational system, the question arises as to whether this system should be limited to emulating human creativity, or if it should follow a human concept of creativity, or if, on the contrary, it should be implemented under a more general concept. It is clear that computational creativity should not be measured under human standards [27], because human creativity aims to satisfy humans. Computational systems capable of performing creative actions could be designed under their own criteria, that is, under non-human criteria. However, that would imply that humans, at least in an initial stage, should create non-human evaluation systems with which to weigh the level of creativity of the results generated by computer systems. This question is very complex as it would force humans to transcend and think as non-humans, which is very difficult considering the limitations of the human neurocognitive system. Yet, some proposals have already been made, such as autonomy-based models [28], or categorization models [29]. However, a creative computational system designed under non-human criteria would create very creative solutions, but they would probably not be to the liking of human beings.

The human process of generating ideas, and especially the human process of evaluating human ideas, is strongly restricted by three factors derived from human nature: shared prejudices in a given cultural environment, different possible neurocognitive structures of the human brain, and by intrinsic human characteristics [30].

- *Shared cultural prejudices*

In the idea generation stage, it is inevitable that some of them are restricted due to prejudices, ideology and cultural and shared social values. Even if you try to generate ideas free of prejudice or social ties, some ideas are censored almost immediately and are not even mentally visualized.

- *Human neurocognitive differences*

Each human being has a slightly different neurocognitive system, as a consequence of genetic inheritance, and achieved development, especially in their first years of existence. Therefore, each human brain has different potentials and limitations.

- *Human intrinsic characteristics*

The ultimate objective of the creative generation of ideas is to solve problems so that the human being can survive, or can live with the greatest possible well-being, both individually and as a member of a community.

Therefore, the generation of creative ideas is strongly limited by the essence, interests and intrinsic characteristics of human beings.

If we could transcend and think more broadly, breaking our own limits as humans, we would be in a position to establish a computational paradigm of creativity.

However, computational systems also have their own limitations (knowledge representation systems, information processing strategies, etc.), so that computational creativity would also be restricted. Once again, it would be necessary to transcend and reason as a computational system without limits, to establish a general paradigm of creativity. Something that, for now, seems out of reach.

At the moment computational creativity is being developed under human criteria, that is, systems that produce creative results to the liking of humans. Computational systems are being designed under classical structural premises, although suitably adapted, trying to achieve the maximum level of autonomy.

The main problem that computational creativity faces is the establishment of adequate evaluation systems. The best taxonomy to delimit evaluation systems established so far is what is known as *the four P*, created in the 1960s [31], but recently embraced by computational creativity [32]. This taxonomy is based on four points:

Person. What makes the agent a creative one.

Process. The actions taken by the agent to generate creative results.

Product. The creative result (object, entity or process).

Press. The cultural environment that evaluates the result.

Within this taxonomy, the main criteria for evaluating the creativity level of the results obtained are *novelty*, *value* and *surprising*, although there are also other criteria such as *effectiveness*, *elegance*, *generalizability*, *imagination*, *appreciation*, etc. [33].

In general, in this doctoral thesis, when referring to creative ideas I will refer at all times to their level of surprise, novelty and value, but in reality, I will be referring to all the evaluation criteria that can be established.

2.3. Basic principles to stimulate the generation of creative ideas

Throughout history, an enormous number of methods have been designed to stimulate human creativity, that is, to solve problems creatively. Some of the most effective and widely used methods are described in the next section, although there are of course many more.

It is very difficult to establish a classification of these methods based on common factors, so they will be described in no particular order.

However, it is possible to establish certain characteristics common to all of them. That is, certain basic principles can be determined on which all known methods to stimulate human creativity are based [34]:

1. Abundance of ideas

The main goal of any method designed to amplify human creativity is to maximize the number of ideas generated, since the more ideas that can be generated, the more creative ideas could be found among them.

Nature follows this same principle and generates an enormous number of alternatives, in the hope that some of them will be successful. Nature generates a huge variety of living beings, with different combinations of attributes, with the aim that some of them are especially successful in an ever-changing and indeterminate environment. That is, nature proceeds by the principle of abundance and not by the rationalization of a certain process.

Therefore, the different methods that can be designed must be capable of generating a huge amount of ideas. In addition, an idea can lead to the immediate generation of a new idea, so the effect is multiplier. Even some partial details of an idea can generate new and creative ideas. It is necessary to generate an enormous number of ideas so that they can be evaluated at a later stage. These ideas can be combined and compete with each other, so the evaluation process can be greatly simplified.

2. Create in group

A group of people is usually more creative than just an individual. Even very creative people, over time, tend to meet from time to time (in small groups) to stimulate their individual creativity.

A single person can also imitate a group, as they can change roles continuously, as if it were a small different group of people.

In general, group work is much more effective than individual work (Engels said that one person cannot carry a 5-meter beam, while two people can easily carry it). In the same way, it has been shown throughout history that group work produces a greater number of creative ideas.

3. Association of ideas

One of the best ways to generate creative ideas is to mix previous ideas together, especially ideas that are seemingly unrelated. This methodology has generated an enormous amount of creative ideas throughout history.

To understand the concept it is convenient to give an example. Toyota created a method of car manufacturing called "just in time" or "series one", in which two seemingly opposing concepts merge, such as the mass production of several cars and the careful manufacture of a single car.

Initially, automobile manufacturing was related to the careful, artisanal manufacture of a single "ready-to-use" product. And Toyota knew how to combine this concept with the concept of mass production.

4. Generation and evaluation process

In general, the idea generation process has two fundamental stages:

- Generation of ideas
- Evaluation of ideas

In the idea generation stage, all kinds of ideas are generated, many of them absurd or ridiculous. However, at this stage no idea can be evaluated, not even a small criticism can be made, since in this way the fluid process of generating ideas would be interrupted.

It is very likely that an absurd idea is simply an intermediate link in a chain that can lead to a creative, novel and valuable idea. Premature evaluation of this absurd idea would interrupt the process and the creative idea that might be generated later in the same idea generation process could never be achieved.

This is valid for both individual methods and group methods. When a single person begins to generate ideas, he should not evaluate them prematurely. He must not take anything for good, but neither must he take anything for bad. In this way, a creative process of generating several ideas is stimulated, which merge with each other and create new ideas.

Only when a certain set of ideas has been created can they be evaluated, to discard certain ideas or refine aspects of other promising ones. New ideas will most likely emerge in this evaluation process.

2.4. Analysis of the main methods to increase creativity and suggestions on why they are thought to work

Throughout history, a set of methodologies in order to solve problems creatively as efficiently as possible have been created. The increase in the size of the human network and the resulting complexity of its social relationships has forced us to seek alternative, creative solutions to solve problems, since due to their complexity and novelty they cannot be solved with conventional methods.

It is very difficult to classify the techniques that allow creative problem solving, since there are a large number of methodologies, and at the same time many of them are variations of the same theme. However, for purely practical purposes, the most important ones are listed below.

1. *Establish analogies with known problems*
2. *Creativity matrix*
3. *Morphological Analysis*
4. *Problem solving (vertical thinking)*
5. *Brainstorming*
6. *Brainstorming variations*
7. *Graphic Brainstorming*
8. *www-Brainstorming*
9. *Attribute List method*
10. *Checklist method*
11. *Scamper method*
12. *Lateral thinking*
13. *Parallel thinking*
14. *Sensanation method*
15. *Systematic Innovation method (TRIZ method)*

These methods will be described and analyzed in next section, describing their strengths and weaknesses. Based on this analysis, a set of suggestions will be deduced for each method in order to design a conceptual model to implement an A.I. computational system capable of emulating these methods, and to overcome its creative efficiency.

2.4.1. Establish analogies with known problems

2.4.1.1. Method description

The most common way to solve problems creatively is to *identify analogies with known problems* that have been previously solved successfully. From childhood we continually establish analogies and do things in a way similar to how other people do things. In the same way, when facing new problems, the first thing we do is try to identify analogies with previously solved problems, and in this way, we establish guidelines for their resolution [35].

Figure 2.1. Low level abstraction analogy-based design. Design of a tap as an analogy to a water extraction system

Analogies can have different levels of abstraction, from concrete and trivial analogies, to conceptual and abstract analogies, difficult to establish immediately. The establishment of analogies with a low level of abstraction implies a low level of creativity. For example, there is a low-level abstract analogy between driving a bus over a one-way bridge (on a two-way highway) and driving a truck over that same bridge. Instead, there is a highly abstracted analogy between driving a bus over a one-way bridge and managing financial investments.

The analogies therefore can be of all kinds and can belong to different fields of knowledge. For this reason, when certain knowledge is acquired, it must be represented at various levels of abstraction, in order that it can be manipulated at different levels of abstraction, and consequently establish analogies at various levels of abstraction.

In general, any activity and any concept learned by human beings can be assimilated with various levels of abstraction. The lowest levels of abstraction are very concrete and are directly associated with the with the basics of the activity learned (Fig. 2.1), whereas the highest levels of abstraction can be associated not only with the activity learned but with a huge range of activities that can share the same general and basic abstract characteristics (Fig. 2.2). For example, when you learn to write a book, you are learning not only to write a book, but you are also learning general compositional strategies that can be used to correctly compose any artistic work. Therefore, these general compositional strategies can be applied, for example, in the composition of a musical theme, or a painting artwork.

Figure 2.2. High level abstraction analogy-based design. A car based on a highly abstracted analogy with a musical group is encouraged. In order for these analogies to be made, knowledge must be represented with an enormous number of attributes, with a great variety of possible values.

An example can help to understand the idea. An expert chef knows exactly how a meat steak behaves when roasted or fried at high temperatures. From his experience, any chef knows that by subjecting a piece of meat to a high surface temperature quickly, the crust crystallizes, changes its texture and its rigidity, thus protecting the innermost layers of the meat. Heat cannot so easily pass through the burned layer and it does not alter the nutrients in the interior. For this reason, the grilled or fried steak has a very attractive texture on the palate and also retains many of its nutritional qualities.

Well, a chef would be in a position to solve a construction engineering problem that apparently has nothing to do with the act of frying, such as protecting a wooden beam from fire. The cook might suggest that the wooden beam be designed a few inches thicker. In this way, if a fire were to start, the surface layers of the wood would be burned, and this burned layer would protect the interior wood from being consumed by the fire (Fig. 2.3). In this way, an architect with cooking knowledge would have a better chance of creatively solving a problem of fire protection of wooden beams, than if he did not have them.

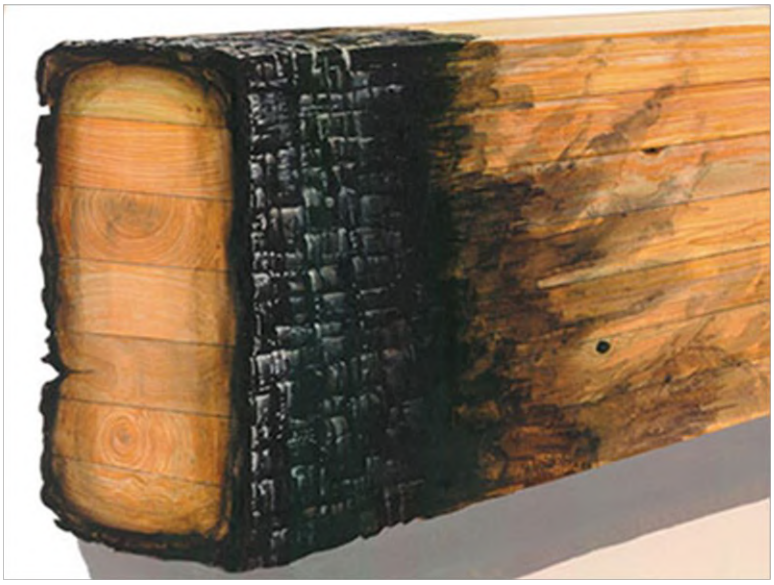

Figure 2.3. Wood beam burned with its interior almost intact. A high-level analogy of abstraction with a steak well fried on the outside, creating an outer charred layer that protects its interior from fire, preventing the nutrients inside from being destroyed.

Therefore, the more information you have about different fields of knowledge, the more analogies, with a high level of abstraction, can be made between them, and as a consequence, a greater number of creative ideas can be generated. This explains one of the common stereotypes that creative people have information from various fields of knowledge, different from their main professional activity.

Analogies are usually made between things that apparently do not have in common, but that share certain high-level abstraction attributes.

For example, to support a roof and at the same time allow passage into an open building, the most basic, direct and functional idea is to use tree trunks or slender stones. With the passage of time the idea was refined, and abstract analogies were established, creating pillars or columns. Through an inverse redundant process, analogies were established between columns and stones, tree trunks, and trees; and different column designs were established. Finally, in the design of the columns, analogies of a high level of abstraction were established again, transforming them into statues of men or women. These analogies could be established by the fact of having correctly defined the knowledge structure of the different objects, establishing a high number of attributes, which can have a high number of possible values. Columns have the attribute "support things", or "slenderness", but equally people can also have these same attributes. Similarly, the attribute "support things" can have a wide variety of possible values. Sooner or later, any craftsman, while working, could see workers supporting blocks of stones, which also had a slender shape. For this reason, and through a semantic transfer of meaning, it was possible to reach the conclusion that human bodies could be used to support building roofs. The idea of using human bodies might seem fanciful, but, failing that, sculptures of human bodies could be used. And nothing more resistant and at the same time, slender, and beautiful, than the sculpture of a woman (Fig. 2.4).

Once a new object is created, a set of attributes and meanings must be associated with it, and the more extensive and varied they are, the more high-level semantic analogies can be established with them.

Figure 2.4. High-level semantic analogy between a column, and a woman

For example, once a column has been associated with a sculpture and a woman, the logical thing is that in this process its list of attributes, and possible values, has been expanded. A column, under the broadest possible concept, must have attributes such as "beauty", "slenderness”, "compositional structure", "proportions", and so on. by which concepts such as "classicism", "elegance", "representativeness", "purchasing power", etc. are associated. These attributes (and their associated meanings) can also be carried over to other objects that are intended to be designed. If you want to design a certain object with these qualities, you must establish certain parallels and perform an extension of attributes and a semantic transfer. Based on them, the process must be repeated, establishing new parallels and new semantic transfers, until the design of the new object is finalized. For example, if you want to design a dress, the capital can be attached to the chest, the shank to the body of the dress, and the base to the lower part of the dress. Once the initial parallelism has been established, the entasis of the shaft can be associated with the shape of the body, the stretch marks with the ruffles of the dress, the folds on the chest with the shape of the capital, etc…. In this way a new, completely new and valuable dress design can be created (Fig. 2.5).

Figure 2.5. High-level semantic analogy between a woman's dress and an Ionic column

The process of establishing analogies, having several levels of abstraction, is very powerful and effective. There are so many possibilities of the process that by many analogies that have been established to solve a certain problem, there will always be an enormous amount of possibilities. Sometimes you tend to think that certain exploration paths in the search tree are exhausted, but that is not the case. What happens is that throughout our lives, serious limitations have been established to our creative neurocognitive capacity. This is why groups are often used, rather than relying on individual people. The group allows for the cognitive diversity that an individual has lost throughout his life. Therefore, the process of establishing analogies, at different semantic levels, must be properly trained.

An additional ability to establish analogies is that the resulting idea can be exported again, and on a recurring basis, to another field of human knowledge (Fig. 2.6).

Figure 2.6. Recurrent establishment of high-level semantic analogies

2.4.1.2. Evaluation

The method of establishing analogies is the one most used by human beings. From the moment we are born we learn to imitate the behavior of others. We never perform an exact imitation, since the imitation mechanism differs subtly between each person, based on their personal characteristics, and those of their environment. Therefore, each time we imitate, we create something a little different.

When we imitate, we also learn the characteristics of the imitated, as well as the characteristics of its environment. In this way we associate a specific problem with a specific process to solve it. As our experience increases, we learn that when a problem is similar to another previously solved, it is possible that the same resolution process can be applied, although some small modifications may have to be made. Sometimes the analogy is very direct, on the other hand, sometimes the analogy is more indirect, and more difficult to detect. However, with the passage of time we enrich both the characteristics of the different objects, entities and concepts that we use. In this way, common attributes can be established between apparently different objects, entities or concepts, but in reality they have remarkable analogies, although they are not obvious to the naked eye. However, when these analogies are identified at a high level of abstraction, the resolution processes applied previously can be used (subtly modified).

Therefore, whenever we are faced with a problem, the first thing we usually do is identify which problem it resembles among those that we have already solved before. Next, we identify the resolution process we have previously used, and that must necessarily be subtly modified to adapt to the environment of the new problem. In this way, over time, we accumulate an arsenal of problem-solving strategies, based on the establishment of analogies.

However, it is not always easy to identify analogies naturally, so considerable effort must be made. Some people find it very easy to establish analogies, while others do not. Initially it seems that the ease of establishing analogies depends on the cognitive structure of our brain, and that therefore it has been established genetically and by the specific environment in which we develop the first years of our existence. However, this ability to establish analogies can be trained at any time. And for this, the information we manipulate must be enriched to the maximum, increasing the number of attributes of objects, entities or concepts.

2.4.2. Creativity Matrix

2.4.2.1. Method description

The *Creativity Matrix* is a method of assured effectiveness to stimulate creativity in solving problems that have a limited range of possible solutions [36].

The method consists of a combinatorial explosion between the different possibilities of each aspect that you want to take into account in solving a certain problem.

It begins by specifying the problem to break it down into its essential elements or basic structures. Below is a list of possible and desired variations for each identified parameter. In this way, a matrix of combinatorial possibilities is created between the different parameters and their possible values. The number of parameters and variations will determine the complexity of the matrix (for example, a matrix with ten parameters, and each of which with ten variations, allows 10 billion potential combinations). Once the matrix is defined, you can randomly walk through the parameters and their variations, selecting one or more from each column and then combining them in completely new ways. In this way, all combinations of the matrix can be examined to stimulate new points of view to solve a certain problem.

When using creativity matrices with many parameters, it may be useful to examine certain combinations at random, or alternatively it may be useful to focus on certain combinations that may seem especially fruitful, depending on the problem specification. Below are two examples that can help to understand their creative possibilities.

Example 1. Creativity Matrix to design new lighter models

In the *Creativity Matrix* (Fig. 2.7) at least two basic parameters must be specified, such as the fuel and the ignition system. In addition, for each parameter, the greatest number of possible values must be established, that is, the greatest possible number of ignition systems and the greatest possible number of types of fuel. Next, crosses are established between the different values of the different parameters in order to focus on each of the possible pairs.

		Ignition system						
Fuel		Stone	Electric arc	Chemical reaction	Heat	Ionization	Solar Radiation	Electromagnetic radiation
	Gasoline							
	Alcohol							
	Electric battery							
	Biomass							
	Liquid gas		**X**					
	Gas							
	Solar radiation						**¿?**	
	Electromagnetic radiation							

Figure 2.7. Creativity Matrix for designing lighters

One of the possible pairs (Fuel: "gasoline"; Ignition system: "stone") is very common and has been widely used for the design of lighters throughout history (Fig. 2.8). On the other hand, when choosing less common combinations, for example (Fuel: "solar radiation"; Ignition system: "solar radiation") is completely new and allows for the devising of a new lighter powered by solar energy. The association limits and the scope of the search for solutions forces focus on a specific design.

Figure 2.8. Design of gasoline-stone lighter

If a designer were asked to design a very novel lighter from an energy point of view, it would surely take a long time to establish this combination. On the other hand, by means of a *Creativity Matrix*, all kinds of combinations that are very novel can be forced and cause any desired combination. Also, once a certain combination is forced, the designer can focus on solving the new design problem created by that combination. In this case, it would not take long for the designer to devise a magnifying glass to concentrate the solar radiation and thus light the cigarette (Fig. 2.9).

Figure 2.9. Design of solar-solar lighter

The creativity matrix is an associative method that encourages the creative design of objects, by forcing combinations that are unusual. These forced associations focus attention on a specific design problem and allow the generation of ideas to solve the problem framed in the specific association. In a first stage, all kinds of strategies can be used to generate ideas, although due to the simplicity of the problem, and the strange nature of some associations, an idea is always generated. However these initial ideas are usually very basic and rudimentary.

Figure 2.10. Evolved and advanced design of solar-solar lighter

In a second stage, you can study the details of each one of the first ideas and refine their design. You can even have new ideas so that the design can evolve (for example, through the *vertical thinking* technique). In this sense, the solar lighter created initially can evolve, and it can be foldable, take up less space, be more protected, be more transportable and be more attractive to the eye (Fig. 2.10).

Example 2. Creativity Matrix to design new pen models

To create a new pen model, four possible attributes can be considered (Fig. 2.11).

Shape	*Material*	*Cap*	*Ink source*
Multi-sided	Metal	Bonded cap	No replecement
Squarre	Glass	**Without cap**	Permanent
Cilyndrical	**Wood**	Retractable	**Metal replacement**
Sculpture shaped	Paper	Disposable cap	Plastic replacement

Figure 2.11. Creativity Matrix for designing pens

As can be seen in a *Creativity Matrix*, both conventional and creative solutions have the same value, which leads us to think that creative solutions are simply infrequent solutions. Therefore, the reason why some solutions are more frequent and less creative must be analyzed, while others are less frequent and more creative.

The main reason is that human beings, in order to guarantee their survival, have developed a cognitive system that rewards the continuous use of known and apparently safe paths, as opposed to less-known paths. For this reason, human beings tend to repeat behavior patterns and problem-solving patterns, and it is difficult for them to identify and choose new paths in decision-making. For this reason, computer systems have a huge advantage over human beings.

2.4.2.2. Evaluation

Each human being has developed a different cognitive system, based on their genetics and their training. For this reason, it tends to solve problems through a certain set of strategies that have been improved upon over time. The development of these optimized strategies allows solving problems in a certain way, exploring common paths, but instead they make it difficult for you to take different paths within the general tree of search for solutions. For this reason, the combinational matrix forces them to necessarily explore certain search paths that they might never have discovered on their own. In this way you can solve problems in surprising ways, and design new and useful solutions.

However, the creativity matrix is very useful only when there are few parameters and few possible values for them. When the number of parameters and values grows, the number of combinations is enormous, and although many combinations can be analyzed, surely many more will remain unexplored. Therefore, the method does not ensure that some creative solution can always be achieved. Thus, the method can be optimized, for example, by adding an initial analysis, and a screening methodology, just as the *Morphological Analysis method* does.

2.4.3. Morphological Analysis

2.4.3.1. Method description

A variation of the *Creativity Matrix* is the *Morphological Analysis* method. Morphological Analysis is an analytical-combinatorial method created in 1969 by Fritz Zwicky, an astronomer at the California Institute of Technology [37].

The objective of the *Morphological Analysis* method is to solve problems by analyzing its basic parameters. Therefore, the method is based on the idea that any entity (object, process, concept or idea), is made up of a certain number of parameters (attributes), and on the idea that these parameters have their own identity and can be isolated. Each of these parameters (attributes) could be made up of a certain number of variants, which can also be differentiated and isolated.

Once the different parameters have been identified, a list of variants should be made and with it, new ideas can be explored.

The method has 3 clearly differentiated stages:

1. Analysis

2. Combination

3. Morphological search

The procedure to be followed is:

1. Definition of the problem to be solved.
2. Analyze the attributes of the problem (its components or parameters)
    - The attributes can be of various types, and refer to physical parts, processes, functions, aesthetic aspects, etc.
    - Attributes must be classified as "relevant" and "not relevant".
3. Analyze possible variants for each attribute.
4. Combine the possible variants of the attributes. All possible combinations must be made. The total number of possible combinations is called the *morphological product*.

Let's take an example to clarify the process of the morphological analysis method:

Suppose that in *step 2* we have found 3 attributes: A, B and C, and suppose that attribute A has 3 variants (A1, A2 and A3), B also has 3, (B1, B2 and B3) and C has 2 (C1 and C2).

The morphological product is the set of all possible combinations = 3 * 3 * 2 = 18. The possible combinations are as follows:

A1-B1-C1	A1-B1-C2	A1-B2-C1	A1-B2-C2	A1-B3-C1	A1-B3-C2
A2-B1-C1	A2-B1-C2	A2-B2-C1	A2-B2-C2	A2-B3-C1	A2-B3-C2
A3-B1-C1	A3-B1-C2	A3-B2-C1	A3-B2-C2	A3-B3-C1	A3-B3-C2

5. Morphological search. It consists of analyzing combinations and seeing their creative possibilities. The morphological search can be done in two ways:

- In an orderly manner. All possible combinations should be listed and analyzed systematically.
- Randomly. A variant of each attribute is chosen at random.

2.4.3.2. Evaluation

This method is also a combinational one but is more general and structured than the *Creativity Matrix method* and is applied both to the design of objects and to the creation of new processes or new concepts. The method is useful for the same reasons discussed when analyzing the *Creativity Matrix method* and has more or less the same limitations.

In the first place, the method is limited by the number of attributes and values that can be determined for the object or process to be created.

Second, when the number of attributes and variations is very large, and as the way of making associations is arbitrary, you may not get any good or acceptable ideas. The number of possible associations is very high, and the method does not propose any process to determine possible associations that may be successful.

Third, many complex problems in real life cannot easily be determined, neither the attributes nor their possible variations, so the method is invalid.

2.4.4. Problem Solving (Vertical Thinking)

2.4.4.1. Method description

The *Problem Solving* methodology is a purely deductive procedure based on cause-effect chains [38]. This thinking can be top-down, or bottom-up. In the first case, a problem is divided into subproblems, and an attempt is made to solve each subproblem, often dividing it into more subproblems, until finally all the partial solutions are concatenated, obtaining a possible final solution. In the second case, simple subproblems are solved, joining with other subproblems, until a certain situation is obtained that may coincide with an initial statement of the problem (Fig. 2.12).

Vertical Thinking is very deterministic and selective, since it only starts from concepts or logical ideas and is activated only if there is a direction or a pre-established pattern in which to move (see section 2.4.12.1.). It is actually a type of analytical thinking that is based on the most logical sequence of ideas.

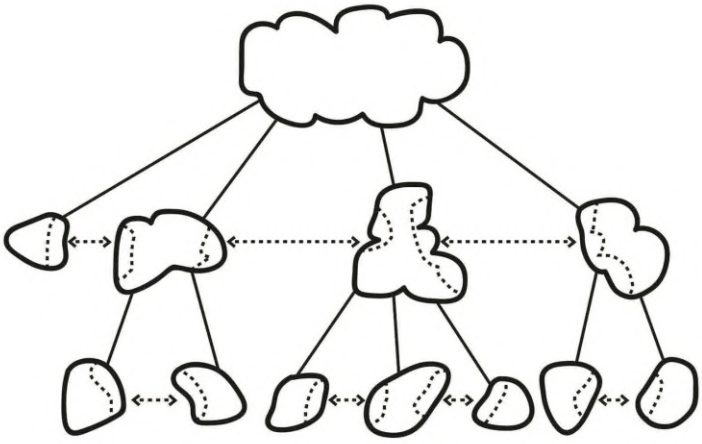

Figure 2.12. *Vertical Thinking method* (Drawing Luis De Garrido)

In *Vertical thinking* the objectives and constraints are known, and certain directions of exploration of the tree of search for solutions are known. Known paths are usually explored, while others are rejected a priori (based on the initial restrictions established). In addition, knowledge related directly to the problem to be solved is used fundamentally. The problem-solving process is based on a sequential chain of decision-making, considered "logical" in context.

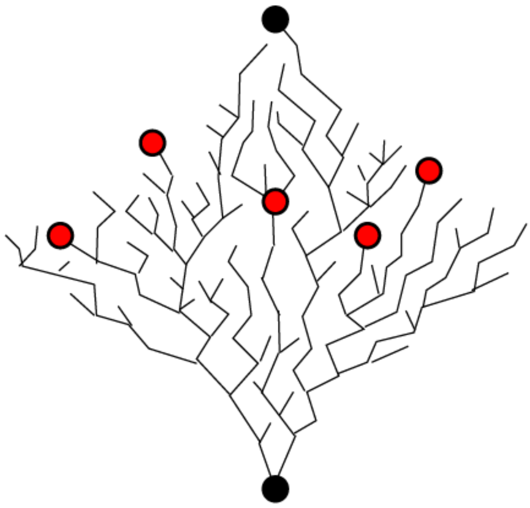

Figure 2.13. Solution search tree (Drawing Luis De Garrido)

Vertical Thinking, based on a traditional *problem-solving* structure, implies the journey of a certain path within the search tree of possible solutions (Fig. 2.13), from the stride to a certain leaf. Therefore, there is a huge number of possible paths within the search tree until a possible decision is reached. In some cases, following a promising path, a satisfactory solution is reached (Fig. 2.14).

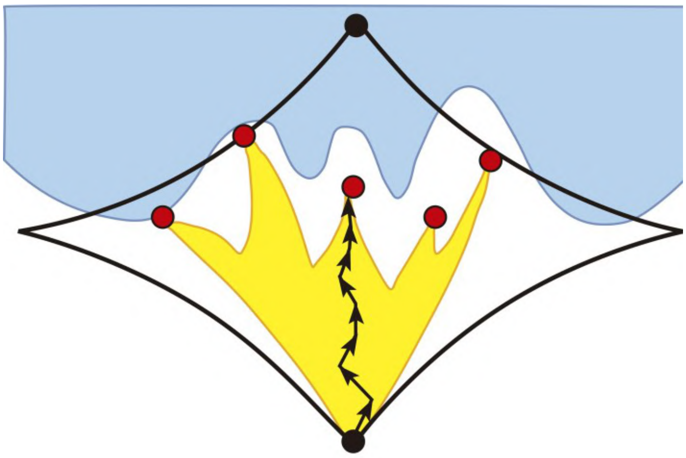

Figure 2.14. Path created by a sequence of logical decisions until a valid solution is reached, following the *Problem solving* methodology (Drawing Luis De Garrido)

In other cases, a promising path (by which it seems that you get a creative, novel and valuable idea) does not finally lead to any valid solution (Fig. 2.15), so you have to go backwards, and in the previous node take another satisfactory decision. This process must be repeated repeatedly, going back through all the previous nodes. From some previous point, perhaps you can take a path to a valid solution, but it is also possible that by the path taken initially, no solution is found (Fig. 2.15).

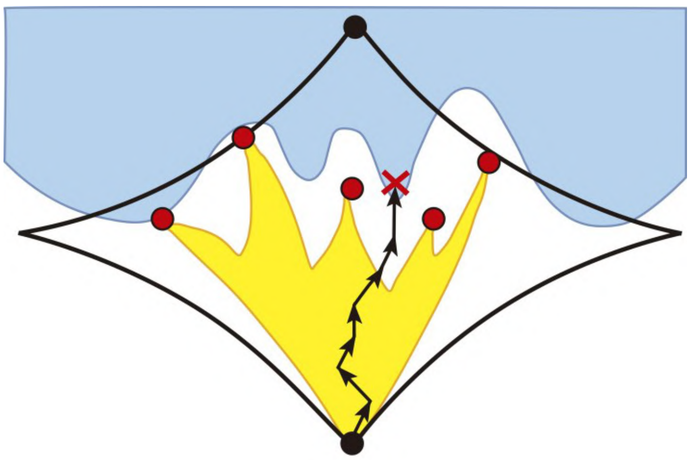

Figure 2.15. Following the *Problem solving* methodology, and based on a concatenation of logical decisions, several paths can be created that do not arrive at any valid solution (Drawing Luis De Garrido)

This is why, strategies must be established based on a *pruning of the search tree* (Fig. 2.16), choosing priorities to travel as a priority only certain paths until reaching a possible solution [39].

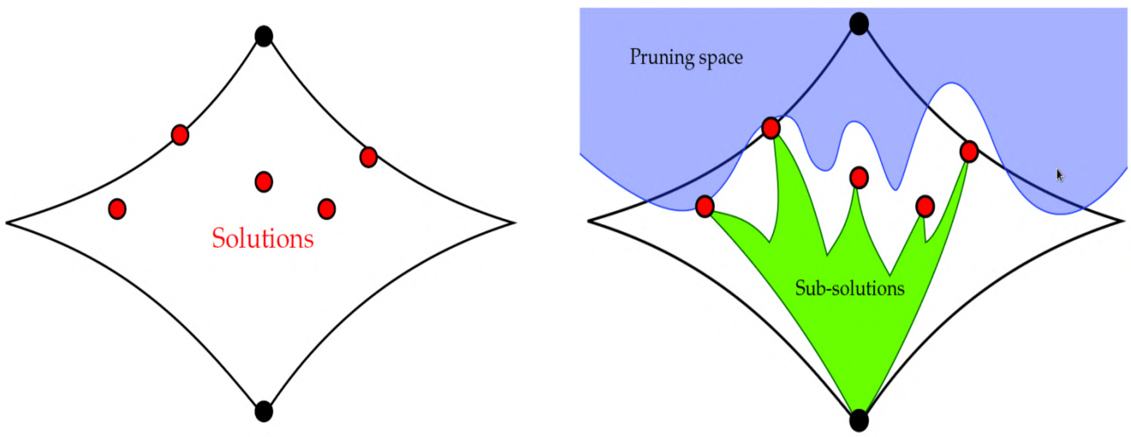

Figure 2.16. Pruning of the search tree (Drawing Luis De Garrido)

2.4.4.2. Evaluation

This method is highly analytical and is especially useful for solving problems that can be decomposed into a concatenation of subproblems, which can be solved individually. The method especially useful for well-defined problems, even if they are very complex, for example: the design of a new car capable of flying.

This problem can be broken down into several interrelated subproblems, which can be solved separately, analyzing all the objectives, setting the set of constraints, proposing a set of possible solutions and evaluating them. The method always ensures that a solution can be reached, although it does not ensure that a surprising and highly creative solution can be reached.

Through the pruning strategy of the search for solutions tree, solutions considered trivial, common, or not very creative can be eliminated, and in this case the number of possible paths is restricted. However, and since the problem is usually very well defined, the search paths that are usually taken are almost always very familiar. Therefore, the method serves above all to solve, in an optimized way, well defined problems, rather than to achieve surprising solutions.

2.4.5. Brainstorming

2.4.5.1. Method description

Brainstorming is probably the oldest and best-known creative problem-solving technique [40]. *Brainstorming* creator Alex Osborn described it in his book Applied Imagination, published in 1954 [41].

The main objective of *Brainstorming* is to break the usual limitations of the human cognitive system and generate a large number of ideas, many of which can be really creative and solve a specific problem.

Brainstorming is suitable especially for solving specific problems (where it is more important to generate many ideas to choose from), but it is not very effective for solving more general problems (where it is necessary to establish analysis and judgments of the possible alternatives). Therefore, it is a perfect method to complement the *Vertical Thinking method*.

2.4.5.1.1. Basic rules of Brainstorming

There are four basic rules for *Brainstorming* to be effective:

- *Eliminate criticism*

When ideas arise, no critical comment is allowed, as this would prevent them from generating new ideas. For this reason, all ideas should be noted as they are generated, and the evaluation should be delayed until a moment after the end of the session.

Since our childhood we have been trained to be instantly analytical, practical and convergent in our thinking, so this rule is difficult to follow, but it is crucial to be creative. In fact, creating and judging at the same time is like pouring hot and cold water into the same glass.

- *Absolute freedom*

The freedom to generate ideas is very important, and absurd thoughts, or ideas that may seem impossible or unimaginable, are especially valued. In fact, in each session there would have to be some sufficiently crazy idea that caused laughter to the whole group. It must be remembered that practical ideas are often born out of impractical, absurd, or impossible ones. Thinking outside the bounds of the usual, of the normal, can emerge great new solutions. The more energetic the idea, the better the results can be, as it is easier to perfect an idea than to come up with a new one. Therefore, work sessions should resemble a party with friends, generating quick ideas.

- *Generate a lot of ideas*

In a first phase, the most important thing is to generate a vast number of ideas so that they can be reviewed later. The greater the number of ideas, the easier it is to choose between them. It should also be considered that the usual thing in *Brainstorming* sessions is that the obvious, conventional and unsatisfactory ideas are the ones that come to mind first, so it is likely that the first 20 or 25 ideas that are presented are mediocre and not very creative. In a complementary way, the longer the list of ideas generated, there will be more possibility of creating new ideas by mixing and modifying them with each other. In fact, in many sessions, you set a goal of getting at least 50-100 ideas.

- *Multiplier effect*

The objective of *Brainstorming* is to generate new ideas, but it is also acceptable to improve those that have already been exposed previously in the session. Therefore, participants in addition to presenting new ideas, can suggest improvements to the ideas of others or get a better idea based on the ideas previously presented. In this way, a multiplier effect is generated in which the participants can use the ideas of others as a stimulus to modify or improve them. Sometimes changing just one aspect of an impractical solution can make it a great solution.

The cognitive system of each human being is slightly different from that of others due to the differential structure of their brain, and the differences in their neural connections in response to their differential life experience, especially in the first years of their life. The most stimulated neural networks gradually consolidate their structure with respect to other less used networks. For this reason, certain synaptic connections are facilitated to the detriment of others less used. With the passage of time, each brain has strengthened certain connections over others, for which a certain way of reasoning is established, responding to both external and internal stimuli.

As a result, each person has a different cognitive system, and sees things from a slightly different point of view. Each person tends to solve problems in a specific way, while having difficulties in solving it in alternative ways due to the specific limitations of their cognitive system. However, if this person is exposed to certain ideas that are strange to him (and that he would never have generated by himself), he can modify them with his own cognitive system and achieve surprising solutions (and that perhaps he would not have generated by himself). In turn, this new idea can be modified by another person (with a different cognitive system), which in turn will generate a new novel idea (and that he would not have generated by himself).

Therefore, the feedback of ideas properly manipulated through a chain of different cognitive systems, allows to explore strange paths in the decision-making tree, and to arrive at surprising and novel solutions. This is the essence of a *Brainstroming.*

2.4.5.1.2. Development of a Brainstorming session

Brainstorming has a basic structure and general operation, which although it can have an enormous number of variations, it must have minimum guidelines (Fig. 2.17).

- *Secretary*

In the first place there must be a secretary, in charge of collecting the ideas generated. In an ideal session, the secretary would have to be a person who would only do this, since it is difficult to develop a mechanical task and simultaneously develop a creative task (this statement will be justified later). However, in small sessions, the secretary is usually one of the participants.

Figure 2.17. *Brainstoming session* (Luis De Garrido in a Braisntorming session leading a group of creative architects)

It is important to use a large board or papers, as large letters help keep ideas present. The explanation for this circumstance could well be due to the fact that well-defined objectives have a greater capacity to reconfigure the neural networks of each brain. In other words, the more emphasized a specific objective is, the more likely there is to reconfigure the cognitive systems of the participants. However, this explanation is speculative since the reason why creativity is stimulated more by using a large graphic to expose the ideas that are generated has not been investigated in depth.

A complementary explanation is that a larger size in the graphics enables feedback from each participant, allows establishing relationships between ideas more quickly by facilitating the realization of "cognitive maps" that are formed in the different participants of each session.

- *Moderator*

In large groups it is important that there is a moderator to choose who will be the next to say an idea and prevent everyone from speaking at the same time. One of the basic functions of the moderator is to remember, when necessary, that group members should not evaluate the results of the session, much less belittle or ridicule any of the ideas generated. This moderator can be the secretary.

- *Relaxed and cheerful atmosphere*

As has been found in many sessions, creativity flows better when participants are relaxed, enjoying, playing around and feeling free, without coercion of any kind. Even when the problem to be solved is of enormous seriousness or importance, the sessions must be easygoing.

To achieve this relaxed atmosphere, it is often good to start with a ten minute warm-up session, where an imaginary problem is addressed. Thinking about an imaginary problem frees people and makes them happy. Then the real problem can be addressed.

The cognitive explanation for the creative efficacy of a relaxed and happy environment is that when the brain does not have tasks directed by external stimuli, it reconfigures itself and adopts a state of functioning called “by default” (generating self-generated thoughts and activating the *Default Mode Network* (DMN) [42], as will be seen in the following chapters). In this state, the cognitive capacity is unconscious and is directed by internally generated stimuli, manipulating information in unpredictable and even random ways, which allows it to explore different paths within the decision-making tree. So, to speak, the brain starts to "play", training automated strategies with random internal stimuli. Much of this invented neural activity makes no sense apparently since it is not intended to solve external problems ... however, the activity is very intense and at a certain moment it can find a solution to a certain conscious problem with which the brain was busy with anteriority. In other words, the automated, haphazard, incessant and unconscious activity of the brain when it does not have external stimuli is capable of looking for alternative paths and solutions to a certain problem, which it could not consciously solve, or did so in a trivial and uncreative way.

- *Short Duration*

The duration of a typical session should be limited to about 15-30 minutes. Longer sessions tend to lose interest. In general, you shouldn't exceed thirty minutes, even though that's the "ideal" length of a session, Osborn recommends. Sessions should be short but at the same time highly effective. For this reason, the moderator must ensure that there is a great fluidity of ideas at all times and avoid that there are periods of time in silence in which ideas are not presented.

- *Gathering ideas*

After the session, you need to clean up the list of ideas and make copies for all participants. Do not try to put the list in any particular order.

- *Post evaluation*

The next day (and never the same day) the group would have to meet again. First, the ideas thought from the previous session would have to be shared. Afterwards, the group would have to evaluate each of the ideas and develop the ones that hold the most promise so that they can be put into practice.

During the evaluation sessions, wild ideas are turned into practice or used to suggest realistic solutions. The emphasis must be placed on analysis and real-world issues. Sometimes ideas found that are thought useful are divided into 3 groups:

1. Ideas of immediate use.	*Ideas that can be used immediately*
2. Ideas to explore further.	*Ideas to be elaborated and discussed further*
3. New approaches to the problem.	*Ideas that suggest new points of view*

It should be noted that the evaluation session should not take place on the same day as the *Brainstorming* session, which allows the *Brainstorming* session to be freer (since participants do not have the fear of an immediate evaluation) and allows an incubation time for new ideas.

2.4.5.2. Evaluation

The *Brainstorming method* works since the search tree for a solution is traversed between several people. Each component of Brainstorming probably could not have traveled by itself a certain path that leads to a creative solution, since its cognitive structure does not facilitate it. On the other hand, a component of the group proposes a certain idea that suggests another idea to another component, and so on. Therefore, each component takes the group to a certain place in the search tree, where another component of the group takes over the group to another certain place, and so on. In this way, the search tree goes through different components of the group, each of which has a different cognitive operative. Therefore, *Brainstorming* forces unusual paths to be traveled, which can lead to creative, novel and valuable solutions.

Brainstrorming always generates solutions, although it does not ensure that they are sufficiently creative and depends on the fortuitous concatenation of ideas that are proposed. One session can be a success, and another session can be sterile. For this reason, a huge number of alternatives have to be created, in order to improve their efficiency.

2.4.6. Brainstorming variations

2.4.6.1. Methods description

Since its creation, a considerable number of *Brainstorming* variants have been though of in order to increase its effectiveness in various aspects. Some variations have been designed to be used for certain types of problems. Among these variants, the following stand out:

2.4.6.1. Stop-and-go Brainstorming

Stop-and-go Brainstorming [43] is a type of *Brainstorming* in which brief periods of idea generation (3-5 minutes) alternate in groups, with periods of silence (3-5 minutes) in which participants have time to think on the proposed problem and can generate new ideas and meditate on them.

2.4.6.2. Sequential Brainstorming

Sequential Brainstorming [44] is a type of *Brainstorming* in which the moderator is sequentially asking the participants to present their ideas. The request for ideas is done sequentially in rounds. If a participant has nothing to say in a certain round, she passes her turn to the next. The necessary rounds are carried out until there are enough ideas, or the preset time runs out. With this method, twice as many ideas are usually obtained as in a conventional *Brainstorming* session.

2.4.6.3. Constructive-destructive Brainstorming

This modality has two well differentiated phases:

- *Brainstorming* to generate and expose destructive ideas, gathering the maximum possible number of negative aspects of the problem.
- *Brainstorming* to generate and present constructive ideas, reinforcing the weak points of the problem.

2.4.6.4. Individual Brainstorming

Brainstorming is usually done in a group, but it can also be done with one person. In this way, in isolation, people are free to explore ideas on their own time, without any fear of criticism and without being dominated by other members of the group.

Group *Brainstorming* develops ideas more deeply, and more effectively, since when a person has difficulties in developing an idea, the creativity and experience of another person can be used to overcome them.

Group *Brainstorming* tends to produce fewer ideas (since time is used to develop ideas in depth) and can lead to the cancellation of creative but quiet people by other more talkative and not necessarily creative people. Therefore, *Individual Brainstorming* sessions force the quietest and most timid people to take an active role and generate ideas for themselves during a given work session [45].

2.4.6.5. Anonymous Brainstorming

Anonymous Brainstorming [46] is a type of *Brainstorming* in which mutual interaction in the production of ideas is suppressed. In this case, the important thing is that each participant can express an idea of solving the problem without the influence of others. Participants write down their ideas on a piece of paper in isolation, and hand it over to the moderator. The moderator then presents the proposals received, one after another, and an open discussion is established in which an attempt will be made to find the best solutions and deepen them.

2.4.6.6. Brainstorming with Post-it (TM)

Brainstorming with Post-it (TM) [47] consists of each member of the group writing down the idea that they have come up with on a Post-it and giving the Post-it to the moderator while saying their idea aloud to the group. The moderator puts all the *Post-its* that are delivered in a panel in view of all the participants.

This variant facilitates the reuse of the ideas of the other members of the group, and helps to organize and converge them.
It is very similar to *Anonymous Brainstorming*, except of course, in the aspect of anonymity. The average duration is usually 30-40 minutes and there are usually 4 to 8 participants.

2.4.6.7. Brainstorming Phillips 66

The *Phillips 66 method* [48] is a variant of *Brainstorming*, in which a large group is divided into small groups of 6 people. The groups have 6 minutes to generate ideas, which are then shared in the larger group to collect them. The 6-minute periods of *Brainstorming* can be repeated multiple times to allow for combining ideas. This method is very suitable to stimulate creativity in very large groups, in which a conventional *Brainstorming* could not be carried out.

2.4.6.8. Brainstorming Buzz

Brainstorming Buzz tries to encourage teamwork to the maximum for the development of creative ideas [49]. The author, Donald Philips of Michigan State University, used the *Philips 66 method* routinely, and created this variant to maximize group work among his students. In fact, the name of the method says it all: "buzz" is the onomatopoeia of noise made by a group of people in intense discussion.
The idea is to divide a large group (for example the students in a classroom) into smaller groups (of 4 to 6 people). Different groups can engage with different problems or different aspects of the same problem for about 6 minutes. Once each group obtains certain results, they are elevated to the largest group in which they work together again considering those results. The advantage of this method is that the activity of each person is maximized.

2.4.6.9. Didactic Brainstorming

In *Didactic Brainstorming* method [50], the director gradually provides information to the group. Through this gradual increase in the complexity of the problem, new simple solution proposals can easily be developed. The usual, and most effective, is to do 30-minute sessions, with about 7 participants.
The director introduces the problem to the group and gradually provides information to them. After each phase of increasing the information, a *Brainstorming* session is

organized. This technique prevents participants from detecting a possible solution too early, preventing them from finding a more ingenious and effective way.

2.4.6.10. Brainstorming SIL (Successive Integration of Solutions)

The SIL method (*Sukzessive Integration Lösungen*) [51] is a type of *Brainstorming* that is especially demanding on the creative collaboration of the participants in the session.

The participants write down their ideas for a certain time (approximately 10-15 minutes), and two of them present them in succession. The group then develops a new solution combining the two ideas presented in the best possible way (*Solution statement 1*). A third participant presents her solution statement. The group develops again a solution (*Solution Statement 2*), integrating the recent contribution and the *Solution Statement 1* previously developed by the group, and so on.

Here it is important to consider the composition of the *Brainstorming* team, so that there are no discrepancies or conflicts between team members. The average duration is usually 30-40 minutes and there are usually 4 to 8 participants.

The strong point of this method is that it allows the gradual improvement of several initial ideas, and gives them a certain random character.

For example, let's imagine two initial ideas for the design of a new type of writing device. One idea could be: “that it can write on any surface”, and another idea could be “that it should never be recharged”. From these two previous ideas, others could emerge such as: "an artifact that modifies the surface layer of any surface in a specific way". If another person had another idea: "make it invisible" ... well, another new idea could come from there, for example: "add a ring to place on a finger", or a false nail, which emit highly concentrated microwaves, consequently altering a surface and writing…. This idea could hardly have been generated in conventional *Brainstorming*.

The forced fusion of several ideas has two advantages. In the first place the method ensures the exploration of new unconventional ways of thinking. Secondly, the idea is acquiring the incremental advantages of several ideas, with which its social acceptance is assured in advance.

2.4.6.11. Brainstorming 635

The method *Brainstorming 635* [52] was developed by Warfield, and it is easier to control than conventional *Brainstorming*, and it is just as effective.

The figures that identify this technique give the keys to its operation:

Six people gather around a table to generate three ideas in a concise and brief way since they only have five minutes to write them on a sheet of paper. Then each person passes their sheet to their partner next door, and the process will be repeated until they write three new ideas in another five minutes, after having read the ideas of the previous participants, which will serve as a source of inspiration.

At the completion of the cycle of six five-minute interventions, eighteen ideas are available, which can amount to one hundred and eight ideas in just half an hour.

2.4.6.12. Brainwriting

The method *Brainwriting* [53] derived from 635 and has been developed at the Batelle Institute. This method allows for anonymity, and does not limit the number of participants, the number of ideas contributed, or the time for each shift, with which similar results are obtained.

2.4.6.13. Collective Notebook

In the method *Collective Notebook* [54], and for a month, each day the participants must write in their notebook at least one idea referring to the solution of the problem. Doing it with perseverance for a month requires a good dose of self-discipline which, together with the natural maturation of the matter in the aforementioned period, are the two keys to this method.

At the end of the month, each participant will analyze the ideas from their own pad and select the one that seems best to them or will propose some guidelines on the way of resolution that they deem most convenient.

All the notebooks will be delivered to a coordinator, who will prepare a report collecting the results obtained, which will be distributed to each participant, then proceeding to evaluate and select the best idea from all the proposals.

2.4.6.14. Brainwriting Pool

The *Brainwriting Pool* was invented by Horst Geschka, and colleagues, at the Batelle Institute. The sessions should have 5 to 8 participants, who write down ideas in a notebook [55].

The group leader presents a problem to the group and writes the problem statement in a visible place for all. Then each participant must write four ideas on a sheet of paper and put them face down in the center of the table. Once all the sheets are in, all the participants must take a sheet of paper from the pile, and they must write on it the ideas or comments they want and put the sheet face down on the pile again. The process can be repeated as many times as desired. At any time, each participant can add any idea on a new sheet, adding it on the central stack. After 20-30 minutes, the process is finished, and the idea sheets are collected to be evaluated.

There are obvious variants like using separate cards or Post-its, one for each idea instead of sheets. Doing it with sheets can provide a better stimulus to ideas, but doing it with cards or Post-its can simplify the subsequent classification of ideas, grouping them, etc.

This technique works well with groups of people who do not know each other, and can generate quite a few alternatives, some of them very crazy. It also allows constructive criticism and discussion of the different proposals.

2.4.6.15. Delphi method

The *Delphi method* consists of requesting and comparing anonymous judgments on the topic of interest through a series of sequential questionnaires interspersed with summarized information and feedback from the opinions expressed in the previous answers [56].

The *Delphi method* retains the advantage of obtaining a variety of judgments, opinions and approaches while eliminating the biases that can and often occur during face-to-face interaction. The basic approach is to collect anonymous opinions and suggestions by means of a questionnaire by mail. For example, group members generate their ideas independently to answer the first questionnaire and return it. The secretary summarizes both the responses and the consensus of the group by sending them along with a second questionnaire for re-evaluation. Based on this feedback information, participants can independently evaluate their previous responses. The underlying belief is that consensus achieves better results for the optimal decision after several rounds of anonymous opinions and judgments in the group. However, even if the procedure continues for several rounds, there are essentially no significant changes after the second round of estimates.

2.4.6.16. Nominal Group method

The *Nominal Group* technique is based, in a first phase, on the meeting of a group of seven to ten people who sit around a table without being able to speak to each other [57].

Each person writes their ideas in a notebook, and after five minutes they exchange them with each other. The secretary writes the ideas on a board in full view of the group, and the process continues until all participants indicate that they have no more ideas to share. At the end of the phase, it is normal that about 30 ideas have been generated.

In a second phase, a structured debate is held in which each idea is discussed before being voted on.

In a third phase, independent voting is carried out in which each participant, in private, selects the voting priorities. The group's decision is the mathematically ordered result of the individual votes.

Both the *Delphi method* and the *Nominal Group* method have been shown to be more efficient than conventional *Brainstorming*, since they are capable of generating a greater number of creative ideas.

However, there are important differences between the two methods, such as the following:

1. Participants in a *Delphi* process are usually anonymous to each other, while participants in a *Nominal group* can be known.
2. Participants in a *Nominal group* meet face to face around a table, while participants in a *Delphi* process are physically distant and never meet.
3. In the *Delphi* process, all communication between participants is through written questionnaires and comments by supervisory staff. In the *Nominal Group*, the participants communicate directly.

2.4.6.2. Evaluation

Brainstorming variants are not always more effective, however, if they have been created it is because it had been observed that *Brainstorming* did not always work. Some of these variants are more effective on certain specific problems, while others are less effective. In general, it can be said that the most efficient variant is the *Delphi method*.

There are two fundamental reasons why *Brainstorming* does not generate the expected results.

On the one hand, each session is different, depending on the type of participants, and their state of mind. Even if the participants are the same, in one session more ideas are generated and, in another session, much less. The almost arbitrary concatenation of ideas can lead to a sterile path in one session, while taking a successful path in another.

The idea put forward by one participant stimulates another participant, whose idea stimulates a third participant, etc. Therefore, the concatenation of sequential ideas takes different directions in each session.

Second, participants tend to express reservations, inhibitions and prejudices in public sessions. Many participants may feel that they are always being judged by members when they express ideas that come to mind. It is possible that these ideas are good, but although they may be correct to solve the specific problem that they are trying to solve, they could betray them in other personal and social aspects. Hence the importance of the moderator being able to remove these inhibitions, that the atmosphere is relaxed, and that the responses are quick. There should be an atmosphere like that of a party with friends.

Some variants of *Brainstorming*, especially the *Delphi method*, can avoid the problem of biases by being anonymous, however, no variant greatly increases the generation of ideas, nor the fact that these ideas are truly creative. Traditional *Brainstorming variants*, especially the *Delphi method*, can avoid the problem of biases by being anonymous, however, no variant greatly increases the generation of ideas, nor the creativeness of these ideas.

For this reason, other recent variants of *Brainstroming* have been designed, which include additional associative methodologies, which allow for a greater type of ideas to be generated, and many of them are truly creative, that is, surprising, novel and valuable.

2.4.7. Graphic Brainstorming

2.4.7.1. Methods description

Graphic Brainstorming has been developed in order to create graphic creations, such as logo design, advertising image, architectural design, industrial design, fashion design, etc. This type of *Brainstorming* is very complex, since the generation of abstract ideas must be complemented with the generation of graphic ideas, in the form of sketches, which represent the seed of the graphic composition that is intended to be achieved. Therefore, *Graphic Brainstorming* consists of at least three stages: idea generation, graphic generation and evaluation.

2.4.7.1.1. *Shape Brainstorming*

Shape Brainstorming was created by Luis De Garrido, in 1989 [58], and is used to create objects and graphic compositions of all kinds. In this method participants must associate certain shapes to the problem or parts of the problem to be solved. It is a very effective method in design problems in which the visual and shape components are important (Fig. 2.18).

Figure 2.18. *Shape Brainstorming* (4-Waves Eco-House. Project made by Luis De Garrido)

Shape Brainstorming is structured in three stages. In the first stage, the different participants must identify one or more qualities or characteristics of the problem to be solved, and must associate shapes with these characteristics. Each participant must describe one shape and aspect of the problem with which it is associated. You must also make a sketch with a pencil or with hand movements. There is no order, and anyone can participate at any time and as many times as they wish. The most suitable size is about 15 people, with an approximate duration of one hour. The secretary of the session must compile all the graphic diagrams generated and deliver a copy of them to the participants.

In the second stage, individually and throughout the day, participants must create several basic sketches of the object to be designed associated with the graphic schemes that have been delivered, and deliver them the next day to the secretary. The secretary will collect all the shapes and hand them out to the participants.

In a third stage, each participant must make a detailed design of the object based on the sketches that have been handed out and deliver them the next day to the secretary.

For example, a session is created to generate ideas for the design of a chair. Each participant must emphasize some characteristic of the chair and must suggest a shape associated with it. Let's say, the "comfort" feature, or the "rest" feature, or the "rotation" feature… and draw some sketches of shapes associated with those features. Each participant, based on what they have seen and heard, must do the same, focusing on some specific characteristics, or on the complete problem to be solved, even providing proposals for new characteristics for the chair to be designed, and making a sketch of the complete chair.

2.4.7.1.2. *Symbolic Brainstorming*

Symbolic Brainstorming was also created by Luis De Garrido in 1989 [59], and is used to create all kinds of objects, and especially architectural objects. The method consists in participants associating several symbols to the problem or parts of the problem to be solved. It is a very effective method in design problems in which the visual components are important (Fig. 2.19).

Symbolic Brainstorming is structured in three stages. In the first session, participants must identify one or more qualities or characteristics of the problem to be solved, and must associate symbols with these characteristics. Each participant should describe these symbols and the aspect of the problem with which it is associated. They should also make a sketch of these symbols with a pencil or hand movements. There is no order, and anyone can participate at any time and as many times as they want. The most suitable size is about 15 people, with an approximate duration of one hour. The secretary of the session must collect all the symbols and symbolic ideas generated and give a copy of them to each participant.

In the second stage, individually and throughout the day, each participant must create several basic sketches of the object to be designed associated with the symbols that have been handed out and deliver them the next day to the secretary. The secretary will collect all the sketches and hand them out to the participants.

In a third stage, each participant must make a detailed design of the object based on the sketches that have been handed out and deliver them the next day to the secretary.

Figure 2.19. *Symbolic Brainstorming* (Mandala Eco-House. Project made by Luis De Garrido)

For example, to generate ideas for the design of a chair, each participant must emphasize some characteristic of the chair and suggest a shape. For example, the “comfort” feature, or the “rest” feature, or the “rotation” feature… and draw some sketches of symbols associated with those features. Let’s say, the characteristic "rest" can be associated with the "symbol of a dock", the characteristic "comfort" can be associated with the "symbol of a cloud", etc. The identified symbols can suggest new symbols to the other participants. The secretary of the session must take notes, draw and collect all the symbols and symbolic ideas generated, and will give a copy to each participant. The next day participants must deliver several sketches of shapes associated with the concept "chair" based on the symbols that have been delivered. The secretary compiles these sketches and gives them back to all participants. The next day each participant must bring the defined sketch of a chair.

2.4.7.1.3. *Metaphorical Brainstorming*

Metaphorical Brainstorming was created by Luis De Garrido in 1989 [60], and is used to create all kinds of objects, and especially architectural objects (Fig. 2.20). The method consists in participants associating several metaphors to the problem or parts of the problem to be solved. It is a very effective method in design problems in which the shape components are important.

Metaphorical Brainstorming is structured in three stages. In the first session, the different participants must identify one or several qualities or characteristics of the problem to be solved and must associate several metaphors to these characteristics. Each participant should describe the metaphors they have come up with and the aspect of the problem with which they are associated. There is no order, and any participant can participate at any time and as many times as they want. The most suitable size is about 15 people, with an approximate duration of one hour. The session secretary must collect all the generated written metaphors and must give a copy to each participant.

In the second stage, individually and throughout the day, each participant must create several basic sketches of the object to be designed associated with the metaphors that have been handed out, and deliver them the next day to the secretary. The secretary collects all the sketches and hand them out to the participants.

In a third stage, each participant must make a detailed design of the object based on the sketches that have been handed out, and deliver them the next day to the secretary.

For example, the design of a chair each participant must emphasize some characteristic of the chair and must suggest a shape. Let’s say, the characteristic "comfort", or the characteristic "rest", or the characteristic "rotation" ... and describe some metaphors associated with these characteristics. For example, the characteristic "rest" can be associated with the metaphor "one rests as if one were among cotton wool", the characteristic "resistance" can be associated with the metaphor "it is as resistant as a bridge"…. The metaphors identified by each participant can suggest new metaphors to the other participants. The secretary of the session takes note and compiles all the generated metaphors, and gives a copy to each participant. The next day, participants must deliver several sketches of shapes associated with the concept "chair" based on the symbols that have been delivered. The secretary compiles these sketches and gives them back to all participants. The next day each participant must bring the defined sketch of a chair.

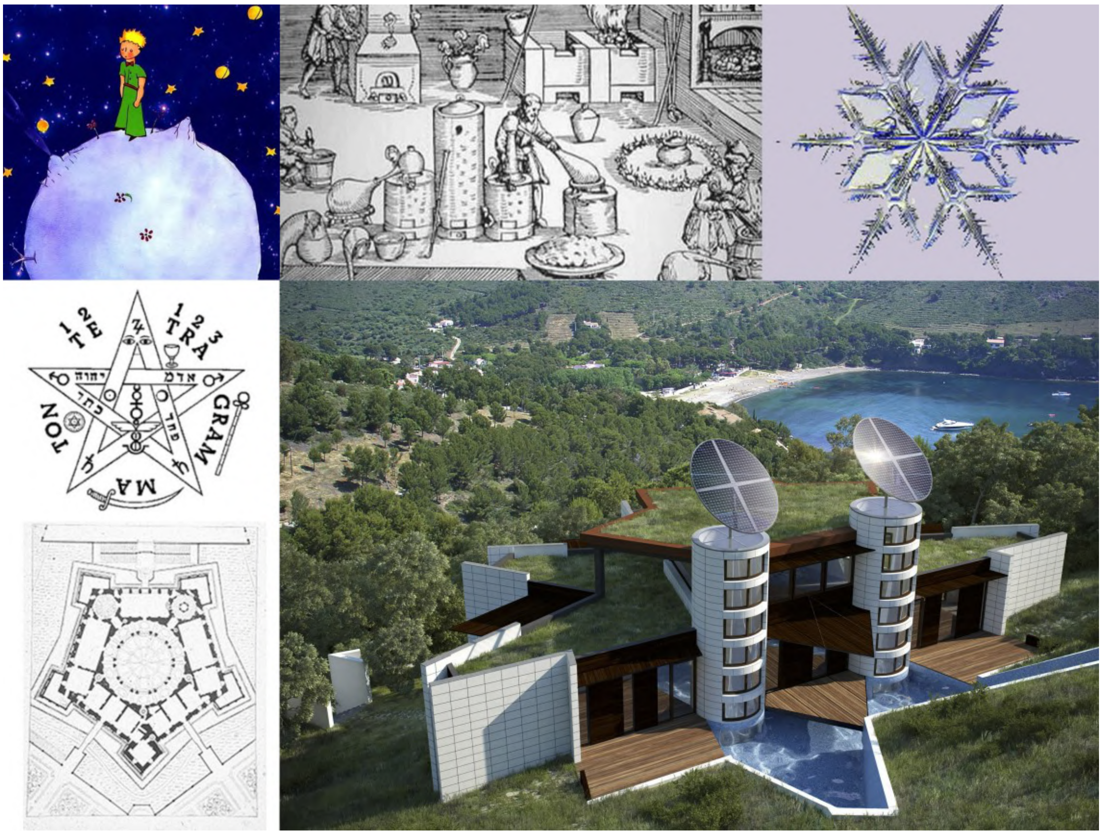

Figure 2.20. *Metaphorical Brainstorming* (Ferran Adriá Eco-House. Project made by Luis De Garrido)

2.4.7.2. Evaluation

The *Graphic Brainstorming*, in any of its three variants, has turned out to be more effective than the rest of *Brainstorming variants*. It has been designed to generate visual shapes, from abstract concepts, and therefore it is a very complex method.

It is possible that part of its success is due to the fact that the participants feel less self-conscious and have less prejudice since it is an indirect method, which in turn implies an associative method. Another factor that explains its success is that it integrates an associative methodology, so the probability of generating a greater number of ideas is greater. Finally, the method provides surprising ideas due to its own indirect structure, since the generated forms can be subsequently interpreted and elaborated. The method allows exploring unheard of paths in the search tree, but at the same time directly or indirectly related to the problem.

2.4.8. *www-Brainstorming*

2.4.8.1. Method description

Www-Brainstorming method was developed by Luis De Garrido in 2010 [61], for the creation of all kinds of graphic compositions and objects, based on obtaining shapes, symbols and metaphors associated with the object to be designed in the global network. Each session lasts approximately one hour, with 15 participants. In the room there should be several projection screens with access to the internet.

The objective is to achieve shapes, symbols and metaphors that serve to generate initial fuzzy shapes (*initial fuzzy proto-solutions*) associated with the object to be designed. These blurred shapes will determine a priori the character and essence of the object to be designed and will be maintained throughout the design process. These *initial fuzzy proto-solutions* already determine an approximate way of grouping the different components of the object to be designed, as well as some of its formal and volumetric characteristics.

The session begins as a conventional *Brainstorming*, in which the participants are required to identify some of the most important characteristics and associated concepts of the problem to be solved, deducing them and proposing them based on the definition of the problem. For half an hour the secretary writes down all the concepts that have been generated by the participants.

Once the concepts have been collected, different search-engines are used to associate each of the generated concepts to specific shapes. The name of the concept is entered in the search engines, which instantly generate a huge number of images associated with those concepts. Participants must choose from among all the images shown those that in their opinion are most suggestive and are associated in any way with the object to be designed. The images can be symbols, natural elements (minerals, plant animals), or objects created by man. Any valid image, especially symbolic shapes.

Later, the images are compiled, and *Brainstorming* is done again to provide feedback and debug a second session.

At the end of the session, the moderator continues with the design process by himself, generating completely new sketches, based on the integration of the collected images.

2.4.8.2. Evaluation

Www-Brainstorming is undoubtedly the most effective method of all. It is capable of generating a greater number of ideas and in turn is capable of generating a greater number of surprising, novel and valuable ideas. In reality, it is an associative *Brainstorming* like *Graphic Brainstorming*, in which a huge number of people distributed around the world participate (indirectly). The method is especially effective in creating visual elements, such as interior design, advertising design, corporate image design, architectural design, fashion design, etc.

The effectiveness of the method is due to the fact that it is an associative method in which a huge number of alternatives are available (to guarantee that the idea is surprising), and in turn related to the problem to be solved (to guarantee that the idea is successful). Furthermore, the method anticipates subsequent evaluation, since the association of images with concepts has been agreed upon by a huge number of Internet users, otherwise it would not have been shown in search engines.

2.4.9. Attribute List method

2.4.9.1. Method description

The *Attribute List method* was created by Robert P. Crawford in 1954 [62], for the generation of creative ideas with the aim of modifying and improving any element (product, service or process).

Crawford was a professor at the University of Kansas in the 1930s. He was probably the first to teach a college-level course on methodologies for generating creative ideas.

Through this method, the attributes of a certain element (product, service or process) are identified, in order to consider each one as a source of modification and improvement. Lists can be made of physical characteristics, uses, synonyms, antonyms, parts, connotations, etc. The attributes can be very numerous to make their treatment difficult, so their number should not be too great. In this sense, the method distinguishes between "essential attributes", and the rest. Initially, only the "essential attributes" will be used in the method.

The method consists of three well-defined stages:

1. Identify the problem to be solved (product, service or process).
2. Analyze the element and make a list of as many attributes as possible
3. Take each attribute and think about how to change or improve it. For each specific attribute, the Scamper method could be used.

The method is effective on problems that can be decomposed into specific and defined attributes. On the other hand, when it comes to improving processes, it is more difficult to identify the attributes, although the method is also applicable.

For example, if you want to design a pen, you can consider the following attributes: shape, color, clamping system, materials, ink load protection system, weight, etc.

In the specific case of improving a product, the method can be specified in:

1. Identify the product to be improved
2. Identify the components of the product
3. Describe the functions of each element, in terms of attributes
4. Analyze the attributes, and decide which are essential and which are secondary
5. Select essential attributes
6. Identify and choose the essential attributes that can be improved
7. Study all the possible modifications of these attributes, so that an improvement of the product results. The improvement can mean changing one attribute for another. A systematic analysis of all the possibilities for improvement of each attribute must be carried out, testing all the ideas that can be generated.
8. Study all the characteristics of the designed object as a consequence of the substitution of attributes
9. Select a new object, as a result of attribute modifications

Just working with the essential attributes is a problem as sometimes a seemingly trivial attribute can be the key to a radical change in the product. Therefore, once the method has been used with the essential attributes, it must be used with the rest of the attributes.

The list of attributes is a good starting point for analytical-combinatorial methods, such as the *Creativity Matrix*, and the *Morphological Analysis*.

2.4.9.2. Evaluation

It is a more efficient method than the usual associative methods (Creativity Matrix, Morphological Analysis, etc.), since it adds an analysis of the attributes, their classification and the establishment of alternatives. Therefore, you can provide more refined ideas capable of solving the problem. This method can expand the number of routes to traverse the solution search tree and generates fewer failed routes.

2.4.10. Checklist method

2.4.10.1. Method description

The *Checklist method* was designed by Alex Osborn [63] to encourage creativity when solving a certain problem and can be used both individually and in groups. The list consists of a group of questions related to the problem you want to solve (Fig. 2.21).

These questions have been designed to support creative and divergent thinking when solving a certain problem. The questions must be answered one by one in order to explore new points of view regarding the problem to be solved.

Other uses	New ways to use as is? Other uses if modified?
Adapt	What else is like this? What could I copy? What other idea does this suggest? Does past offer parallel? Whom could I emulate?
Modify	Change meaning, colour, motion, odour, taste, volume, shape? Other changes?
Magnify	What to add? More time? Greater frequency? Stronger? Higher? Larger? Longer? Thicker? Heavier? Duplicate? Multiply? Exaggerate?
Minify	What to subtract? Smaller? Condensed? Miniature? Lower? Shorter? Narrower? Lighter? Omit? Streamline? Split up? Understate? Less frequent?
Substitute	Who else instead? What else instead? Another place? Another ingredient? Another material? Another time? Another process? Another power? Another approach?
Rearrange	Interchange components? Another pattern? Another layout? Another sequence? Transpose cause and effect? Change place? Change schedule? Earlier? Later?
Reverse	Transpose positive and negative? How about opposites? Turn it backward, upside down, inside out? Reverse roles? Change shoes? Turn tables? Turn other cheek?
Combine	How about a blend, an alloy, an assortment, an ensemble? Combine units?

Figure 2.21. *Checklist method*

These checklists are often used in *Brainstorming*, where you can choose between different questions at random, it can be useful to write each statement on a card and select a card at random, and cause group members to generate related questions and generate various answers.

2.4.10.2. Evaluation

This method can be a complement to *Brainstorming* since it can substantially improve its effectiveness, by suggesting specific exploration paths within the tree of search for solutions. The fact of asking questions related to aspects of the problem expands the possibility of search paths, but in reality, they are close to the usual ones.

On the contrary, this method does not favor the appearance of initially strange, absurd or unheard-of ideas, which, although they do not solve the problem, can allow the tree to travel an unsuspected path, and achieve a truly surprising, novel and valuable solution.

Therefore, the method could be a second part, even individual, of any *Brainstorming*.

2.4.11. Scamper method

2.4.11.1. Method description

The *Scamper method* (S-C-A-M-P-E-R) [64] is a checklist capable of generating ideas based on action verbs that suggest changes to an existing product, service or process. This mnemonic was created by Bob Eberlee from the verbal checklists originated by Alex Osborn, creator of *Brainstorming*.

The original verbal checklists designed by Alex Osborn were arranged like this:

Other uses
Adapt
Modify
Magnify
Minify
Substitute
Rearrange
Reverse
Combine

Over time, many companies have used checklists to create or improve products or services.

Bob Eberlee rearranged the list mnemonically to make it easier to remember. He kept Alex Osborn's verbs and added a few more:

S	*Substitute*	
C	*Combine*	
A	*Adapt*	
M	*Magnify*	*Modify*
P	*Put to other uses*	
E	*Eliminate*	*Minify*
R	*Rearrange*	*Reverse*

The idea of *Checklists method* is based on the fact that a certain item (product, service, or process) can be improved by applying a series of related questions (verbs) and pursuing the answers to see where they go. These verbs indicate possible ways to improve an item (product, service, or process), by making a series of changes.

In the case of Alex Osborn's list, more alternatives may be suggested from the definitions and additional phrases that accompany each of the main verbs. For example, if the item under consideration is a laptop and the verb "minimize" is being used, the result would be to reduce the laptop, the cellular phone, or anything else suggested when shrinking.

There are only two steps to use the *Scamper checklists*:

1. Identify the item (product, service, or process) to be improved
2. Ask the *Scamper* questions about the item and observe the ideas that arise

2.4.11.2. Evaluation

Scamper method is simply a systematization of the *Checklist method*, so the evaluation is the same.

2.4.12. Lateral Thinking

2.4.12.1. Method description

Lateral Thinking is a method of thinking that can be used as a creative problem-solving technique, created by Edward de Bono in 1967 [65]. *Lateral Thinking* is a specific way of organizing thought processes, to find a solution through unorthodox strategies or algorithms, which would usually be ignored by logical thinking.

When evaluating a problem, there is usually a tendency to follow a habitual, conventional pattern of thought, which tends to seem "natural" (usually we tend to think that: a chair is used to sit, a brick is used to build, a ruler is used to measure, a glass is used to be filled with a liquid, etc.), which would limit the possible solutions. *Lateral Thinking* allows dissolving this usual rigid pattern, and therefore allows obtaining much more creative and innovative ideas, since it encourages alternative or unusual paths of reasoning. Following these new paths allows the resolution of problems indirectly and with a creative approach (for example, it may be thought that: a chair serves as a ruler, a brick serves as a pencil holder, a pitchfork serves as a tie, a ruler used to make percussion music, a glass serves as a flowerpot,…).

In order to use this method, the different concepts must have a huge number of attributes that define it as broadly as possible. In this way different objects can share some attributes, or what is the same, they can have things in common. Initially it is difficult to think of using a chair to make a straight line on a blackboard. But if the concept "chair" is represented by having as components some "legs", and among the attributes of the legs is that they can have a straight "shape", it turns out that a rule and a chair do have something in common. Therefore, in the absence of a ruler, a chair could be used to draw a straight line on a blackboard (Fig. 2.22).

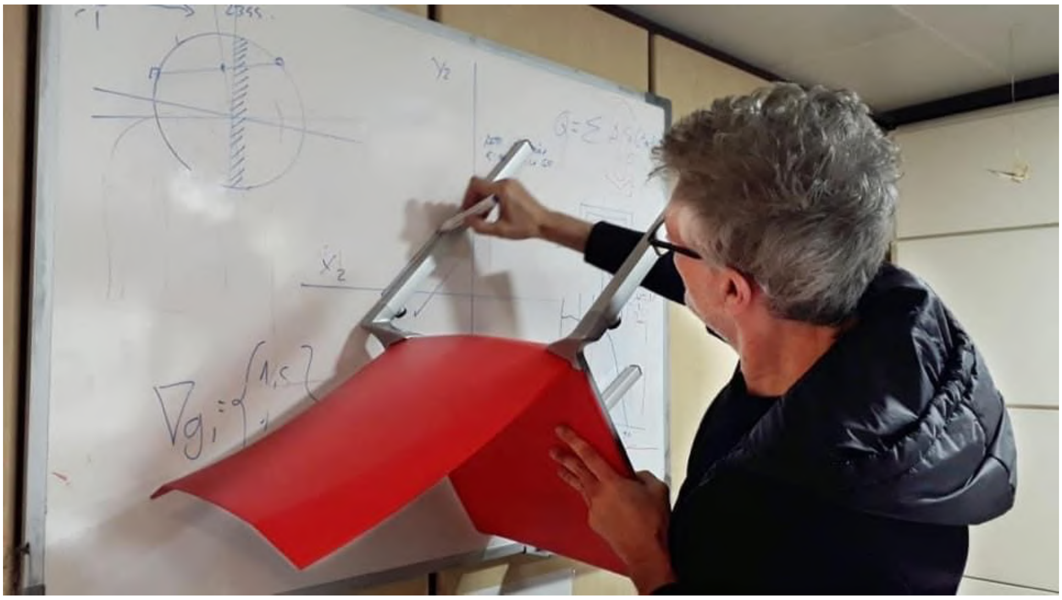

Figure 2.22. Example of Lateral thinking, using a chair to draw a straight line

In particular, the technique is based on the fact that, through thought provocations, a deviation from the path or habitual pattern of thought is stimulated, which allows the opening to more possible solutions, and to look at the same problem from different points of view.

De Bono points out that the thoughts have a first phase of perception, and a second phase of processing in which the first perceptions are elaborated and treated. Perceptions generate a set of patterns in our thinking following a “logical” system (a personal logic for each individual). The brain tends even to find causes even to fortuitous or random events, for this reason it continuously creates a network of “cause-effect” associations, which as a whole facilitates forms of thought that seem "natural", "true" and "unique", but that in many cases they are not, and are only the result of poor training.

To break the rigid logic of these perceptual patterns, typical of human beings, certain techniques can be designed in order to generate conceptual leaps. In this way the perception of the environment will be modified and as a consequence new and different solutions can be generated.

Contrary to *Vertical Thinking*, *Lateral Thinking* aims to find surprising and alternative conclusions, thus avoiding the most common logical sequences. *Lateral Thinking* is not linear, sequential, or logical, and it originates from a dynamic of continuous creation of ideas, causing changes of ideas by rearranging conventionally established guidelines.

a. Differences between Vertical Thinking and Lateral Thinking

The most important differences between vertical thinking and lateral thinking are:

Vertical Thinking	*Lateral Thinking*
It is an analytical process	It is a divergent process
Paths in decision making are rejected	No path is rejected in decision making
It is based on the sequence of ideas	You must jump from one idea to another
Categories, classifications and labels are fixed	Categories, classifications and labels can vary
You know what you are looking for	You do not know what you are looking for
Triggers only if there is a direction to move in	Always triggers to create new directions
The most obvious paths are sought	The least obvious paths are also sought
Every decision must be correct	False steps can be taken
What it is not related to the topic is excluded	What it is apparently unrelated to the topic is explored
It is a finite process	It is an infinite process

Therefore, the Lateral Thinking method implies taking not a defined path within the solution search tree. Instead, jumps are made, following a fuzzy direction, looking like fluttering decisions are being made. It is as if several paths are used at the same time within the search tree, jumping from one to another, while moving forward. At a certain point, a surprisingly valid solution is reached (Fig. 2.23).

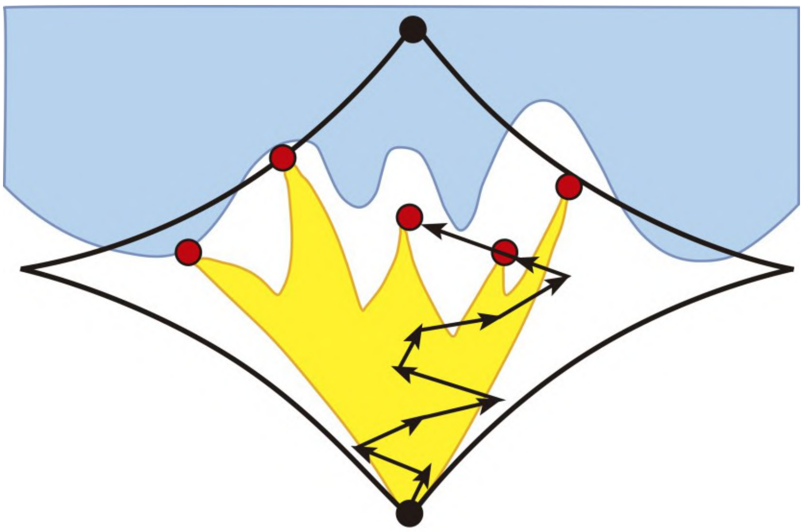

Figure 2.23. Using the *Lateral thinking* method, a wide path is followed, modulated in a certain direction, and unpredictable jumps are made, until one or more novel and valuable solutions are reached

b. Operational structure to stimulate Lateral Thinking

The general operational structure of *Lateral Thinking* is based on four basic characteristics.

- *Checking assumptions*

It is not always possible to approach a problem from a *Vertical Thinking* perspective, as the solution may not be as straightforward as we thought. Therefore, the pre-established conventional assumptions, ideas or concepts whose validity is commonly accepted (without being analyzed) must be continuously reviewed.

That is, in general you must act with a clear mind and open to anything, in order to be able to cope properly with each situation.

- *Asking the right questions*

The most important question of this method is to know the most appropriate questions. The session should begin by asking simple, general questions to initially frame the problem. Next, the known data must be examined with much more specific questions, examining the most obvious hypotheses, until an alternative vision close to the solution is reached.

- *Enhance imagination*

Imagination is a fundamental part of human creativity, and it is a powerful tool of *Lateral Thinking*. In the end, it's about approaching each challenge creatively from another point of view. The lateral perspective will be more effective at solving seemingly unconventional issues, where direct logic would not be of much use.

- *Refine logical thinking*

To achieve effective *Lateral Thinking*, it is necessary to refine both logical analysis, deduction and the discipline of reasoning, since without these elements *Lateral Thinking* would be a lost pilgrim thought, which would only be limited to extracting eccentric ideas. That is, once the answers have been developed, there must be a logic in *Lateral Thinking* that allows it to be explained to others.

c. Techniques that facilitate the development of Lateral Thinking

There are an enormous number of techniques that stimulate *Lateral Thinking*, although some of them have always proven themselves. Below is a partial list of the most common techniques, simply for the purpose of illustrating the methodology.

- *Random Words ("Random Imput")*

It consists of creating the starting point of a new line of thought through words chosen at random, with no apparent relation to the object to be created. Next, and using this word, random associations are made, generating phrases, or generating verbs, adjectives and nouns, based on some relationship with the object. With each association, new ideas are generated, repeating the process using the previously generated association as a starting point, and so on repeatedly until it is considered sufficient (Fig. 2.24).

Typically, very long association strings are generated, so the time consumed in each association session must be controlled.

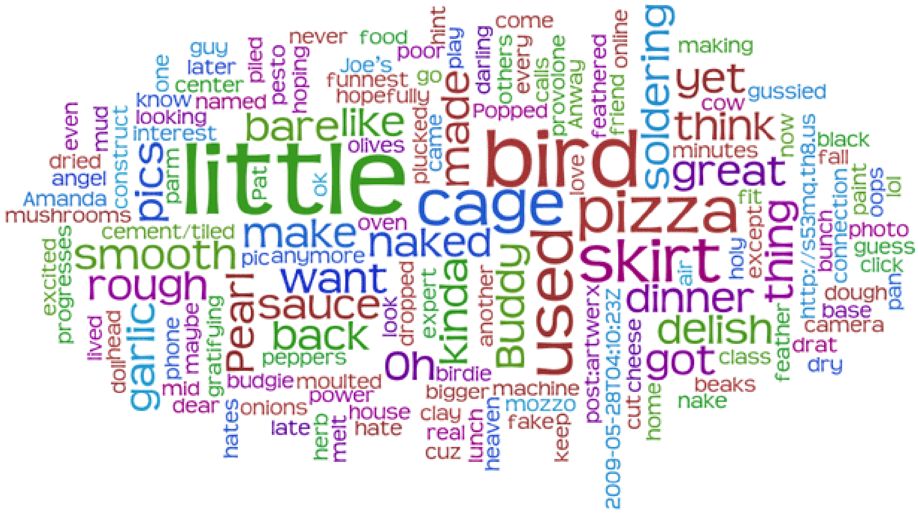

Figure 2.24. Random words method

This method allows finding new lines of thought, and therefore new ideas that provide a different point of view for the resolution of a certain problem. The association of a word applied to a situation out of context generates new connections in our mind, and this allows finding new paths in the solution search tree, and therefore find new creative solutions.

This method is widely used in many fields, although it is especially effective in creating children's stories. One of the authors who has used it the most has been Guanni Rodari, who comments that in order to create children's stories "*… the isolated word acts only when it finds a second one that provokes it ... the thought is created in pairs ... It takes a certain distance between the two words, it is necessary that one is strange enough to the other, and their approach discreetly unusual, so that the imagination is forced to set off to establish a kinship between them….*" [66].

- *Suppress some feature of the problem*

In general, we tend to think with prejudices, and therefore many of the assumptions of a certain problem are false. So, the denial of any of these assumptions allows thinking beyond the conventional logical way. To apply the method for the resolution of a certain problem, in the first place, a set of assumptions of the same must be chosen, to give them as true, and then deny them (Fig. 2.25). From this new environment, new solutions are sought through conventional *Problem-Solving* strategies (*Vertical Thinking*).

Figure 2.25. *Suppress some feature of the problem method*

- *Modify or exaggerate any aspect related to the problem environment*

It consists of exaggerating, distorting or modifying the problem environment in any way. In this way a certain object or entity is shown as it is desired to be, and not as it really is (Fig. 2.26).

Figure 2.26. *Exaggerate any aspect related to the problem method*

For example, if we are looking for ways to make a boat move through very shallow areas. We know that a ship floats on water and has a certain amount of submerged space due to its buoyancy, but by exaggeration we designed the provocation “a ship that has no submerged space”.

- *Establish analogies with other situations or problems*

Analogies serve to generate new approaches to a problem and allow the development of functions, processes and relationships that are then transferred to the problem to attempt its restructuring. The analogies must be based on very concrete situations and with which you are familiar. These situations do not require having a large number of processes, functions or relationships. However, there must be an action and events that lend themselves to different outcomes, although not necessarily real (Fig. 2.27).

Figure 2.27. *Establish analogies with other situations or problems method*

- *Reverse the problem, or analyze its opposite and see how it could be solved from that reverse perspective*

It consists of taking a principle considered to be true and inverting the elements that operate on that principle, thereby causing a forced rearrangement of the information.

It is about seeing the problem from different angles to get closer to another solution, more or less eccentric. When problems are reversed, the sense of process is altered, and when trying to solve them, new lines of thought are created, which could generate new search paths to solve the original problem. For example: apples have trees, cigarettes are smoked by people, wheels have bicycles, buildings have cities, etc. (Fig. 2.28).

The goal of this method is not to solve a certain problem squarely but taking the main idea by inverting it will help you get closer to your solution. The investment method also tries to avoid the chain of ideas and closure, looking for the wildest solutions can sometimes work. Seeing the problem from different points of view, not looking at just one, having different angles of vision that allow us to have a clearer vision of the problem, not seeing it superficially.

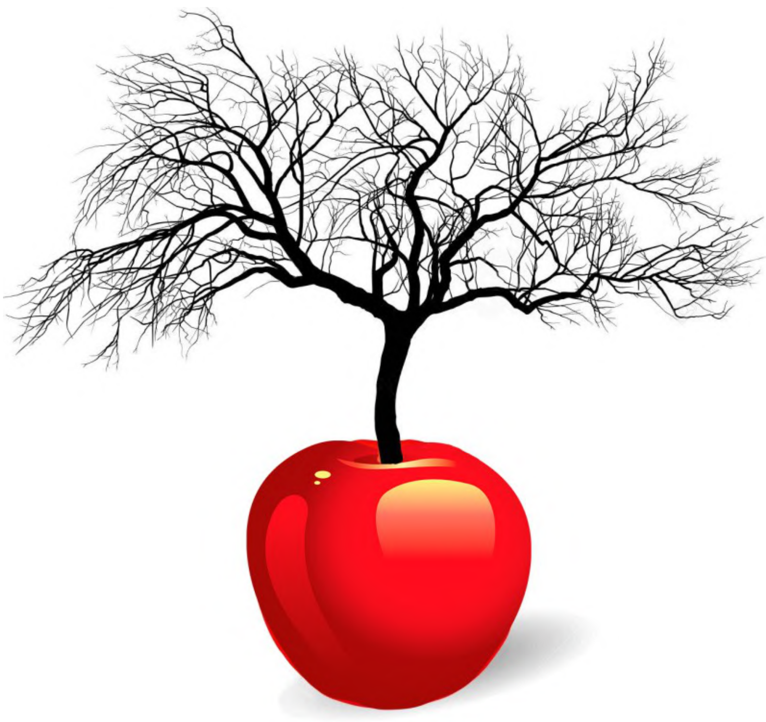

Figure 2.28. *Reverse the problem method*

- *Break the problem down into parts*

The objective of fractionation is to avoid the effects of the inhibition implicit in the fixed models by means of their decomposition. That is, it is based on the breakdown of the solidity and unity of the models of ideas.

Sometimes it is difficult to divide a problem into different fractions, so it is possible to resort to an artificial technique that consists of dividing a problem into two fractions and then successively repeating the same operation, until the desired number of parts is obtained. This technique does not try to divide a situation or a problem into its natural components, as in the case of logical analysis, but to obtain material that allows a restructuring of the models (Fig. 2.29). That is, it does not try to explain anything, but to rearrange. It does not try to affect the successive divisions so that the resulting parts are of equivalent importance, but rather that any type of division is correct. Fractions can be both highly artificial and of uneven importance, but they can be useful.

Figure 2.29. *Break the problem down into different components method*

- *Take the problem out of its usual context*

The method consists of displaying the object that you want to create, but outside of its usual context. For example, to design a car, you can imagine yourself on the moon, or in the middle of a bedroom. This is a fairly common practice in literature and is known as "citing out of context." This strategy aims to distort the original meaning that it had in its usual context and provide it with another desired meaning ("contextonomy"). In fact, this strategy is often used in the media to make false statements and put them in the mouths of other people. Many studies have shown that the effects of this contextual distortion persist for a long time, even though it has been made clear that the statements were taken out of context and that they were actually false.

By removing a certain object from its usual context, it can be given a different meaning than it had. In this way, new objects, entities or processes can be created, since by stripping them of their usual context, it is easier to seek for solutions and the search tree can be traversed in completely different ways.

This method also encourages creativity as it directly induces new approaches to the same problem, as well as new ideas to solve it. It is capable of breaking the initial structure with which the brain has stored information, and creating new, more general, broad structures, which in turn allows the generation of new ideas (Fig. 2.30).

Some examples are the following: designing a house imagining it at the bottom of the sea, designing a wall in the middle of the desert, designing a toilet by imagining it in a museum, imagining the usefulness of a brick by imagining it inside a bathroom, designing shoes by imagining them in a tree, etc.

Figure 2.30. *Take the problem out of its usual context method*

2.4.12.2. Evaluation

Together, the methodologies included in the *Lateral Thinking method* have enormous creative potential, since all of them aim to reach a solution, but by unusual paths. When you walk through the search tree looking for solutions, there are always two completely different problems. If the tree is traversed along the usual paths, a solution can be reached, but it will be uncreative, unsurprising, and may be unsatisfactory in some cases. On the other hand, if the tree is traveled by completely different paths, it is possible that no solution will ever be reached.

Therefore, the objective of the different methods that stimulate creativity is based on approaching the search tree through intermediate paths, which are not the usual ones, but which are not random either. In some way, the paths to be traveled must have some relation to the problem to be solved, even if they are not perceived with the naked eye.

The methods usually included within the *Lateral Thinking* concept have this characteristic, they usually generate solutions along paths not too far from the usual paths, which is why novel and valuable ideas are usually generated.

Lateral Thinking is usually the first part of the creative process, since in a second stage the raw ideas achieved must be adapted and polished properly to completely solve the problem in all its aspects.

2.4.13. Parallel thinking

2.4.13.1. Method description

The *Parallel Thinking* was designed also by De Bono [67], as a powerful method to stimulate creativity. The stimulation of parallel thinking is perhaps the most creative strategy of all.

Our western civilization is immersed in a system of thought based on analysis, judgment and argumentation. But today the human environment has changed and transcended. The continuous convulsions to which our society is subjected, the rapidity of events and their dynamic transformation through a huge social mass, make this system of thought no longer sufficient. The bottom line is that we need to design a new style of thinking capable of moving forward from parallel possibilities.

Parallel Thinking allows contradictory opinions to coexist in parallel without having to be true (or accepted) at each stage. In a process of *Parallel Thinking* there can be no disputes, no confrontations, and it is not even important if something is true or false. The important thing is to maintain thought processes in parallel, which progress separately and evolve, enriching each other, although evidently certain objective evidence and certain intersubjective accounts shared by society must be respected. The important thing is to reach agreements between several interlocutors. As *De Bono* points out, "*creativity implies a willingness to challenge, a willingness to take risks, a willingness to be provocative, and a willingness to come out of the judgments that are a summary of past experience*" [68].

Parallel thinking can include all kinds of strategies, although the most effective is *Brainstorming*, the second part of which involves, in this case, a confrontation between the different group components, and in which a solution can only be reached that is absolutely accepted by all of them.

In fact, in the Renaissance, and specifically in the design of the *new basilica St. Peter* Julius II created a very effective system of *Parallel Thinking*. The pope forced three architects to compete and collaborate with each other, and an idea would only be heard when they had previously reached a consensus [69]. Architects should create ideas for themselves, but they should expose them to others, and try to persuade them. In some cases, the architects defended their ideas against others, but in other cases they enriched their ideas with those of others. And they know that if they do not reach agreements, the pope wouldn't listen to them. Without a doubt one of the most successful examples of *Parallel Thinking* that has existed throughout history.

2.4.13.2. Evaluation

Parallel thinking is a method that fuses several ideas into one, in such a way that the different ideas correspond to a personal point of view of the solution of the problem. This method can be the final stage of any other method in which several components participate.

There is also another individual and more powerful variant of parallel thinking, when several ideas generated in different temporal stages by the same person merge.

Parallel thinking is a synthesis of several ideas that coexist at the same time, which means that it goes through the tree in search of possible solutions along several paths at the same time. This guarantees that several ideas can be generated and at the same time there is a high probability that some of them will be very reactive, novel and valuable.

2.4.14. Sensanation method

2.4.14.1. Method description

The *Sensanation method* was created by Mike Vance [70] during his time working for Walt Disney. “Sensanation” means thinking simultaneously in the five senses of sight, sound, taste, touch, and smell.

Think about your problem in terms of your five senses. What taste, smell, feel, look, sound, does your problem have? Observe your reactions to trigger new perceptions of your problem and its solution.

The *Sensanation method* broadens the range of ways of thinking. To start the creative process, it must be triggered or followed by some mental mechanism. In his book, Mike Vance provides some lists of associations for each of the senses, but any other can be made, for example by creating synonyms and antonyms with the help of a dictionary.

2.4.14.2. Evaluation

The *Sensanation method* is an associative method, which has a determined methodology. It is probably suitable for certain problems in which the senses have certain relevance, but how can it be used to create a business strategy? What does a corporate policy smell like? What color is a business strategy? Therefore, the scope of application is narrow, and when applied indiscriminately it is highly likely that no truly novel and valuable solution will be reached.

2.4.15. Systematic Innovation method (TRIZ method)

2.4.15.1. Method description

The *TRIZ method* (*Teoriya Resheniya Izobreatatelskikh Zadatch*), is an alternative theory of inventive problem solving. It was created in 1946 by the engineer Genrich Altshuler, as a result of analyzing a huge number of patents [71].

The TRIZ method (as well as the *Systematic Innovation method* which is an update of it) was the result of more than 2000 person-years of research not only in patents, but also of successful and creative solutions to problems of various kinds [72].

The conceptual bases of the *Systematic Innovation method* are:

1. The same problems and the same solutions appear over and over in different companies. But these companies try to solve the same kinds of problems by themselves and from the beginning, rather than looking beyond their own experiences or the experiences of their direct competitors. That is, most companies try to reinvent the wheel, instead of creating new ideas based on the analysis of the advantages and disadvantages of existing wheels.
2. The most creative and successful solutions are based on the elimination of compromises and trade-offs that are usually seen as inherent in problems.
3. There are few possible strategies to resolve such contradictions.
4. The most creative and successful solutions also make the most of resources. Most of today's companies tend to solve problems by adding resources, rather than making existing resources work more effectively, or transforming faulty components into something useful.
5. Evolutionary trends in technology follow very predictable paths.

Systematic innovation works on several levels (Fig. 2.31). The lowest level is made up of a group of tools. At the second level there is a set of problem-solving processes that link different tools to solve any type of problem in an innovative way. At the third level there is a set of philosophical ideas.

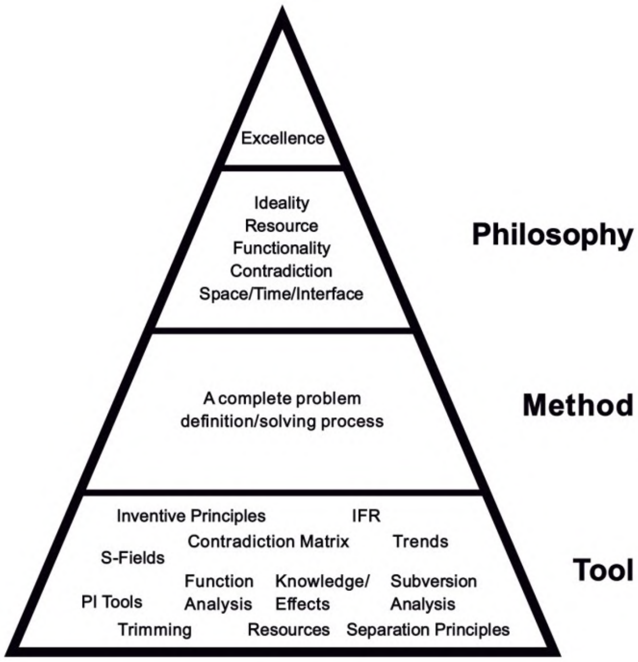

Figure 2.31. Levels of operation of the *Systematic Innovation method*

2.4.15.2. Evaluation

Undoubtedly, this method is the most organized of all, and it is also the most "ecological" since, from its own declaration of intent, it intends to optimize resources, to obtain the greatest amount of benefits, in this case, the greatest number of creative ideas, with the least possible cognitive effort.

The method generally ensures getting ideas, but in no case does it favor the generation of “crazy” or absurd ideas, which by themselves do not solve the problem, but which lead to a specific place in the tree of search for solutions, which favors unusual paths that can lead to surprising, novel and valuable solutions. Without a doubt, the method is a suitable second part of *Brainstorming*.

2.5. Conceptual models of the creative process

In general, what the methods implemented to enhance human creativity do is force the search tree for solutions (Fig. 2.13) to be traversed by paths different from the usual ones. We usually solve problems more or less in the same way, since we usually use the same procedures. For this reason, the aforementioned methods force us to carry out cognitive processes different from the usual ones, when it is evident that these are sterile. This shows that the creative process is much more flexible and complex than could be derived from analyzing the conceptual models of the creative process proposed to date.

From the analysis of the behavior of creative people, and from the analysis of the methods to stimulate creativity, different conceptual models have been identified on the structure of the creative process [73]. The proposals made have been very varied and heterogeneous, but to a greater or lesser extent, they are all very simplified and deficient.

The first proposed conceptual model identified 4 phases of the creative process: *preparation* (analysis of the problem), *incubation* (based on non-conscious thought), *illumination* (happy thought) and *verification* (evaluation of the idea) [74]. Since then, the process has been slightly completed [75], until reaching models based on 8 stages: *find the problem*, *acquire knowledge*, *gather related information*, *incubation*, *generate ideas*, *combine ideas*, *select from best ideas*, *and externalize ideas* [76]. These methods, however, continued to be excessively simplified, so the approach was changed, and more complex and flexible methods began to be proposed, which were not structured in a sequence of stages, but in the flexible articulation of 8 essential characteristics: *iteration*, *ambiguity*, *exploration*, *emergency*, *failure and dead ends*, *deliberate and intentional*, *conscious reflection*, *the importance of constraints* [77].

Based on these previous investigations, a much more detailed conceptual model has been proposed in this Thesis (Fig. 2.32). According to this model, the creative process consists of a complex process of generating and evaluating ideas. This process has a sequential component, and also a transversal one, in which top-down and bottom-up decisions are made at all times. That is, abstract concepts are built on the basis of more concrete concepts, and in turn, concrete concepts will be generated by particularizing more abstract concepts. In addition, the creative process takes place at various levels of abstraction in each of its stages, in which a wide range of decisions can be made, from the most abstract and general, to the most concrete and detailed.

The idea generation process has a conscious component (imagination) and an unconscious component, and both are based on the alteration and association of previously created concepts or ideas. The unconscious component is more powerful and complex, because the alteration of concepts is intensified, and more random associations are made (many mixing information of the moment, and personal information). In general, unconscious processes only occur after an exhaustive conscious process of searching for solutions. Conscious analytical cognitive processes can solve a problem creatively (when the problem is well defined, or very simple). On the other hand, it is possible that, after trying to solve a certain problem, consciously and repeatedly, no valid or satisfactory solution is reached (when the problem is poorly defined, or very complex). In this case, breaks are usually taken, in which precisely a set of unconscious processes are launched that try to solve the problem in different ways, manipulating the information in a complex and varied way, and sometimes even randomly. The creative process is also very flexible, as it follows different paths each time, and in many cases it is indeterminate, as small changes in input information can generate very different ideas.

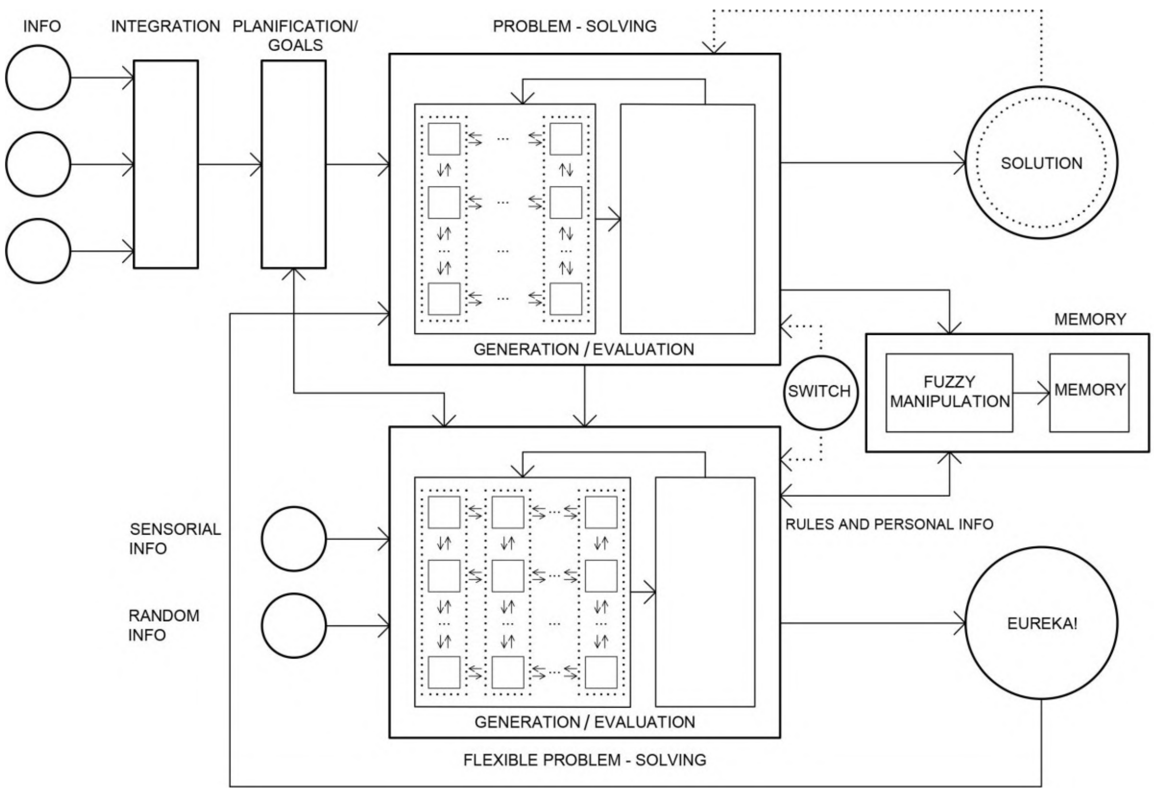

Figure 2.32. Conceptual model of the creative process, proposed by Luis De Garrido.

Both the model proposed here and the previous models have been defined based on the observation, analysis and conceptualization of the behavior of creative people. The analysis of the different successful methods to stimulate creativity has also been useful. However, when attempting to detail these conceptual models, convincing information is always lacking, so all kinds of speculations are made that are difficult to justify. Therefore, these models will always be incomplete and inaccurate, unless the neurocognitive activity of the brain is investigated when performing creative tasks.

If the neurocognitive factors of human creativity were known, the conceptual models could be completed, and the number of speculations would be reduced by defining them in more detail.

In recent years this is already being done, and conceptual models of the creative process are serving to focus research on the neurocognitive bases of human creativity. In the same way, these investigations, in turn, will serve to establish more accurate, complex and detailed conceptual models of the creative process.

2.6. The need to know the neurocognitive bases of human creativity

Human creativity has manifested in a natural way throughout history. The need and adaptation to an ever-changing environment has forced creative answers to be sought to solve increasingly complex problems. However, some humans show a greater creative capacity than others, and the reason why this circumstance occurs has never been known. For this reason, methods capable of fostering creativity have been developed, both in creative people and in people who are not so creative.

As seen, some of these methods are individual, while others have been designed to take advantage of the amplifier effect of a group. Each of these methods offers different results. Some promote the generation of creative ideas more than others, some promote the generation of creative ideas in a certain field of knowledge, and on the other hand, other methods are more suitable for other disciplines. For this reason, these methods have been modified in order to improve results, with more or less success.

These methods have been proposed, and have been improved throughout history, through a trial-and-error strategy, when studying the methodology of the creative process. Therefore, the results have not always been as promising as expected.

At no time has the functional structure of the human brain been taken into account, neither to design methodologies that improve human creativity, nor to improve existing ones.

The human brain has always been a mystery, and despite the great discoveries made so far, its functional operation remains full of unknowns.

However, today enough of the human brain is known to delimit the reasons why it can generate creative and surprising ideas that are novel and valuable. Knowledge of the neurocognitive bases of human creativity offers a vast field of research, and based on this, new methodologies and strategies can be generated to amplify human creative capacity, improve existing methodologies and create new, much more effective ones.

This is the main objective of this Doctoral Thesis. In the next three chapters the neurocognitive bases of human creativity are delimited, and in Chapters 6 and 7 a computational and human paradigm of creativity is proposed, and new methods are proposed to amplify it.

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CHAPTER 3

Functional structure of the human brain, and its relationship to the creative process

Chapter 3. Functional structure of the human brain, and its relationship to the creative process

To determine the neurocognitive bases of human creativity, the most recent research that determines the brain structure and the functional structure of the human brain must first be analyzed. Based on the most advanced techniques, a functional paradigm of the neurocognitive activity of the brain has been consolidated based on the dynamic collaboration of a set of large-scale networks. In this chapter the total set of large-scale networks is analyzed, and emphasis is placed on the three networks directly involved in human creativity: the *Default mode network* (DMN), the *Executive control network* (ECN), and the *Salience network* (SN), whose functional interrelation constitutes what is usually called as *triple network model*. Finally, and based on those previously exposed, and based on the most recent studies, the neurocognitive bases of the essential processes of creativity are analyzed with detail: Imagination process, idea generation and evaluation process, "inner self" evaluation process and the semantic process.

3.1. Neurocognitive paradigm based on large-scale brain networks

At present, a neurocognitive paradigm has been consolidated in which the functional structure of the brain is based on modularity and connectivity [1]. Modularity refers to the specialized processing of different brain regions, and connectivity refers to the flow of information through different large-scale distributed networks.

To determine modularity and connectivity in the brain so far functional connectivity magnetic resonance imaging (fcMRI) studies have proven to be very useful. This technique is used to detect brain regions whose fluctuations in the blood oxygen level dependent (BOLD) signal are correlated over time in task-free or resting state [2].

For this reason, in recent years there has been an increased interest in detecting *Intrinsic connectivity networks* (ICN), that is, large-scale networks (including several interdependent brain areas) detected at rest [3] since they allow to identify in more detail the organization of the brain [4], and especially its functionality [5].

Using fcMRI, different large-scale neuronal networks have been identified in the resting state that are involved in sensory, motor and cognitive functions [6], therefore these results support the intuitive notion that the brain "at rest" is never really at rest.

Based on these investigations, different conclusions have been reached that, together, make up the current neurocognitive paradigm of brain activity.

Perhaps the most basic conclusion is that the activity of the brain can develop an extremely complex information processing, based on the simultaneous activation of serial and parallel processes.

3.1. Serial and parallel processing in the brain

Distributed brain systems are organized to facilitate serial and parallel processing [7].

The serial processing model was the first to be proposed. In fact, the concept of serial hierarchies has undergone since the first studies on the organization of the brain [8]. And it has long been known that hierarchical processing through sensory systems converges in areas of cross-modal association [9].

The parallel processing model has been suggested more recently. When the existence of large-scale networks involving connections between various cortical regions was discovered, parallel processing was evidenced. However, the existence of feedback projections from higher to lower sensory areas was also observed, which implied serial processing. In other words, the organizational structure of the cerebral cortex is a complex combination of serial and parallel processing.

Nevertheless, the organization of the association cortex in networks distributed in parallel [10] deviates from hierarchical (serial) organizational models for two reasons:

- Distributed networks consist of association areas involving the frontal, cingulate, temporal and parietal cortices. These networks have strong interconnection ties, both within their component regions, as well as between the different regions of the same network [11].
- In the cortex there are several large-scale networks adjacent to each other. Thus, adjacent regions in the parietal cortex (belonging to separate networks) are differentially connected to adjacent regions of other networks that extend into the frontal, temporal and cingulate cortices [12].

Therefore, most of the cerebral cortex is structured based on multiple parallel circuits that are interdigitated along it.

3.2. Large-scale brain networks

In recent years, a paradigm based on large-scale neural networks has been consolidated to understand the neurocognitive bases of cognition [13]. In this way, brain activity has been conceptualized based on the activation of a set of multiple different interactive networks, which involve different specialized regions of the brain.

This paradigm explains that human cognition is based on the incessant and continuous activation of different large-scale neural networks that group different brain regions, each of which is involved in a varied set of functions. In turn, the functionality of each region depends on the pattern of its connections with other functionally related brain regions [14].

In the last decade of the last century, neural networks were defined for the first time as large-scale brain systems, involving different anatomical areas, and having different cognitive functions [15]. In this decade, and based on fMRI functional magnetic resonance imaging techniques, five main functional networks were identified:

- The *spatial attention network*, which includes areas of the posterior parietal cortex (CPP) and the frontal ocular fields.
- The *language network*, which includes the Wernicke and Broca areas.
- The *explicit memory network,* which includes areas of the hippocampal-entorhinal complex and the lower parietal cortex.
- The *facial object recognition network*, which includes areas of the midtemporal cortex and the temporopolar cortex.
- The *working memory-executive function network*, which includes areas of the inferior parietal cortex and prefrontal cortex.

Subsequently, a huge amount of research was carried out to define these networks in more detail, and to detect new networks.

One of the first investigations was the identification of two opposing macro-networks: One network includes the regions that are usually activated when certain tasks are executed, and another includes the regions that are activated when tasks are not performed [16].

3.2.1. Task positive and Task negative dynamic anticorrelated functional networks

During cognitive tasks that demand attention, certain regions of the brain increase their activity, while others decrease it.

Functional imaging techniques such as positron emission tomography and functional magnetic resonance imaging (fMRI) have been used for investigating the functioning of the human brain. With these technologies, brain activity can be detected in response to certain stimuli.

When brain activity is analyzed when performing cognitive tasks that demand attention, two different types of responses were detected:

- Some regions increase their activity, such as the frontal cortex and the parietal cortex increase their activity [17]. Increased activity in the frontal and parietal regions is related to top-down control of attention and working memory, which are basic processes of cognitive tasks [18].
- Some regions decrease their activity, such as the posterior cingulate cortex, the medial and lateral parietal cortex, and the medial prefrontal cortex (MPF) [19].

As the demand for task attention increases, there is still more difference, since the activity of the regions involved increases even more [20], while activity in negative regions decreases even more [21]. The level of decrease in activity is proportional to the difficulty of the task [22] but can be attenuated by self-referential components of the task, such as emotion [23], or episodic memory [24], and also by the appearance of thoughts independent of the task [25].

That is, when cognitive tasks that require attention are carried out, the activity of a set of regions that collaborate in the execution of the task increases, and on the other hand, the activity decreases in the regions that apparently support non-task-related or irrelevant processes.

These data have been confirmed by means of alternative strategies in which spontaneous brain activity is observed in the absence of a task. These resting-state functional connectivity studies analyze the correlations in slow spontaneous fluctuations (<0.1 Hz) in the blood oxygen level dependent signal (BOLD) [26].

The result of these studies shows that the regions activated when performing certain tasks (or as a consequence of certain external stimuli) show correlated spontaneous fluctuations also in the absence of tasks or stimuli [27]. To determine the regions that are usually activated during goal-directed task performance, an extensive study was carried out [28] in which both the correlations and the anticorrelations in the BOLD fluctuations associated with six previously predefined regions of interest were analyzed. These six regions were chosen because previously three of them were activated when performing tasks that require attention, and another three were deactivated during these tasks were executed [29].

The resulting maps of the resting state functional connectivity correlate with previous work and show 3 task-positive regions and 3 task-negative regions (Fig. 3.1).

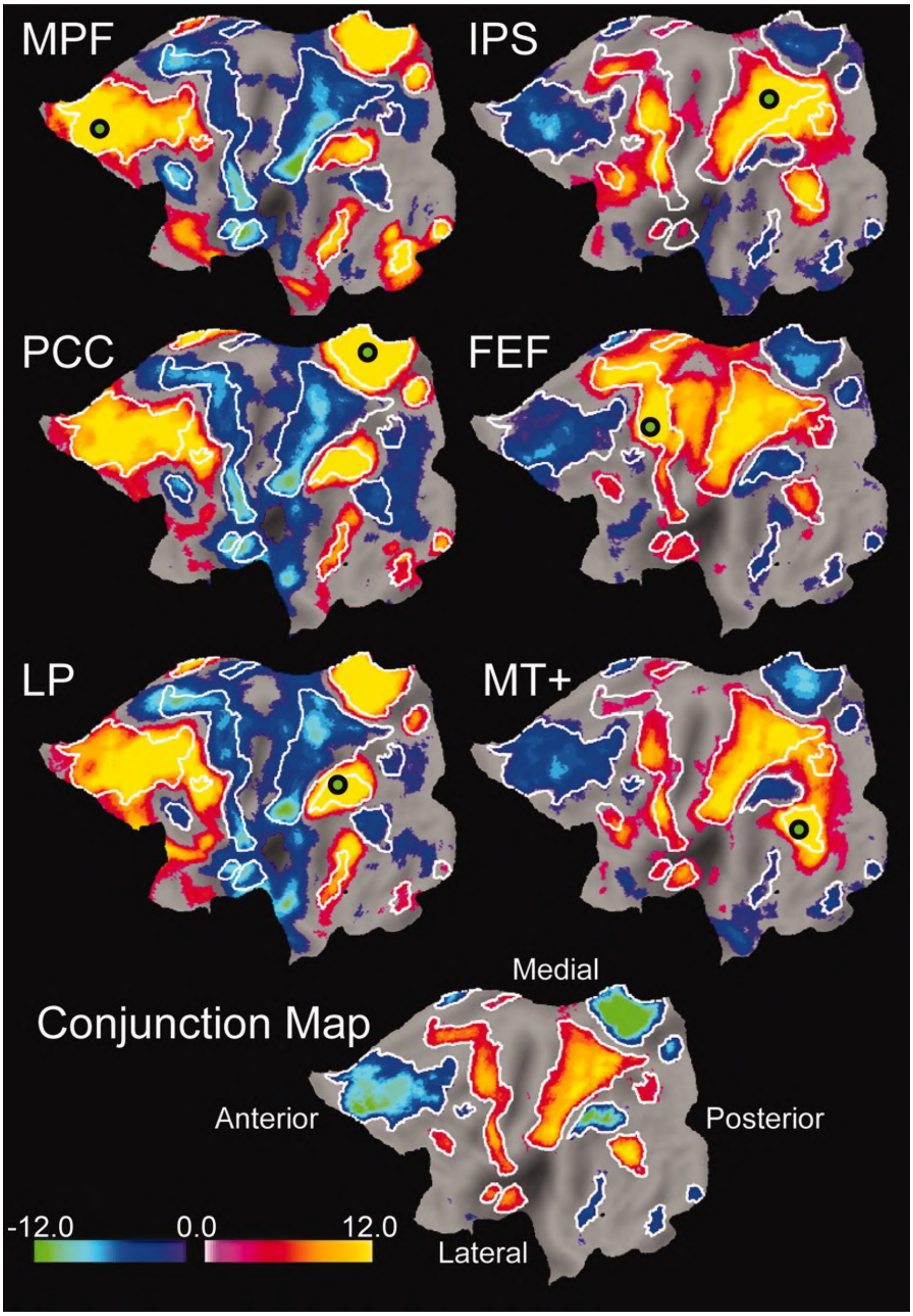

Figure 3.1. Images showing nodes significantly correlated or anticorrelated with six seed regions.
Left. Task-negative seed regions: MPF, PCC, LP.
Right. Task-positive seed regions: IPS, FEF, MT +.
Lower. Image of the average, including only nodes significantly correlated or anticorrelated with five of the six seed regions.
(Source: Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences*, 102(27), 9673-9678)

The six correlation maps were combined by using a modified conjunction analysis, and a conjunction map was obtained (Fig. 3.1). Automated peak search was used to identitfy regions of maximum importance in the conjunction map. As a result, 15 regions were obtained as part of the *task-positive network*, and 15 regions as part of the *task-negative network* (Table 3.1).

The *task-positive network* consists of a group of regions that are activated when goal-directed tasks are performed [30]. As expected, this network includes regions of the *dorsal attention network*, such as the intraperietal sulcus (IPS) and the frontal eye fields (FEF), active during directed attention [31], and dorsal-lateral and ventral prefrontal regions, insula and supplementary motor area (SMA), activated when demanding cognitive tasks are performed [32].

The *task-negative network* consists of a group of regions that decrease their activity during task performance [33] and are involved in various aspects of self-referential processing [34]. As expected, this network includes regions of the *Default mode network* (DMN) that have more activity at rest than when performing goal-directed tasks [35]. A component of this network, the cerebellar tonsils, had not been previously identified, and suggests that this region of the cerebellum must contribute in some way to the functioning of the *task-negative network*.

This study suggested that resting-state brain functionality is based on a dynamic interaction between large neural systems that represent opposite components of our mental state.

Therefore, the previous paradigm that described the brain as a system that responds to changing stimuli and tasks was abandoned and replaced by a paradigm that describes the brain as a self-operating system in which sensory information modulates its operability.

3.2.2. Funtional neural networks are active during activation and rest

In recent years, new technologies have been developed, such as diffusion tensor imaging (DTI) and resting state fMRI, which have been very effective in identifying and characterizing structural and functional brain networks. In fact, these techniques have identified several important brain networks that are activated when the brain is active [36], and that they also remain active (with different intensity) when the brain is at rest [37].

These main functional brain networks (as well as the subnets that compose them) show an important correspondence in independent analyzes of resting state and task-related connectivity patterns [38], suggesting that functional networks that are activated at rest are also commonly involved during cognition.

Brodmann's areas	Regions	Talairach coordinates
Task-positive network		
7	Intraparietal sulcus (IPS)	(-23, -66, 46) (25, -58, 52)
7/40	Inferior parietal lobule	(-42, -44, 49) (47, -37, 52)
19	Orbital gyrus (vIPS) ventral intraparietal sulcus	(-26, -80, 26) (35, -81, 29)
6	Frontal eye fiels (SPrCeS) sup. precentral sulcus	(-24, -12, 61) (28, -7, 54)
6	Inferior precentral sulcus	(-54, 0, 35)
6/32	SMA/pre-SMA	(-2, 1, 51)
46	Dorsal lateral prefrontal cortex (DLPFC)	(-40, 39, 26) (38, 41, 22)
19/37	Middle temporal area (MT^{+})	(-47, -69, -3) (54, -63, -8)
	Insula/frontal operculum	(-45, 5, 8) (45, 4, 14)
Task-negative network		
31	Posterior cingulate cortex (PCC)	(-2, -36, 37)
30	Retro-splenial	(3, -51, 8)
39	Parietal lobe (LP)	(-47, -67, 36) (53, -67, 36)
32/10	Medial prefrontal cortex (MPF)	(-3, 39, -2) (1, 54, 21)
8	Superior frontal	(-14, 38, 52) (17, 37, 52)
20/21	Inferior temporal	(-61, -33, -15) (65, -17, -15)
35	Parahippocampal gyrus	(-22, -26, -16) (25, -26, -14)
	Cerebellar tonsils	(7, -52, -44)

Table 3.1. Intrinsically anticorrelated networks
(Source: Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences,* 102(27), 9673-9678)

In general, the analysis of the results of the resting-state fMRI allows identifying the organization and connectivity of several important brain networks that cannot be detected with other techniques.

3.2.3. Identification of the main large-scale brain networks

With the development of functional magnetic resonance imaging (fMRI) technology, it was observed that the FMRI time series that various regions of the cerebral cortex are linked together forming functional networks, even when the brain is in a resting state [39]. Since then, several other networks have been identified with different temporal characteristics [40], which also continue to covariate even when the subject is asleep [41], or under anesthesia [42]. As a result, and so far, several networks have been found to be spatially consistent in different aspects [43]. These functional networks were called "resting state networks" (RSNs).

It remained to be shown that the RSN functional networks matched the set of functional networks used by the active brain undergoing tasks.

Therefore, a first big study [44] was carried out in which the main resting-state networks identified by functional magnetic resonance imaging fMRI (of 36 resting subjects) were compared with separate activation maps derived from the *BrainMap* database of functional imaging studies involving 29,671 human subjects (using independent component analysis (ICA)) [45]. To aid in the interpretation of the components (and to show the accuracy of the experimental descriptions in *BrainMap*), the "behavioral domain" categorizations were extracted from the *BrainMap* database for each ICA component. The results (Fig. 3.2) were found to be consistent with the known location of brain function. When comparing both results (fMRI y *BrainMap*), it was observed that there was a close correspondence.

As a result, ten groups of maps, or pairs of images (fMRI - ICA *BrainMap*), were identified, corresponding to the ten *major representative* functional networks of brain (Fig. 3.3). Of these 10 networks, 8 correspond to RSN networks that had been identified and described previously [46], although two different visual maps (corresponding to two different networks) were differentiated from a previously identified network (maps 2 and 3), and a cerebellar network was also added (map 5). The 10 networks correspond to interpretable functional categories, and the *main representative* functional networks can be considered as independently derived from both the activation meta-analysis and the data at rest.

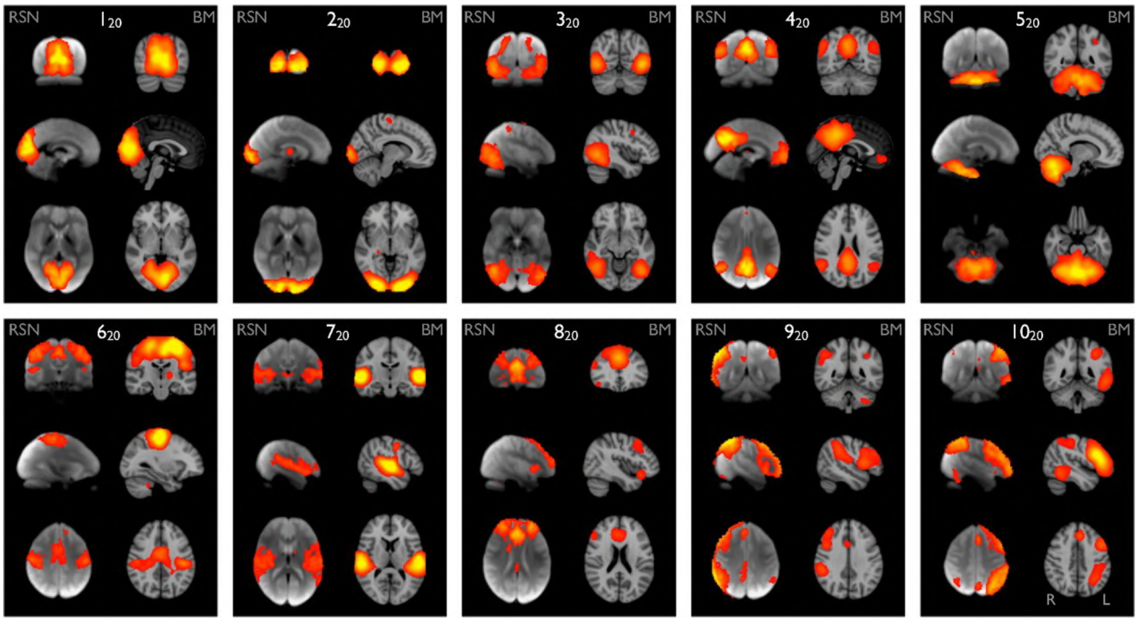

Figure 3.2. Comparison of the 10 most important neural networks identified in two different ways (20 components).
Left side of images: Images made by superimposing data obtained from resting fMRI of 36 subjects.
Right side of images: Images from *BrainMap* database (using 20 components), superimposed on the MNI152 standard space template image.
(Source: Smith, S. M., Fox, P. T., Miller, K. L., Glahn, D. C., Fox, P. M., Mackay, C. E., Filippini, N., Watkins, K. E., Toro, R., Laird, A. R., & Beckmann, C. F. (2009). Correspondence of the brain's functional architecture during activation and rest. *Proceedings of the National Academy of Sciences*, 106 (31), 13040-13045)

The top 10 *representative networks* are as follows:

- Networks 1, 2 y 3. *Visual Networks*. They include the medial, occipital pole and lateral visual regions. Although the three networks are involved in visual activities, the occipital pole is involved in the cognition-language-spelling behavioral domains, and the lateral visual regions are involved in cognition-space behavioral domains.

- Network 4. *Default Mode Network*. It includes the medial parietal cortex (precuneus and posterior cingulate), the bilateral inferior-lateral-parietal cortex, and the frontal ventromedial cortex. The DMN is the network that is most clearly deactivated when performing tasks, so this map does not correspond to any specific behavior domain. In fact, this map generally corresponds to negative contrasts with cognitive paradigms.

- Network 5. *Cerebellum network*. It is located within the cerebellum. This network is involved in the action-execution and perception-synthesis-pain domains of behavior.

- Network 6. *Sensorimotor network*. This network includes the supplementary motor area, the sensorimotor cortex, and the secondary somatosensory cortex. This network is involved in the action-execution and perception-synthesis domains of behavior.

- Network 7. *Auditory network*. This network includes the superior temporal gyrus, Heschl's gyrus, and the posterior insula. Includes association and primary auditory cortices. This network is involved in the action-execution-speech, cognition-language-speech and perception-hearing domains of behavior.
- Network 8. *Executive control network*. This network includes several medial-frontal regions, including the anterior cingulate and the paracingulate. This network is involved in various cognitive processes, and in the action-inhibition, emotion, and perception-synthesis-pain domains of behavior.
- Networks 9 and 10. *Frontoparietal networks*. It includes several frontoparietal areas. These networks are lateralized and are mirror-image of each other. They are involved in the domains of cognition/language. Specifically, network 9 is involved with perception-somesthesis-pain, and network 10 is involved with cognition-language activities and corresponds to the Broca and Wernicke areas. The images show the lateralization of the function of language.

These are the *main representative networks*, although some additional networks have been identified since this study. In addition, it has been found that some of these networks consist of other sub-networks, each with a different function, although related.

In fact, in the mentioned study [47], the process was repeated, but with *BrainMap* 70-component ICA decompositions, and resting fMRI data, in the hope of obtaining a more detailed identification of functional subnets that could be related to both the 20-component results and, to 70 component level, between *BrainMap* and FMRI components at rest. As a result, several sub-networks were detected, which had not been detected using 20 components. For example, 8 pairs of well-paired networks were identified in the visual cortex, and 2 pairs covering the sensorimotor cortex (Fig. 3.4).

Therefore, it can be concluded that the primary large-scale networks are divided into subnets both in active-task and resting-state, in almost identical ways. There is a greater functional (temporal) correlation between subnets within a primary network than between primary networks.

The activation networks essentially match the networks identified in the data at rest, in at least two-thirds of the extracted network components. This implies that the resting brain makes full use of the set of functional networks exhibited. In addition, the functional amplitude of the networks when the brain is at rest is of the same order as those found under explicit activation [48]. All regions involved in all functional networks continuously interact with each other when the brain is at rest, with the same functional hierarchy existing when it is active, executing tasks.

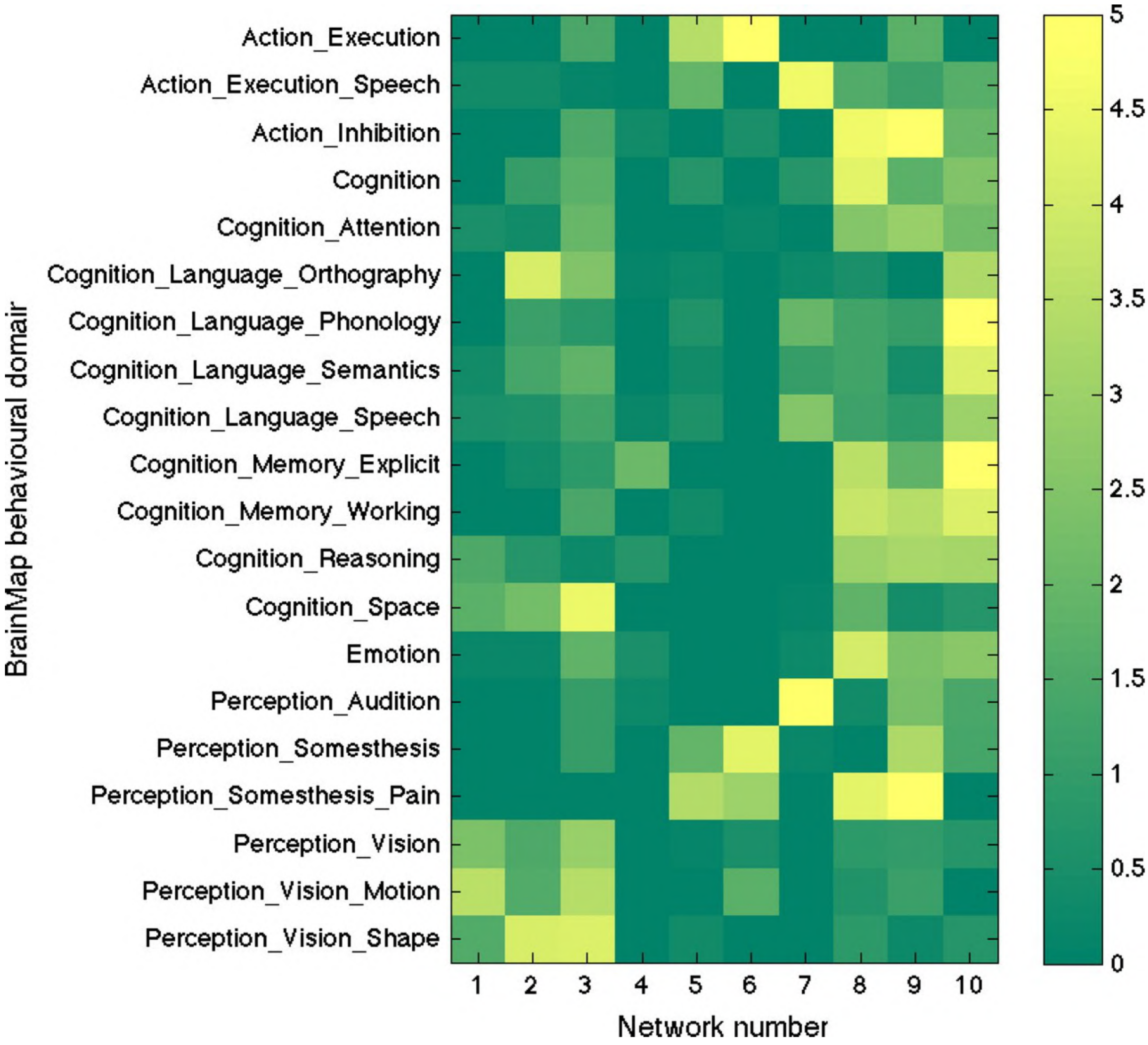

Figure 3.3. Diagram showing the 10 *primary functional networks* indicating their *behavioral domains* (classifications of experimental paradigms) from the *BrainMap* database. Each *BrainMap*-derived ICA spatial maps has an experiment-ID *time course* that quantifies its relevance for each of the 7,342 original *BrainMap* activation images. Each of those activation images is listed in *BrainMap* among 66 values (*behavioral domains*). (To simplify the original 66 behavioral domains, here are shown only those that correspond to the 10 *primary functional networks*)
(Source: Smith, S. M., Fox, P. T., Miller, K. L., Glahn, D. C., Fox, P. M., Mackay, C. E., Filippini, N., Watkins, K. E., Toro, R., Laird, A. R., & Beckmann, C. F. (2009). Correspondence of the brain's functional architecture during activation and rest. *Proceedings of the National Academy of Sciences*, 106 (31), 13040-13045).

The fact that the activation networks essentially coincide with the networks identified at rest, means that many regions of the brain are still active (with large fluctuations in amplitude) when the subject is at rest, and even when the subject is asleep [49] and under anesthesia [50]. However, to this day, no definitive explanation has been provided for the observed fact that the same networks that are activated when the brain is performing a task, remain active (although with less intensity) when it is in a state of rest.

Neural connections, which are the material structure and functional networks of the brain, are always present, whether they are active or not. However, it has been shown that the brain's neural networks are always active, whether the brain is performing a certain task or at rest

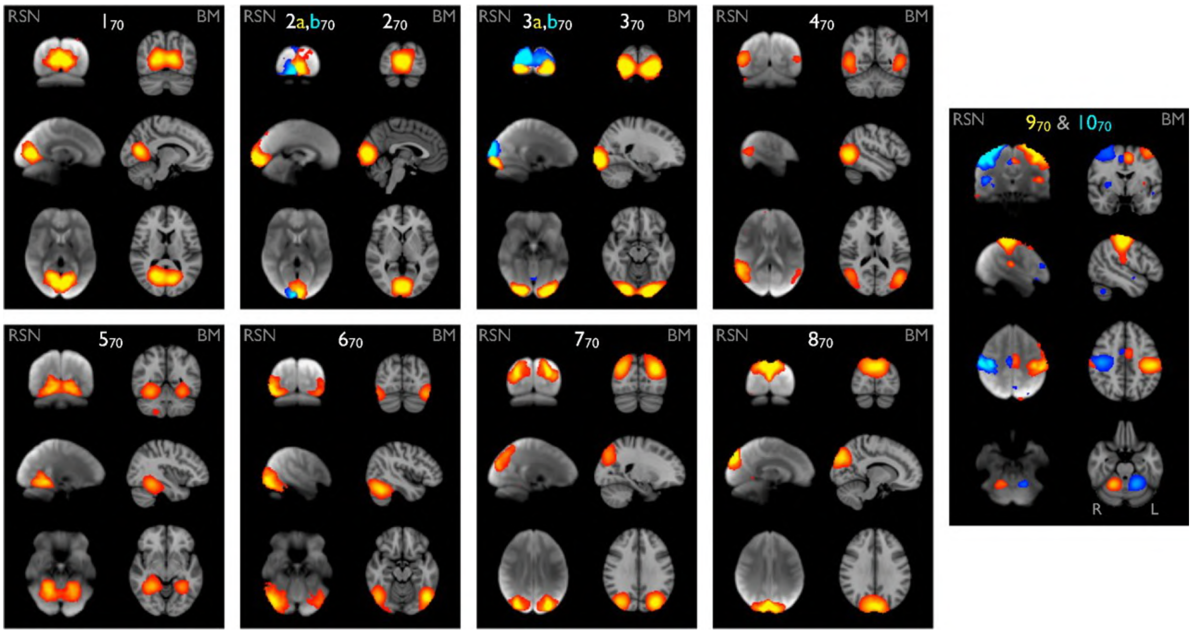

Figure 3.4. Comparison of neural subnetworks identified in two different ways (70 components)
Left side of images: Images made by superimposing the data obtained from resting fMRI of 36 subjects.
Right side of images: Images from *BrainMap* database (using 70 components), shown superimposed on the MNI152 space template image.
Images 1, 2 and 3 correspond to visual networks (Images 2 and 3 show a differentiation with respect to the images made with 20 components. Image 2 shows a distinction of right versus left visual hemifield, and image 3 shows superior versus inferior visual hemifield distinction).
Image 4 corresponds to motor control network
Images 5 and 6 correspond to ventral-ventrolateral visual flow network
Images 7 and 8 are associated with the dorsal visual flow network
Images 9 and 10 correspond to the sensorimotor cortex, both the precentral and postcentral convolutions, although they overlap the latter more completely (In images made with 20 components, these appeared as a single network, but in the images more detailed, made with 7 components, are divided into lateralized networks).
(Source: Smith, S. M., Fox, P. T., Miller, K. L., Glahn, D. C., Fox, P. M., Mackay, C. E., Filippini, N., Watkins, K. E., Toro, R., Laird, A. R., & Beckmann, C. F. (2009). Correspondence of the brain's functional architecture during activation and rest. *Proceedings of the National Academy of Sciences*, 106 (31), 13040-13045)

Some researchers suggest that networks continue to be active in resting state to perform rehearsals, to consolidate what has been learned (when executing tasks), and to prepare future acts [51], although these are not conclusive data.

As will be seen throughout this chapter, and in the next chapter, this activity of the brain in resting state is fundamental for the human creative process since it allows us to make innumerable tentative proposals, which can be very creative, based on the consolidation of certain rules, and based on the creation of innumerable attempts.

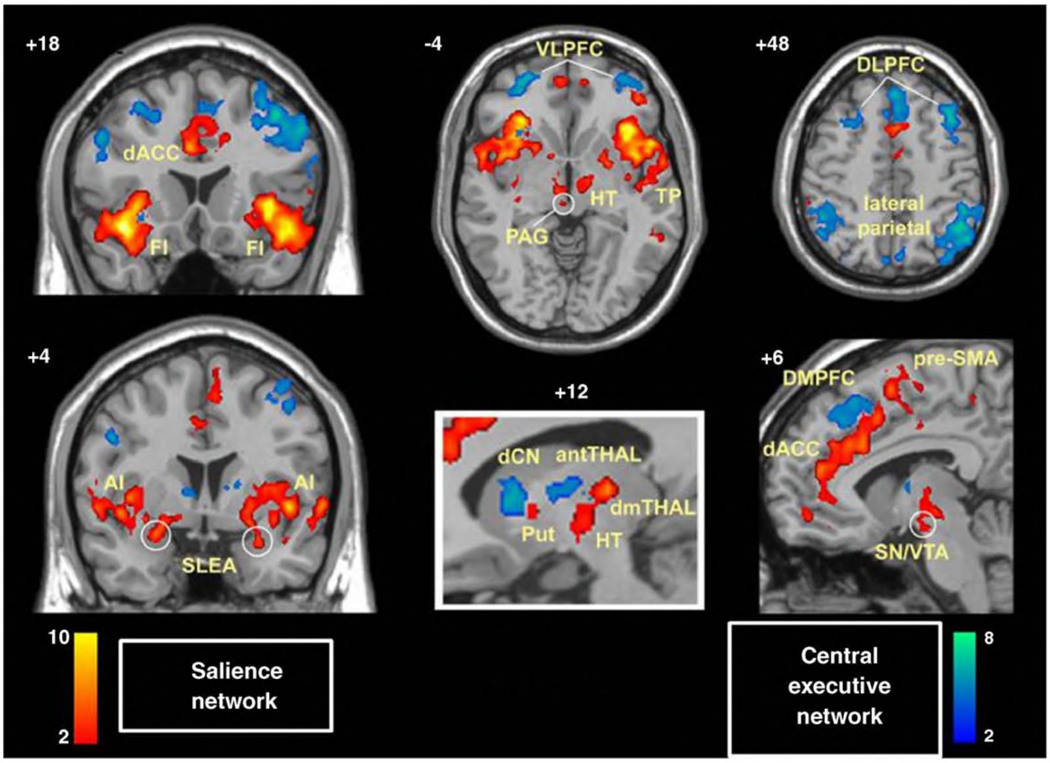

Figure 3.5. *Salience network* (SN) and *Executive control network* (ECN), identified using intrinsic physiological coupling in resting state fMRI data.
(Source: Bressler, S., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Science*, 14, 277-290)

3.2.4. Identification of the large-scale networks included in the *triple network model*

A current technique, such as independent component analysis (ICA), has been very effective in identifying intrinsic connectivity networks (ICN), using resting state fMRI data [52].

This ICA technique has been used to identify several ICN [53]:

- *Executive control network*
- *Episodic memory network*
- *Autobiographical memory network*

- *Self related processing network*
- *Detection of salient events network*
- *Sensoriomotor network* (bilateral somatosensory and motor cortices)
- *Visuospatial attention network* (intraparietal sulci and frontal eye fields)
- *Higher-order visual network* (inferior temporal and lateral occipital cortices)
- *Lower-order visual network* (striatum and the extrastriate cortex)

This technique has also allowed the use of ICN (Fig. 3.5) and task related fMRI activation patterns (Fig. 3.6), to identify three large-scale networks, functionally coupled, that form a central tandem in the human neurocognitive system. These three networks also play a fundamental role in the neurocognitive process of creativity, and they are often referred to as the *triple network model*. These three networks are the *Executive control network* (ECN), the *Default mode network* (DMN), and the *Salience network* (SN) [54].

These networks can be activated in several different cognitive tasks. The *Executive control network* (ECN) and *Salience network* (SN) typically show an increase in activity when executing a task, while the *Default mode network* (DMN) shows a decrease in activity when executing a task [55].

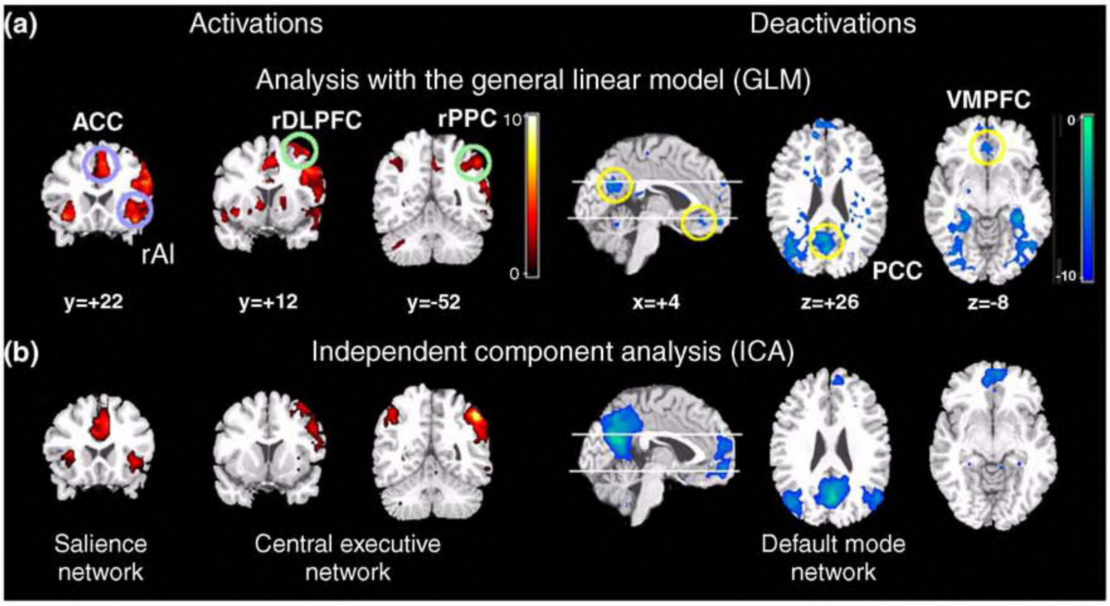

Figure 3.6. Images of the major functional networks in the human brain.
Task-related activation patterns in the *Executive control network* (ECN) and *Salience network* (SN), and deactivation patterns in the *Default mode network* (DMN).
(Source: Bressler, S., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Science*, 14, 277-290)

- The *Executive control network* (ECN).

Among other areas of the brain, the ECN integrates the dorsolateral prefrontal cortex (DLPFC) and the posterior parietal cortex (PPC) (Fig. 3.7). This network is essential for maintaining and processing information in working memory, and for making decisions through goal-directed strategies [56].

- The *Default mode network* (DMN).

Among other areas of the brain, the DMN integrates the medial temporal lobes (MTL), the angular gyrus (AG), the posterior cingulate cortex (PCC) and the ventromedial prefrontal cortex (VMPFC). This network is involved in autobiographical, self-control and social cognitive functions, although a unique function cannot be assigned to each of its component nodes [57].

- The *Salience network* (SN).

Among other areas of the brain, integrates the anterior insula (AI) and the anterior cingulate cortex (ACC). This network is involved in examining a large number of different incoming sensory stimuli and adjusting the response to the task-relevant ones. As a result, the SN can dynamically switch the activation of DMN and ECN [58].

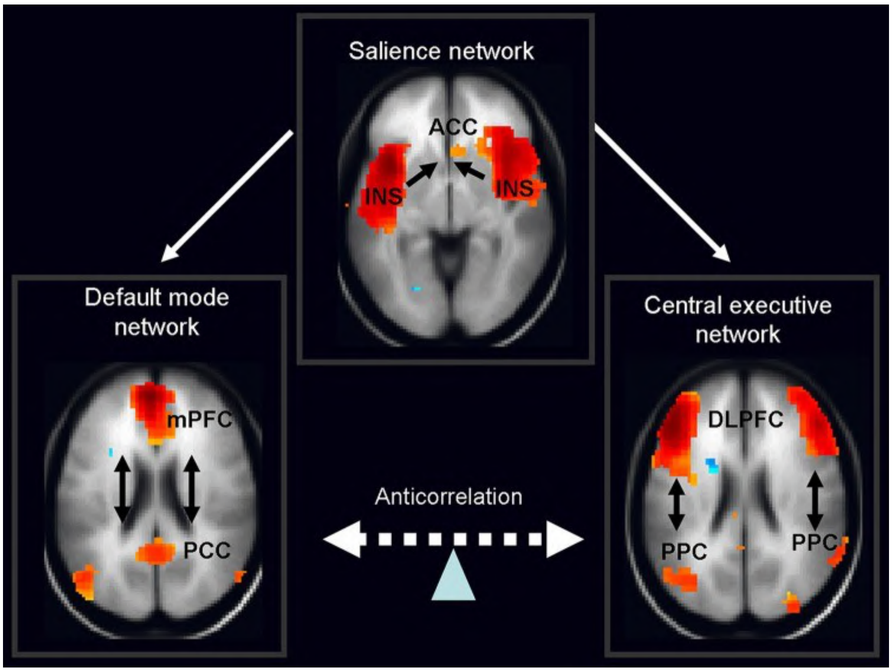

Figure 3.7. *Triple-network model*. The *Salience network* (SN) is hypothesized to initiate dynamic switching between the *Executive control network* (ECN) and *Default mode network* (DMN).
(Source: Nekovarova, T., Fajnerova, I., Horacek, J., & Spaniel, F. (2014). Bridging nonsense symptoms of schizophrenia: A triple network dysfunction theory. *Frontiers in behavioral neuroscience*, 8. 171. 10.3389 / fnbeh.2014.00171)

As will be seen in section 3.5.4., these three networks play a fundamental role in the human creative process. However, before analyzing them, and their interrelated operation, and in order to study them exhaustively in context, it is useful to know all the functional networks that make up the cortex, as well as the multimodal organization of the human brain

3.3. Complete maps of the organization of the human brain

An important study was recently carried out that aimed to identify in detail all the functional networks of the human brain, as well as the subnets into which they can be broken down [59]. This study is the most complete carried out so far and is very useful to better understand how functional connectivity patterns provide the organizational characteristics that underlie distributed brain systems.

In this study the fMRI data of 1,000 people were analyzed with two main objectives:

- Make precise reference maps showing all the neural networks of the cortex.
- Measure the functional connectivity between the different regions of the cortex

To make these maps, a clustering approach was carried out in order to identify the limits of the different functionally distinct cortical regions, and their relationships with other regions distributed throughout the cerebral cortex with which they form a large-scale network.

The study began by defining the connectivity profile of a cortical region as its functional coupling to 1,175 region of interest (ROI) vertices (Fig. 3.8). The 1,175 ROI vertices were uniformly sampled in the *FreeSurfer* surface space, as shown in the *Caret PALS* space (vertices about 16 mm. apart).

The *Pearson Product Moment* correlation between the fMRI time series at each spatial location (18,715 vertices) and the 1,175 ROI vertices was calculated for each of the 1,000 participants. Therefore, each spatial location is characterized by its functional coupling to the 1,175 vertices of ROI. Next, and for each person, the 18,715 × 1,175 correlation matrix was binarized, maintaining the top 10% of the correlations. The binarized matrices were then independently averaged in each group of 500 subjects in the discovery and replication samples. Finally, a separate clustering algorithm was applied to the discovery and replication samples to estimate networks of cortical regions with similar connectivity profiles.

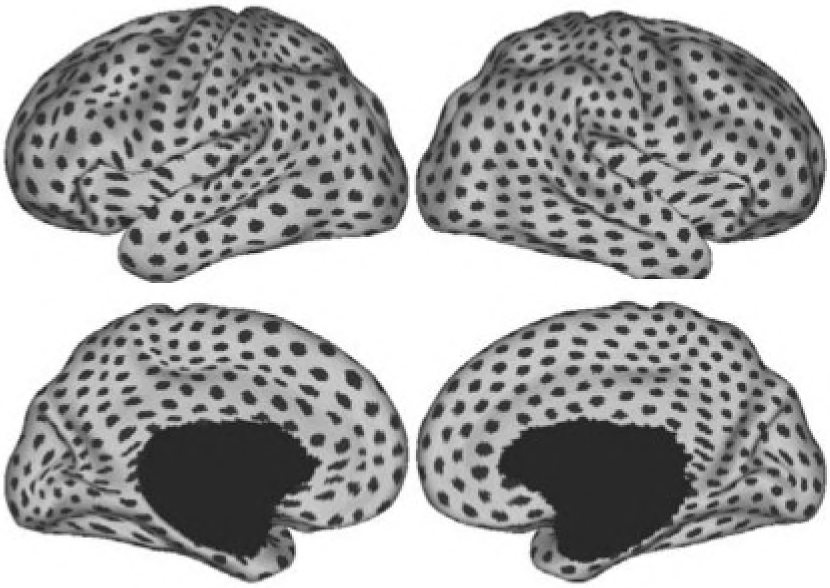

Figure 3.8. Cortical regions used to make functional connectivity profiles.
1,175 regions were sampled uniformly on the surface-based representations within the FreeSurfer surface coordinate system and are shown in Caret PALS space (each dark patch is the location of a single regional vertex). Each vertex in the surface coordinate system is characterized by its profile of functional connectivity to the 1,175 regions.
(Source: Yeo, B. T. T., et al. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology*, 106, 1125-1265)

As a result of the study, 2 maps were generated showing the parceling of the cerebral cortex, one containing 7 main networks (Fig. 3.9), and the other containing 17 networks (Fig. 3.10). The 17-network map was created based on the subnetting of the networks shown in the 7-network map [60]. Some of the networks identified in these maps involved adjacent regions (such as the visual cortex), while others are distributed throughout the cortex (such as the heteromodal association cortex).

One of the things that initially stands out when examining the maps of the networks is the separation of the early sensory and late motor cortices from the association cortex (blue and purple colors), which is consistent with previous studies of local functional coupling [61]. Another curious characteristic is that the sensory and motor cortices (whose functional connectivity networks are fundamentally local) comprise only 35% of brain surface and constitute an exception with respect to the general structure of large-scale networks. In fact, most of the surface of the human cerebral cortex is made up of multiple distinct networks of association areas.

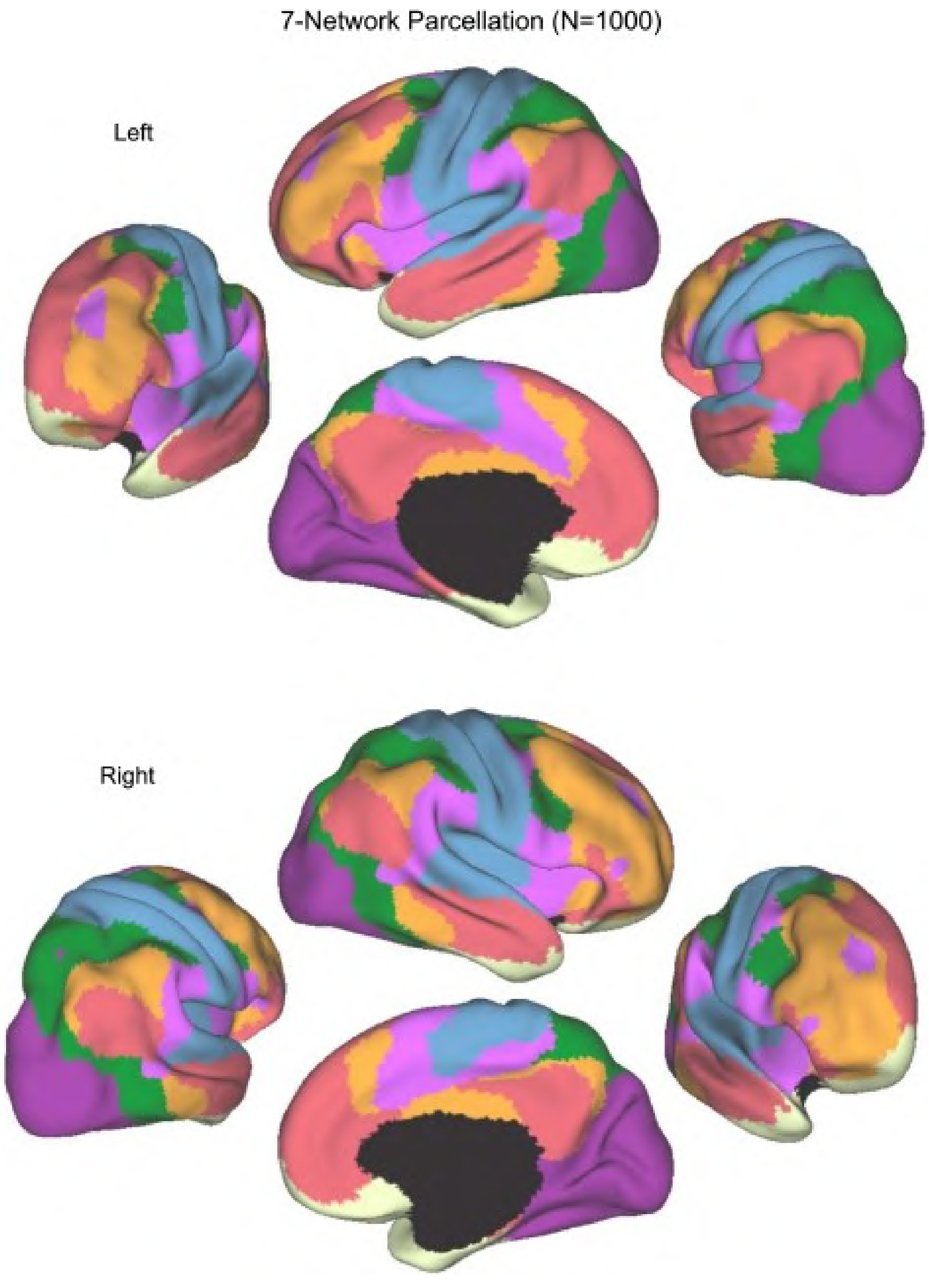

Figure 3.9. A rough (7-network) parcellation of the cerebral cortex based on 1,000 subjects.
To identify in the most detailed way possible the 7 networks, clustering was performed on the fMRI data of 1,000 subjects. An important characteristic is the separation of the early sensory and late motor cortices (blue and purple) from the association cortex. The association networks are similar of large-scale networks previously described in previous resting-state studies.
(Source: Yeo, B. T. T., et al. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology*, 106, 1125-1265)

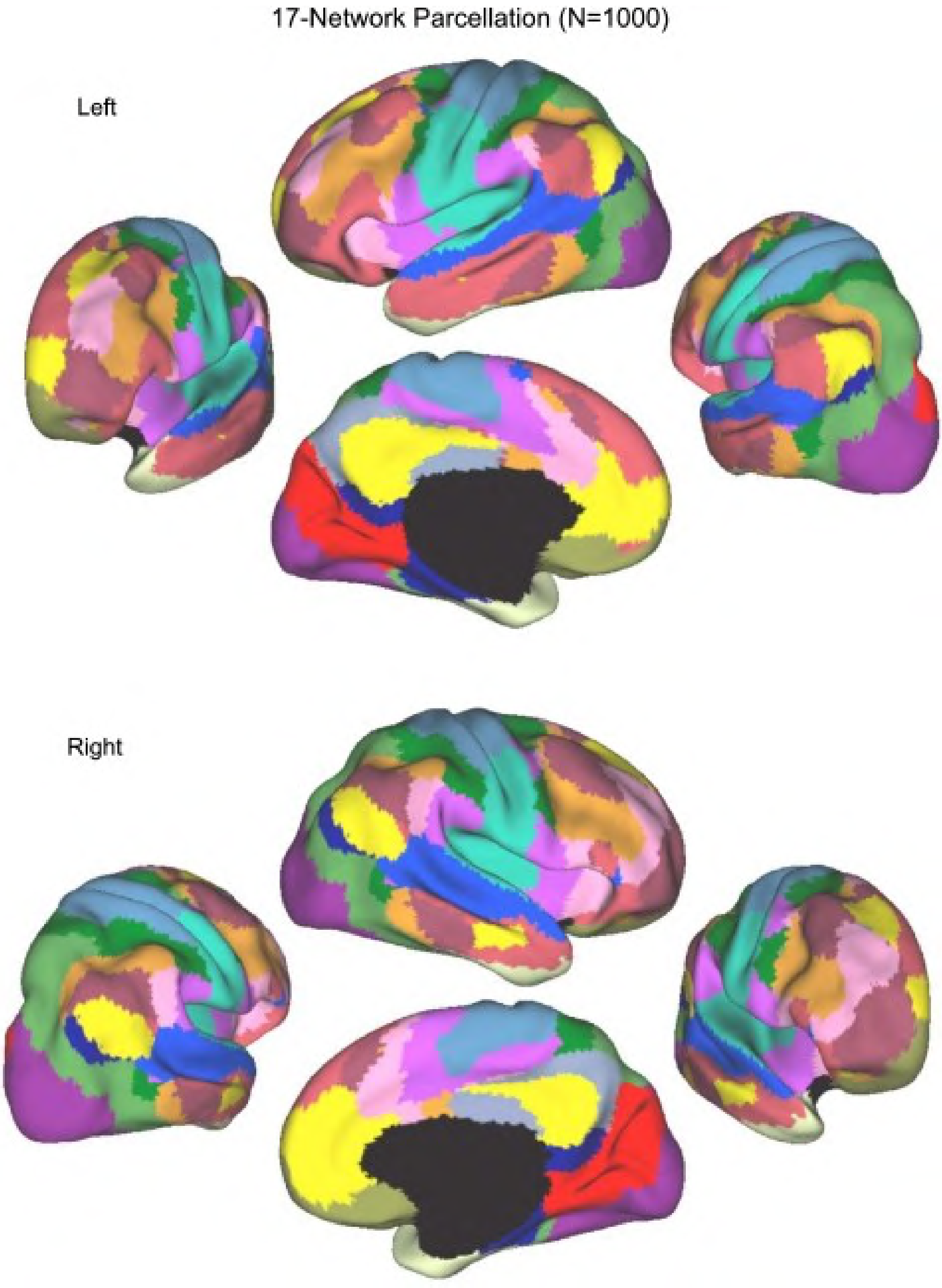

Figure 3.10. A fine-resolution (17-network) parcellation of the cerebral cortex based on 1,000 subjects. To identify in the most detailed way possible the 17 networks, clustering was performed on the fMRI data of 1,000 subjects. The 17-network parcellation subdivided the 7-network into smaller networks. (Source: Yeo, B. T. T., et al. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology*, 106, 1125-1265)

Another important characteristic of these maps is that the association networks (in the maps of 7 networks) coincide, and detail them, with the networks previously described in resting-state studies: *Dorsal attention network* (DAN), *Ventral attention network*

(*Salience network*) (SN) [62], *Executive control network* (ECN) [63], and the *Default mode network* (DMN) (red) [64] (Fig. 3.11).

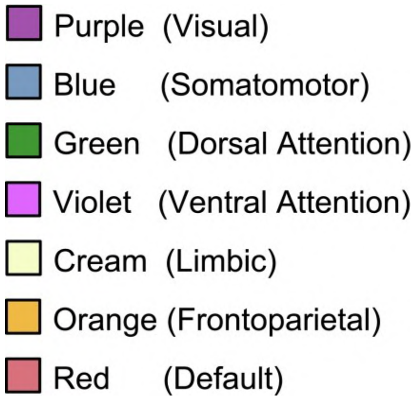

Figure 3.11. Table of colors assigned to networks in the 7-network mapping. Common names associated with each network in the neuroimaging literature are included in parentheses. This should not be taken to mean that our estimated networks correspond exactly to those in the literature or that the networks code solely for functions associated with their assigned name.
(Source: Yeo, B. T. T., et al. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology*, 106, 1125-1265)

The maps of 7 networks of the parietal cortex also coincide with previous results from studies with seed-based approaches [65] and using the *area boundary detection method* [66]. The convergence of multiple different analysis approaches suggests that the parceling is intrinsic to the resting state data.
On the other hand, the estimate of 17 networks is actually a splitting of the 7 networks into smaller subnets. Some aspects of fractionation, such as the appearance of a parahippocampal-retrosplenial-lateral parietal network, had already been detected in previous studies using *hierarchical clustering* techniques [67].
On the other hand, other details of the subdivision were surprising, as is the case of the appearance of subnets within the visual and motor cortices that did not respect the boundaries of the area, but seemed to be aligned with the topographic organization
These maps are the best current representation of the fMRI-based organization of the human cerebral cortex. Its validity is supported by the enormous number of people involved in the study, and the use of surface-based alignment procedures that allowed for topographic details with considerable confidence. However, these maps still have limited resolution and will likely be refined in the next few years.
In summary, these maps provide a detailed description of large-scale cortical networks, and in at least two respects:

- The somatomotor and visual cortices form their own networks in the division of 7 networks and are divided into subnets in the division of 17 networks.
- The association cortex is composed of several interdigitated networks that are distributed throughout the cortex. These networks had previously been identified separately using seed analysis [68], and ICA independent component analysis approaches [69]. However, many aspects of the organization, especially in the division of 17 networks (Fig. 3.10), are new.

3.4. Multimodal organization of the brain

Currently, it is not very well known how the integration of external sensory information with internal cognition is carried out in the brain in order to generate a coherent and holistic experience of the world, as well as the sense of reality.

The dynamic integration of information in the brain has always been an intrigue, since it was first raised when studying vision, when it was called the *binding problem* (the problem of how the unity of conscious perception is brought about by the distributed activities of the central nervous system) [70]. Since then, several functional and anatomical studies have shown the existence of areas with high local modularity and hierarchical connections in the sensory cortices [71]. Integrative association areas receiving generalized projections of distributed brain systems were also detected [72].

Based on these findings, the researchers began to study where and how brain systems integrate perception information to incorporate them into the more complex texture of cognition [73]. Based on these studies, the existence of a group of brain regions (currently called *cortical hubs*) was discovered, in which many distant functional connections converge in the human brain. For this reason, cortical hubs are considered the main hierarchical areas of integration [74].

However, how transitions from modular sensory regions to limbic and heteromodal processing systems organized in parallel are still not well understood.

In recent years, anatomical, neurophysiological, and neuroimaging research on multimodal integration has provided information on the union of three main types of perception: vision, audition and touch. For example, brain regions such as the posterior temporal lobe (PTL) and lateral occipitotemporal junction (LOTJ), and regions such as the posterior parietal lobe (PPL), have been routinely described as essential for *bimodal* or *trimodal integration processing* [75]. A large region covering the entire superior temporal sulcus (STS) appears to be essential for trimodal integration in non-human primates [76]. Other regions of the brain at the subcortical level, such as the superior colliculus, have also been described as multimodal processors [77].

Furthermore, rather than integrating multimodal information in isolated or disconnected regions, activation studies of fMRI suggest that perceptual multimodal binding is likely to be achieved through the mutual interaction of multiple regions [78]. The recent perspective places a special emphasis on the functional connections of the brain, and can greatly aid the understanding of the underlying network structure of the human brain through the study of the *connectome*.

Today it is commonly accepted that interdigitated networks occur as a whole in the brain and this generates human cognition. Therefore, the subdivisions of sensory, multimodal and cognitive processing should be studied from the point of view of interdigitated systems and network interactions, and not as segregated parts [79].

In this sense, a recent study [80] has identified a functional *connectome* of the modal brain (visual, auditory and somatosensory) using a method called *stepwise functional connectivity* (SFC).

The SFC method allows exploring the convergence and interactions of sensory systems at the connectivity level. Most of the studies of functional connectivity and magnetic resonance imaging in the resting state focus on identifying and differentiating the different neural networks (for example, ICA and K-means), but they cannot detect how the different neural networks join each other, nor how is the transition from one to the other carried out.

For this reason, the SFC method has been developed to detect the complex connectivity transitions that take place from the distributed cognitive systems of the brain to those of a higher order.

3.4.1. Identification of the *Multimodal integration network* (MIN)

The *multimodal integration network* (MIN) integrates the primary sensorimotor cortices with the parallel systems at the top of the functional hierarchy of the brain.

When analyzing the primary visual cortex with the SFC method, direct connections, decreasing connectivity gradients, and convergence pathways were identified, until reaching, after the last steps, the distributed cortical regions, now known as *the cortical hubs* of the human functional brain [81] (Fig. 3.12). The same was done when analyzing the primary somatosensory cortex (Fig. 3.13), and the primary auditory cortex (Fig. 3.14).

The *multimodal integration network* was identified using a combined approach to highlight the topological convergence of the stepwise connectivity patterns in the three sensory modalities previously analyzed [82] (Fig. 3.15). Specific and consistent regions have been identified as a common destination for sensory modalities, serving as transition bridges from perception to higher-order cognitive regions (*cortical hubs*). In addition to the mentioned regions (SPC, OP, AI+ and DACC+), regions that currently exist as convergence links of the three sensory modalities have been identified: an area in the dorsolateral prefrontal cortex (DLPFC; BA10/46) and another area in the LOTJ, in the confluence region of BA19/22/37/39 and touching the superior temporal sulcus (Fig. 3.15).

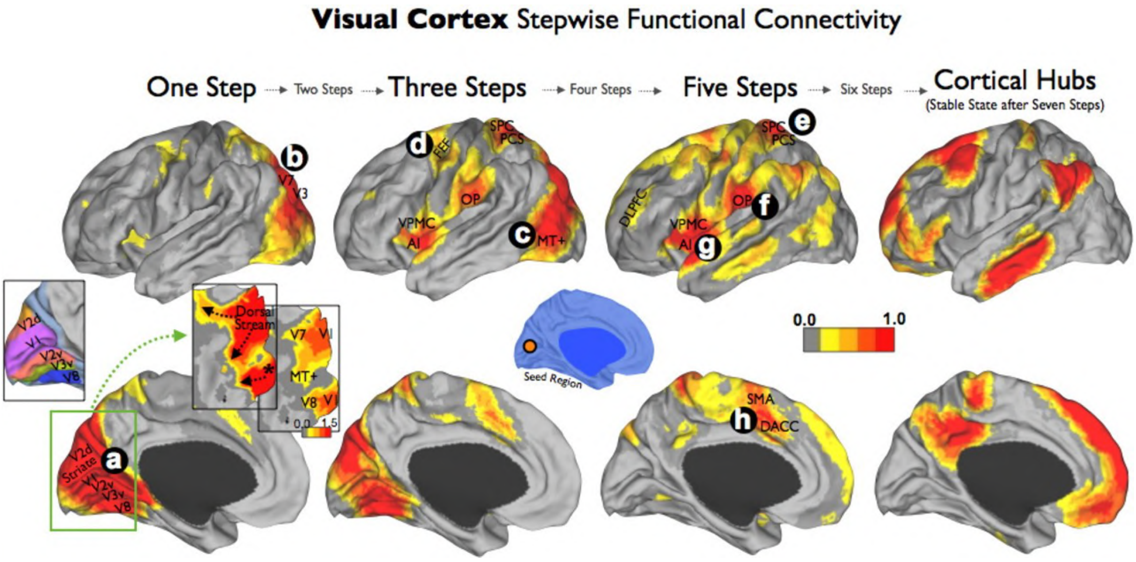

Figure 3.12. Visual cortex stepwise functional connectivity (SFC).
Visual cortex SFC analysis shows that visual cortex's direct connectivity follows three different pathways: one ventromedial pathway (a), and two dorsal pathways (a – c).
In subsequent steps, the visual cortex connectivity evolves and reaches the frontal eye field (d), the multimodal network (e – h), and finally, the cortical hubs of human brain.
(Source: Sepulcre, J., Sabuncu, M. R., Yeo, T. B., Liu, H., & Johnson, K. A. (2012). Stepwise connectivity of the modal cortex reveals the multimodal organization of the human brain. *Journal of Neuroscience*, 32(31), 10649-10661)

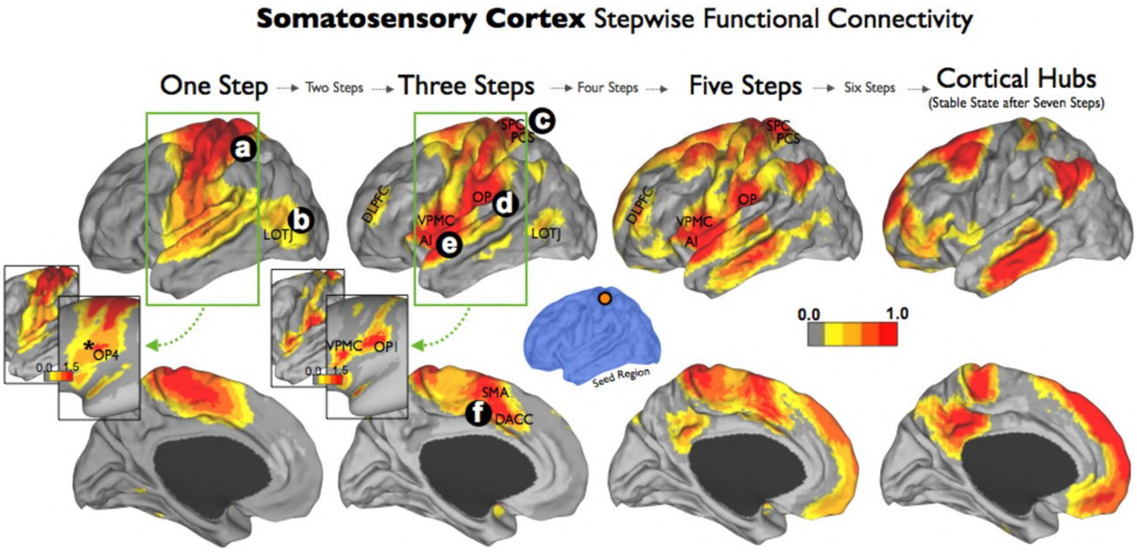

Figure 3.13. Somatosensory cortex stepwise functional connectivity (SFC).
Somatosensory cortex SFC analysis shows dense connections within the somatomotor cortex, strong direct connectivity with the secondary somatosensory area SII in OP4 (a; inset, star) and, to a lesser extent, to the LOTJ (b).
Primary somatosensory cortex had later connectivity to the multimodal network (c – f) and to the cortical hubs. PCS, Posterior central sulcus, SMA, supplementary motor area.
(Source: Sepulcre, J., Sabuncu, M. R., Yeo, T. B., Liu, H., & Johnson, K. A. (2012). Stepwise connectivity of the modal cortex reveals the multimodal organization of the human brain. *Journal of Neuroscience*, 32(31), 10649-10661)

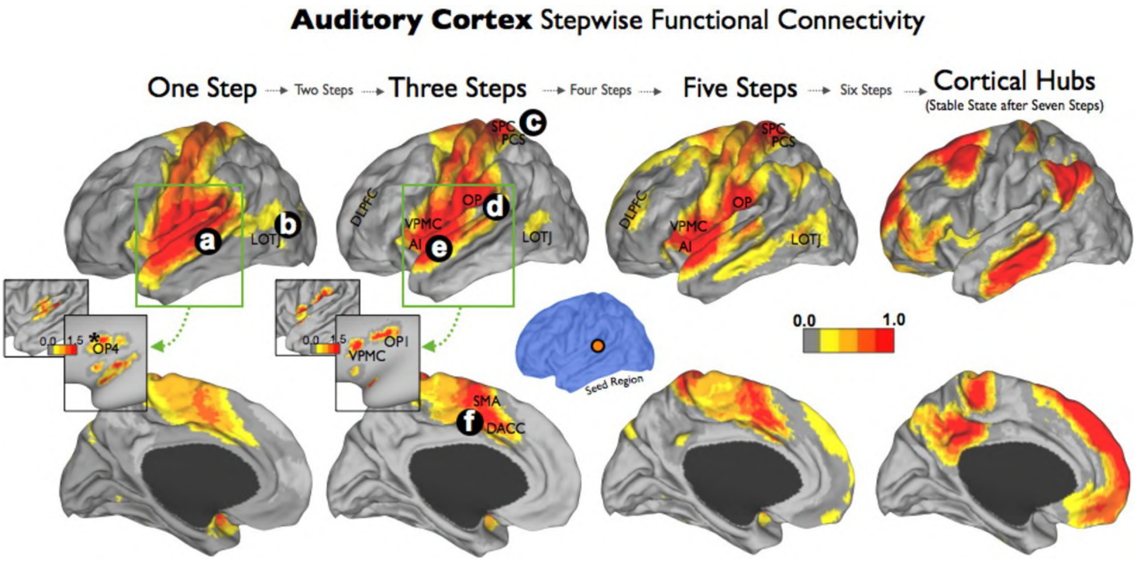

Figure 3.14. Auditory cortex stepwise functional connectivity (SFC).
Auditory cortex SFC analysis showed dense connections within the local auditory-related regions, strong direct connectivity with OP4 (a) and, to a lesser extent, to the LOTJ (b).
In the subsequent steps, auditory connectivity reached the multimodal network (c – f) and the cortical hubs. PCS, Posterior central sulcus; SMA, supplementary motor area.
(Source: Sepulcre, J., Sabuncu, M. R., Yeo, T. B., Liu, H., & Johnson, K. A. (2012). Stepwise connectivity of the modal cortex reveals the multimodal organization of the human brain. *Journal of Neuroscience*, 32(31), 10649-10661)

Once the component regions of the MIN were identified, it was not surprising that some of them have been previously described in the attention and stimuli salience processing studies. For example, the AI+ and DACC+ regions of the MIN have been described as part of the *Salience network* [83], and regions similar to OP and AI+ have been implicated in multimodal and ventral attentional processing [84].

The fact that the MIN regions coincide (especially the AI+ and DACC+ regions) with the regions identified in previous studies based on attention paradigms [85], suggest that concepts such as the integration of multimodal connectivity, salience or goal-directed attention refer largely to a common brain mechanism. To be sure, many different cognitive processes bring multisensory integrated representations into play, and presumably activate similar cortical regions.

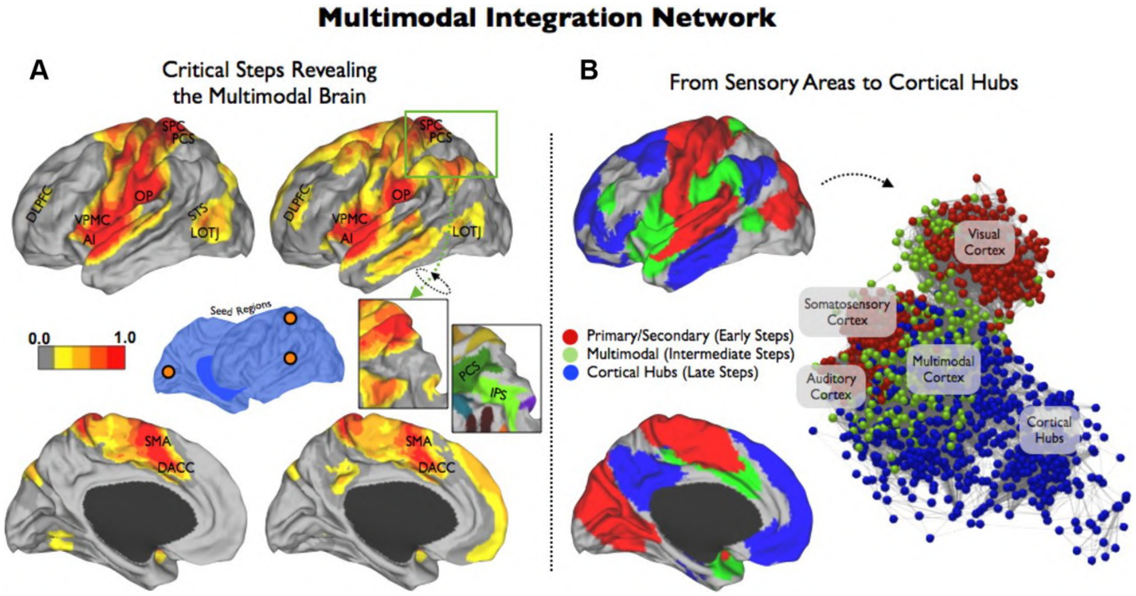

Figure 3.15. Multimodal integration network.

An SFC analysis combining the three sensory seeds simultaneously showed the complete map of the multimodal integration network of the human brain.

A. Three-step and five-step maps of the combined SFC analysis.

B. Initial cores (binarized average of the one-step and two-step maps), intermediate cores (binarized average of the three- to five-step maps), and terminal cores (binarized average of the six- and seven-step maps).

It is noteworthy that the multimodal integration network (green cortex and nodes) acts as a strong network interface between the unimodal-related systems (red cortex and nodes) and the cortical hubs core (blue cortex and nodes).

(Source: Sepulcre, J., Sabuncu, M. R., Yeo, T. B., Liu, H., & Johnson, K. A. (2012). Stepwise connectivity of the modal cortex reveals the multimodal organization of the human brain. *Journal of Neuroscience*, 32(31), 10649-10661)

3.4.2. Differences between left and right hemispheres of the MIN

There is an important asymmetry in the *multimodal integration network* (MIN), especially near the temporo parietal junction (TPJ). The *multimodal integration region* is more extensive in the right hemisphere than in the left hemisphere [86]. Furthermore, the maps of the last steps also show important differences between both hemispheres, in the ventrolateral prefrontal cortex, and especially in Broca's language area (Fig. 3.16).

TPJ is an area traditionally associated with *neglect syndrome*, especially in the right hemisphere [87]. *Neglect syndrome* is an attention disorder in which patients are unaware of spatial stimuli in a hemifield. Therefore, the fact that the MIN is larger in the right hemisphere -in this area- could explain that the greater number of cases of *neglect syndrome* are due to lesions of the right temporoparietal junction (TPJ).

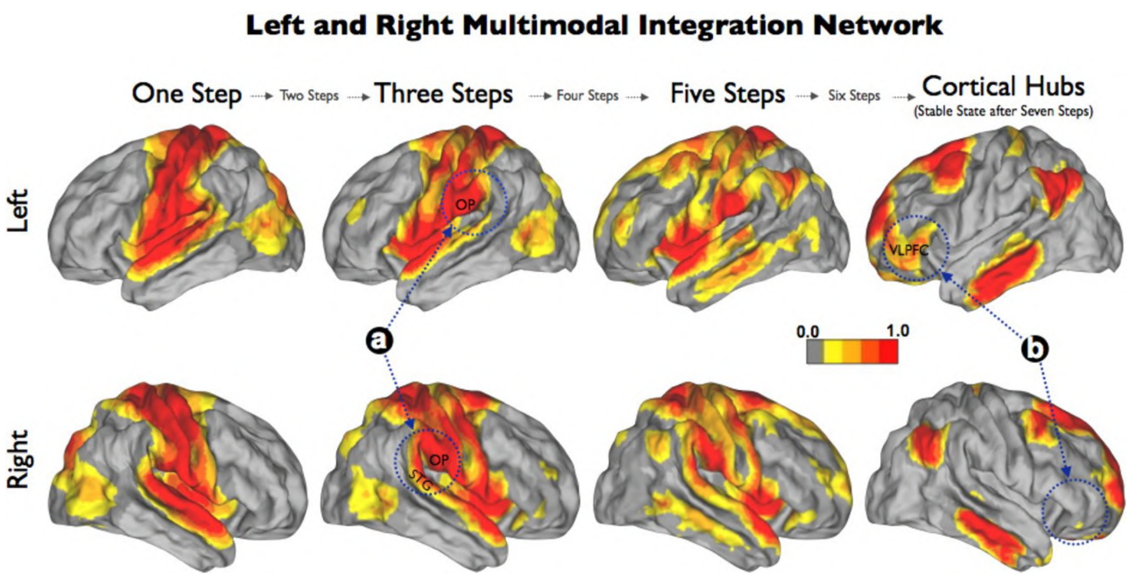

Figure 3.16. Multimodal integration network in the left and right hemispheres.
We compared the left and right hemispheres to check for brain asymmetries in the multimodal integration network. Sensory cortices of the right hemisphere have connectivity to a wider multimodal region in the temporoparietal junction than the left hemisphere (a and b). On the other hand, with a higher number of steps, only primary sensory cortices of the left hemisphere have connectivity to VLPFC and part of the Broca's language area (b).
(Source: Sepulcre, J., Sabuncu, M. R., Yeo, T. B., Liu, H., & Johnson, K. A. (2012). Stepwise connectivity of the modal cortex reveals the multimodal organization of the human brain. *Journal of Neuroscience*, 32(31), 10649-10661)

Therefore, and although it is frequently described after focal lesions of TPJ, *neglect syndrome* appears to be in fact a network disease [88]. This point of view is consistent with the fact that other regions such as the dorsal anterior cingulate cortex (DACC) or the prefrontal cortex (PFC) have been involved in the *neglect sindrome* [89]. Even recently characterized regions of the *multimodal integration network*, such as superior parietal cortex (SPC), have been associated with the *neglect syndrome* [90]. In summary, the *neglect syndrome* from the point of view of the MIN provides a new path of investigation.

3.4.3. Current functional paradigm of the human brain based on the hierarchical flow of information from the perceptual cortex to multimodal regions

Research on the brain's functional connectivity large-scale networks as isolated structures is being abandoned, and studies are now being conducted to understand how networks interact and merge in the brain. In this sense, the SFC method provides an approximate image of large-scale brain processing, from sensory to cognitive cortical areas.

In a recent study carried out with the SFC methodology [91], it was observed that the cortex is structured in such a way that it uses the MIN to interact between external sensory information and cognitive hubs. In general, cortical hubs, and specifically the DMN, are involved in autobiographical and social functions [92]. In addition, and due to the connectivity properties of cortical hubs, it is assumed that they are in the upper part of the hierarchical structure of the brain at rest [93].

Therefore, the results of the SFC study reinforce the traditional paradigm in which information flows through the cortex in a hierarchical way [94], and sensory information flows into the upper multimodal, heteromodal, and transmodal convergence zones [95].

As a consequence, the current paradigm on the functioning of the human brain and the genesis of cognition is based on the hierarchical flow of information from the perceptual cortex to multimodal regions and, ultimately, to areas that support more conscious and cognitive functions of higher order.

This general cognitive paradigm seamlessly integrates accumulated knowledge about large-scale neural networks.

Let's analyze for example the DLPFC multimodal region. According to the MIN paradigm, cortical hubs represent the upper part of the hierarchy of the brain network, and this may be consistent with our knowledge that other networks perform important cognitive functions during specific tasks such as the ECN (frontoparietal network) [96]. The anatomical proximity between the regions of the multimodal network and the regions of the ECN are especially notable in the DLPFC tiered connectivity maps.

Another example is the *Salience network*. It is known that this network (specifically the anterior insula and the dorsal cingulate cortex) functions as a dynamic switching between the ECN and DMN networks [97]. According to the MIN point of view, it is possible that some regions of the *multimodal integration network*, especially the previous sub-module, including the DLPFC, are involved in cognitive interactions or transitions between active and passive tasks.

On the other hand, sensory awareness seems to depend on a specific but flexible union between the sensory-related processing regions and the frontal and parietal cognitive networks that are related to the active control of information and working memory [98]. From a MIN point of view, this is especially relevant for the DLPFC region. The DLPFC connectivity network directly merges the multimodal and frontoparietal control networks and can contribute to the fine spatio-temporal integration of sensory information in highly distributed networks.

3.4.4. Implications of the MIN on human creativity

The current MIN-paradigm on the functioning of the human brain and the genesis of cognition is based on the hierarchical flow of information from the perceptual cortex to multimodal regions and, ultimately, to areas that support more conscious and cognitive functions of higher order.

Sensory information is transformed in a hierarchical way, modifying itself transversely throughout the process, until it finally achieves a high level of abstraction. This allows the generation of creative information and high-level self-generated thoughts.

As seen in the previous chapter, one of the most effective possibilities for generating creative ideas is the association mechanisms of various levels of abstraction. In this sense, and due to its hierarchical MIN structure, the brain manipulates information at different levels of abstraction, which is why it greatly favors this associative mechanism of high levels of abstraction. Information can be processed at various levels of abstraction, and at the same time have a certain reaction with the primary sensory information that has been generated over time.

Abstracting the information to the maximum allows for high-level manipulation, which can be transformed in a simple way, mixing it with additional information from lower levels. This mechanism favors the possibility of taking great leaps in the solution search trees, and also favors the creation of self-generated thoughts.

3.5. Neural networks involved in creative process.

As seen in section 3.2.4., three large-scale networks are involved in the creative process, forming part of what is usually called the *triple network model*. In this section, these networks are analyzed in depth, showing all their component regions and their general functionality. The role of each network in the creative process is discussed below.

Initially, and through the task-free connectivity analysis technique, it was possible to identify in detail two different networks that are normally activated when performing tasks and that are directly involved when performing creative activities: the *Salience network*, and the *Executive control network* [99].

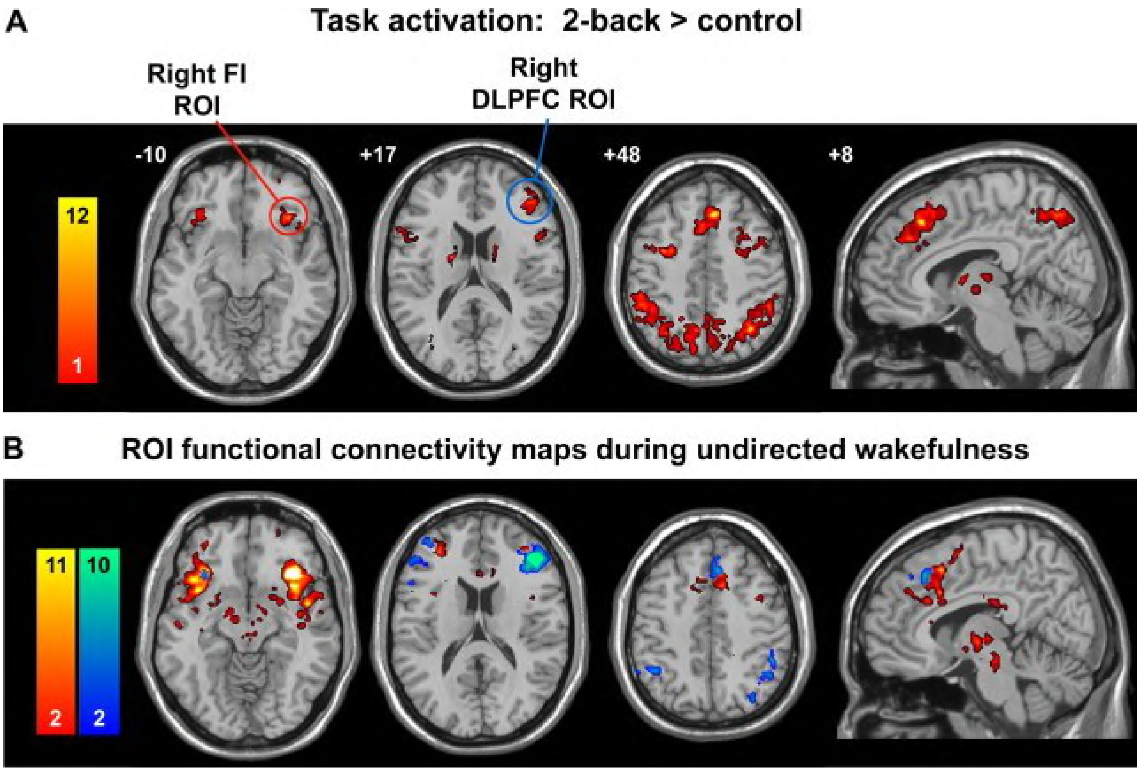

Figure 3.17. Task-activation ensemble using task-free fcMRI.
A. Spatial working memory activation map was used to select seed ROIs in right frontal lobe
B. Temporal correlations in BOLD signal determined the intrinsic connectivity patterns with the frontoinsular, and dorsolateral prefrontal ROIs
(Source: Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., Reiss, A. L., & Greicius, M. D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *Journal of Neuroscience*, 27(9), 2349-56)

Both networks are usually activated when performing external tasks, which is why previously they used to be interpreted as constituting a single unitary network.

However, both networks were characterized and identified two decades ago, by means of a complex double analysis based on ROI and ICA data [100]:

- First analysis: *Selection of regions of interest* (ROI selection). The ROI analysis was made scanning 14 subjects. To identify the networks involved in task execution (TAE), brain activations triggered during a spatial working memory task [101] were used to select two ROIs in the right frontal lobe (Fig. 3.17). One ROI was located on the right FI and was chosen for its role in autonomous and interoceptive processing [102]. Another ROI was located on the right DLPFC and was chosen for its role in control processes and working memory [103]. Using this approach, the TAE could be separated into two different networks (Fig. 3.17).

- Second analysis: *Independent component analysis* (ICA). Intrinsic connectivity network maps were constructed using ICA method in a separate group of 21 subjects. An automated template comparison procedure [104] was used using the FI and DLPFC networks as templates, identified with the ROI-based analysis. The ICA method showed that there are two distinct and stable networks anchored in FI and DLPFC (Fig. 3.18).

As a result, two different ICNs were identified:

- The ICA-derived right DLPFC network (usually called *Executive control network*)
- The ICA-derived right FI network (usually called *Salience network*)

These two networks, the *Executive control network* (ECN), and the *Salience network* (SN) are fundamental to behavior and thinking [105], so it is convenient to know their functional structure, and the way in which they interact with each other, and with the *Default mode network* (DMN).

The *Default Mode Network* (DMN) was discovered in 1979, when conducting studies on resting wakefulness [106].

Later, and with positron emission tomography (PET) technology, several studies were carried out to detect the activated regions in the brain when a task was performed. In this way, certain regions of the brain that had more activity at rest then during task were detected, such as the retrosplenial cortex, inferior parietal cortex, dorsolateral frontal cortex, inferior frontal cortex, left interior temporal gyrus, medial frontal regions and amygdala [107].

For this reason, this large-scale network was designated as the “default mode network” DMN [108]. These studies were conducted using structural magnetic resonance imaging (MRI) [109]. Years later, using functional magnetic resonance imaging (fMRI), it was detected that DMN also involved hippocampal formation [110].

The three networks that are part of the triple-network model are studied in detail below: the *Executive control network* (ECN), the *Salience network* (SN), and the *Default mode network* (DMN) (Fig. 3.7 and 3.19).

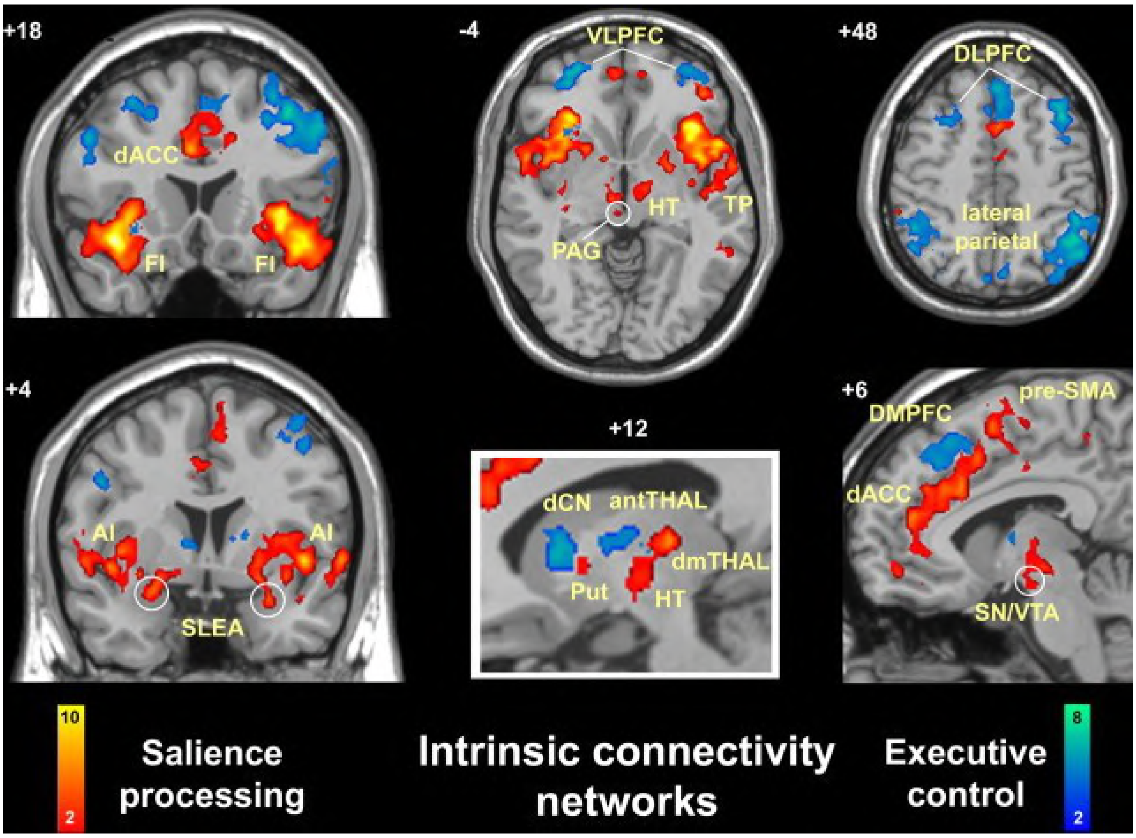

Figure 3.18. Intrinsic connectivity networks identified by independent component analysis ICA.
The *Salience network* (SN) is anchored by frontoinsular cortex and paralimbic anterior cingulate cortex. It features extensive connectivity with subcortical and limbic structures.
The *Executive-control network* (ECN) is anchored in dorsolateral frontal cortex and parietal cortex. It has more selective subcortical coupling.
(Source: Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., Reiss, A. L., & Greicius, M. D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *Journal of Neuroscience*, 27(9), 2349-56)

3.5.1. *Executive control network* (ECN)

The *Executive control network* (ECN) is called this way because it is involved in control processing and working memory. It is also called *frontopariental network* since it includes the dorsolateral prefrontal cortex (DLPFC) and the lateral parietal cortex (LPC) among its most prominent regions). The ECN is activated when the brain is involved in external tasks. Such task activities require attention to be directed to specific stimuli, while behavioral choices are weighed against changing conditions, homeostatic demands, and current context. To achieve the needed response flexibility, the brain must have control over the posterior sensorimotor representations, and it must take into account the relevant data until the actions are selected appropriately.

The ECN involves the following brain regions [111]:

- Dorsolateral prefrontal cortex (DLPFC)
- Inferior parietal cortex (IPL)
- Ventrolateral PFC
- Dorsomedial PFC
- Dorsal anteror cingulate cortex (dACC)
- Left frontoinsula

This group of regions is anatomically related to other regions [112], which would therefore form part of the same functional network:

- Anterior thalamus
- Dorsal caudate

The ECN can perform its control function as it is composed of the set of brain regions that have the most appropriate functionality:

- The DLPFC and the IPL are involved in sustained attention and working memory [113].
- The Dorsomedial PFC/pre-SMA are involved in response selection [114].
- The Ventrolateral PFC are involved in response suppression [115].

3.5.2. *Salience Network* (SN)

The *Salience network* (SN) is called this way because it is involved in the detection of salient stimuli, and integrates the interoceptive-autonomous, conflict monitoring and reward-processing centers.

The nervous system is continuously stimulated by both internal and external stimuli. Many of these stimuli are not important, while others can be vital, so one of the highest priorities of the brain is to identify the most relevant stimuli. Therefore, the brain must have a system capable of integrating highly processed sensory data with visceral, autonomous and hedonic “markers” in order to decide what to do at any given moment [116]. This system is the *Salience network* (SN).

The SN involves the following brain regions [117]:

- Anterior insula (AI)
- dACC/paracingulate cortex
- Superior temporal pole
- Fronto insula (FI)

- Dorsolateral prefrontal cortex (DLPFC)
- Suplementary motor area (SMA)/pre-SMA
- Frontal, temporal and parietal opercular regions

The *Salience network* also includes anatomically related subcortical regions [118]:

- Subtenticular extended amygdala
- Ventral estriatopallidium
- Dorsomedial thalamus
- Hypothalamus
- Periaqueductal gray
- Substantia nigra / ventral tegmental area

The *Salience network* can perform its function of detecting the most important salience events because it is made up of the brain regions with the most appropriate functionality:

- The ACC is involved in the processing of errors and conflicts ([119]).
- The dACC and the FI are involved in interoceptive-autonomous processing [120]. These regions are coactivated in response to various types of saliences, including the emotional dimensions of pain [121], empathy regarding pain [122], touch, hunger and stress [123], musical emotion [124], faces of loved people [125] or allied people [126], and social rejection [127]. The dACC and the FI are also involved in interoceptive feedback and sympathetic output [128].
- On the other hand, the subcortical regions of the *Salience network* are involved in reward, homeostatic regulation, and emotion [129].

3.5.2.1. Importance of Anterior insula (AI)

The most important region of the *Salience network* is the anterior insula (AI), which is a mediation center for dynamic interactions between large-scale networks involved in externally oriented attention, and in internally oriented cognition (self-related) [130] (Fig. 3.19).

The insula is involved in affective, regulatory and cognitive functions, including emotional responses, empathic processes, and interoceptive awareness. The insula has a very complex structural connectivity pattern, and in task-related functional images it has been difficult to isolate its responses, as it is usually activated at the same time as DLPFC, ACC, VLPFC, and PPC.

The insula is involved in the following tasks:

1. Detection of salient events

3. Modulation of autonomic reactivity to salient stimuli (based on the interaction between the anterior and posterior insula)

2. Switching between other large-scale networks to facilitate access to attention and working memory resources when a salient event occurs

4. Functional coupling with ACC to facilitate quick access to the motor system

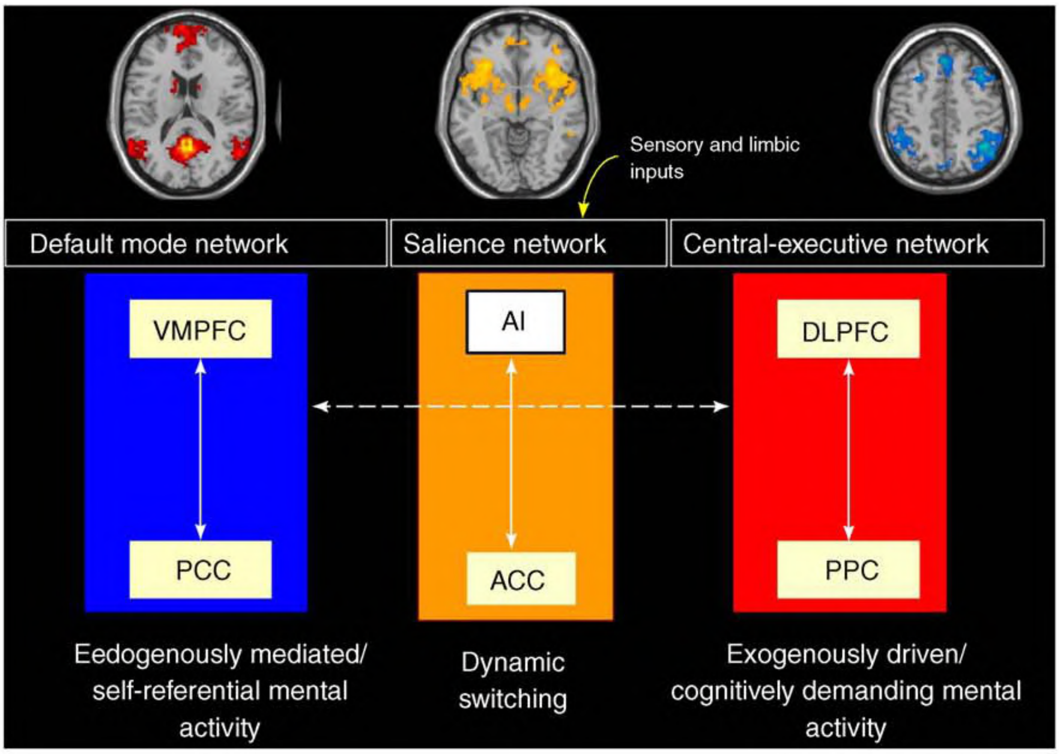

Figure 3.19. The *Salience network* (SN) is hypothesized to initiate dynamic switching between the *Executive control network* (ECN) and *Default mode network* (DMN), and to mediate between attention to external and internal events.
(Source: Bressler, S., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Science*, 14, 277-290)

Therefore, it can be said that the insula is responsible for detecting outstanding events and marking them for further processing, at the same time generating the appropriate control signals.

In general, the *Salience network* (with the AI as the main center) helps the brain regions involved in generating adequate behavioral responses in response to salient stimuli.

Several studies have suggested that certain regions of the SN, such as the inferior frontal gyrus (FG) and the anterior cingulate cortex (ACC), are involved in various decision-making, monitoring and cognitive control processes [131]. However, AI had not been studied carefully.

The main function of the anterior insula (AI) is to identify the most relevant stimuli from the enormous continuous flow of stimuli detected by our senses [132]. When a relevant stimulus is detected, the AI assists in the processing of the related information by creating the appropriate transient control signals. These signals are responsible for involving the areas of the brain that mediate working memory, attention and higher-order cognitive processes, and additionally disengage the DMN. Once a stimulus activates the AI, it will have preferential access to the brain's working memory and attention resources.

On the other hand, the main function of the anterior cingulate cortex (ACC) is the selection of sensory, motor, and association cortices [133].

As a consequence, the AI and the ACC (as part of the *Salience network*) collaborate in the integration of bottom-up attention switching with top-down control, as well as in the polarization of sensory inputs.

The AI receives a wealth of multimodal sensory information, ACC, and the associated dorsomedial prefrontal cortex (DMPFC) receive very little sensory information [134]. On the other hand, the ACC and the DMPFC have great connectivity with the motor system, the AI has very little. Complementarily, the ACC and the DMPFC have direct connections with the spinal cord, and with the subcortical oculomotor areas [135], so they have direct control over the action. This anatomical connectivity, together with the *von Economo* neurons (which allows a rapid connection between the AI and the ACC), allows the *Salience network* to involved in both attention and motor responses to salient sensory stimuli.

In this way, the AI plays both a direct and an indirect role in attention, cognition, and behavior control. This input-output pattern suggests that the AI can generate the appropriate signals to activate a hierarchical control.

3.5.2.2. Importance of Von Economo neurons

It is important to remember that both the ACC and the FI include the Von Economo neurons, which are also included in the dlPFC, but do not exist anywhere else in the brain [136]. These neurons are very elongated cells, thus allow a rapid communication between relatively separate regions of the brain. Von Economo neurons have only been found in the anterior cingulate cortex (ACC), the insula (I) and the dorsolateral prefrontal cortex (DLPFC). These neurons have a special functionality in the human brain as they allow long-distance connection and are of great evolutionary importance [137]. In fact, it has been suggested that they have evolved in very large brains to enable rapid information processing and transfer through very specific projections, which have evolved with the increasing complexity of human social relationships [138].

The ACC, the FI and the DLPFC are part of the SN, which is responsible for the detection of salient events, and the dynamic control switching of other networks and brain regions. The SN helps the brain regions involved in generating adequate behavioral responses in response to salient stimuli, therefore it must have strong connectivity with the regions it must control. According to the *Tethering hypothesis*, the human brain increased in size by dividing into pieces, around which high-level cognitive functions developed. In this sense, the SN maintained many of its strong connections, but had to develop many others, and some of them were topographically remote. This is probably why a new type of very elongated neurons was developed, which connected the nodes of the SN with the remote regions that it had to control, the Von Economo neurons. The DLPFC is also part of the ECN that also helps to control the information generated in other parts of the brain, and some of them very far away.

3.5.3. *Default mode network* (DMN)

The *Default mode network* (DMN) has a complex structure and functionality, which is still not well understood today, although it is known to play a fundamental role in high-level human cognition, and therefore has a decisive role in human creative potential. For this reason, this network will be studied in much more detail.

In this section its general functionality is analyzed, and the next chapter analyzes its fundamental role in higher-level cognitive functions, as well as in creativity.

3.5.3.1. Self-generated cognition and its importance in creativity

Self-generated thinking can happen at any time. Throughout the day, and despite the enormous amount of sensory information available, from time to time, the brain is capable of generating thoughts internally, independently of external stimuli. Even in the midst of an intense cognitive process (such as solving an engineering problem or participating in a work meeting) we realize that we are thinking about past experiences, fantasizing about future plans, or thinking about other persons.

These self-generated thoughts are a complex and heterogeneous type of cognition:

- In some cases, they are generated due to a certain purpose, and can be related to certain personal goals and aspirations
- In other cases, they are generated without any intention, and they last until we are forced to pay attention to a salience stimulus, or due to a flash of consciousness [139].

Furthermore, self-generated thoughts can be related to the sensory information available at any given moment in two ways:

- Loosely related to sensory inputs
- Not related to sensory inputs. This is the case of internally directed, spontaneous or autobiographical thoughts [140].

In the same way, self-generated thoughts can be related to the current task in two ways:

- They can be generated as part of a task (when a decision must be made that depends on an internal representation to reconstruct, or imagine, a situation, understand a certain stimulus, or generate an answer to a question).
- They can be generated independently of a task (either in the middle of developing the task, or when taking a break without doing anything).

For this reason, their nature and content can cause self-generated thoughts to have completely different consequences:

- Self-generated thoughts can induce human creative activity, as they can provide novel solutions to ongoing problems [141].
- Self-generated thoughts can also be a factor capable of generating anguish and unhappiness [142].

Many of the neural systems that support externally focused tasks display coordinated activity at rest (such as the motor network or the visual network). An important question raised by these observations is whether spontaneous changes in regions outside the DMN contribute to an individual's self-generated experiences and, if so, what cognitive or experiential properties do they represent.

3.5.3.2. Identification of the DMN

It has only been 15 years since it was observed that the DMN is a large-scale network, and today it is known to have a dynamic and complex nature, since it plays a fundamental role in two completely different cognitive processes [143].

- On the one hand, it is known that DMN plays a fundamental role in internally directed or self-generated thinking. Self-generated thoughts are a heterogeneous construction whose component processes are sustained by various subsystems of the DMN.

- On the other hand, it is known that the DMN interacts with executive control networks to regulate certain aspects of internal thinking.

The regions that make up the DMN were originally defined by deactivation patterns when performing goal-directed tasks.

Currently, and based on the use of new technologies, the DMN is identified much more precisely based on its temporal correlation patterns using resting-state functional connectivity MRI (RSFC) [144].

In fact, and based on a recent exhaustive study, it has been possible to determine with great precision the components of the DMN. This study was carried out applying data pooling techniques from RSFC collected from 1,000 participants, the cortex, striatum and cerebellum were divided into seven large-scale intrinsic brain networks (all of them decomposed to turn into subnets, creating a total of 17 intrinsic brain systems on a large scale) [145].

Based on this study, it has been seen that DMN is made up of the following brain regions (Fig. 3.20):

- Medial prefrontal cortex (dmPFC, rostral anterior cingulate and parts of the anterior and ventral mPFC)
- Lateral frontal cortex (superior frontal cortex, and inferior frontal gyrus)
- Medial parietal cortex (posterior cingulate, and retrosplenial cortex)
- Medial temporal lobe (hippocampus, and parahippocampal cortices)
- Lateral parietal cortex (angular gyrus, and posterior supramarginal gyrus / TPJ)
- Lateral temporal cortex (extending anteriorly to the temporal poles)
- Cerebellum (including subdivisions Crus I and Crus II)
- Striatum (medial wall of caudate, and posterior putamen)

Alternatively, in this study DMN was also identified using RSFC and with large scale meta-analyses of functional neuroimaging data using *NeuroSynth* (Fig. 3.20) [146].

When comparing both studies, a clear correspondence was observed between the two results, so the set of constituent components can be considered good.

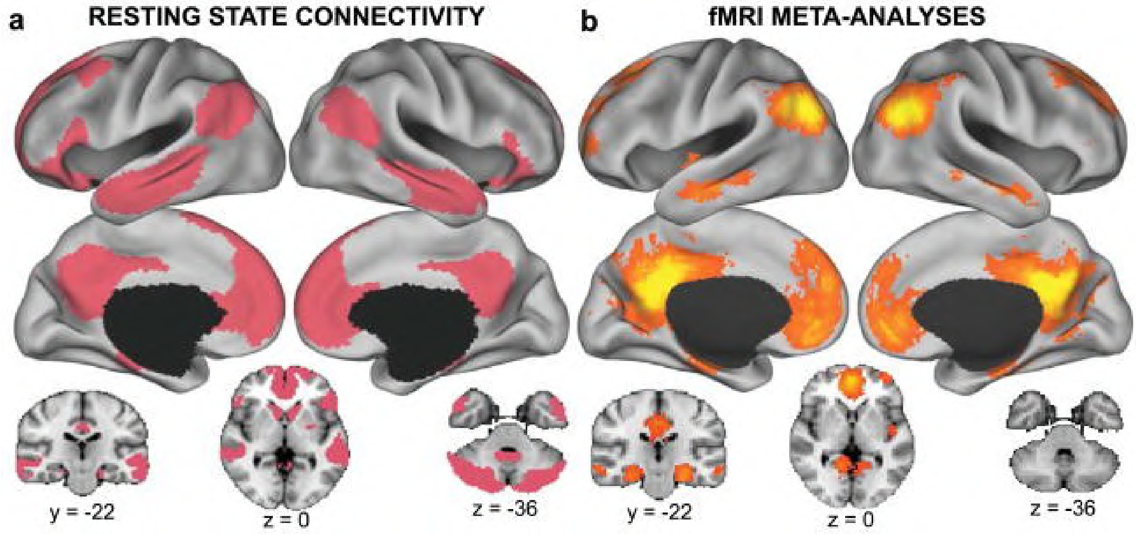

Figure 3.20. The *Default mode network* (DMN) identified in two different ways.
A. DMN identified by resting-state functional connectivity MRI of the cortex, striatum, and cerebellum.
B. DMN identified by a meta-analysis of functional neuroimaging data using NeuroSynth65 software.
(Source: Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, 1316(1), 29-52)

3.5.3.3. DMN and self-generated thoughts

Initially, when DMN was discovered, it was found to activate in the absence of external stimuli, and to deactivate significantly during externally focused goal-directed tasks [147]. For this reason, from the beginning it was known as a "task-negative network" and the idea that it supports passive mental states instead of active ones [148].

However, this view of the DMN turned out to be wrong, since among other things it terribly simplified people's cognitive goals [149].

In fact, recent studies have revealed that DMN increases its activity during goal-directed cognitive tasks that require self-generated thoughts. Tasks that activate the DMN often require the use of episodic, autobiographical, or semantic information. Some of these tasks are: imagining novel scenes, planning aspects of the personal future, referring to information about oneself, self-reflection, detecting mental states of other people, reasoning about moral dilemmas or other scenarios, evaluating emotional information, understanding narratives, etc. [150]. Therefore, DMN is also activated when performing goal-directed tasks, but only when there is a need to self-generate mental content in order to achieve the desired goal.

The DMN can also be activated from time to time during externally focused tasks, when they are easy to perform, when they are boring or when they have been previously very practiced. In this case, a state of mental wandering is created, produced by a change in the focus of attention towards self-generated information, without paying attention to the perceptual stimuli relevant to the task that is being developed [151].

In this sense, spontaneous self-generated thoughts can contribute to the activation of the DMN during unconstrained periods of rest (called “resting state”). In fact, recent studies have shown that in periods of resting state there is activity related to autobiographical memory, and this has been attributed to the presence of spontaneous thoughts that consisted of “a mixture of past memories wandering freely, future plans and other thoughts and personal experiences" [152].

It should be noted that recent studies using advanced experience-sampling methods have shown that people spend a lot of time involved with self-generated thoughts during periods of resting state [153].

In the next section, the characteristics of self-generated thoughts are analyzed, showing that they usually involve an active mental process.

3.5.3.4. Complex cognitive processes of self-generated thoughts

The presence of self-generated thoughts, unrelated to external sensory information, is common in our daily lives, in fact, recent studies estimate that adults spend between 30% and 50% of their waking time generating these types of thoughts [154].

Many studies have focused on mind wandering [155], and many others have focused on just one or two aspects of self-generated thinking (Fig. 3.21) [156]. These studies shows that self-generated thoughts can be characterized according to multiple dimensions, such as their personal importance, social orientation, level of detail, temporality, somatosensory awareness and its format (stories or images) [157].

The analysis of self-generated thoughts suggests that their content is very heterogeneous and complex, and they also have an adaptive purpose, since they allow people to prepare for future events [158], generate a sense of self identity [159] and so that they can function in the best possible way in our complex social environment [160].

In general, people tend to think that their self-generated thoughts have some kind of relationship with their personal goals [161], although many of their self-generated thoughts also habitually involve other people [162]. In addition, self-generated thoughts tend to be forward-looking and future-proof [163].

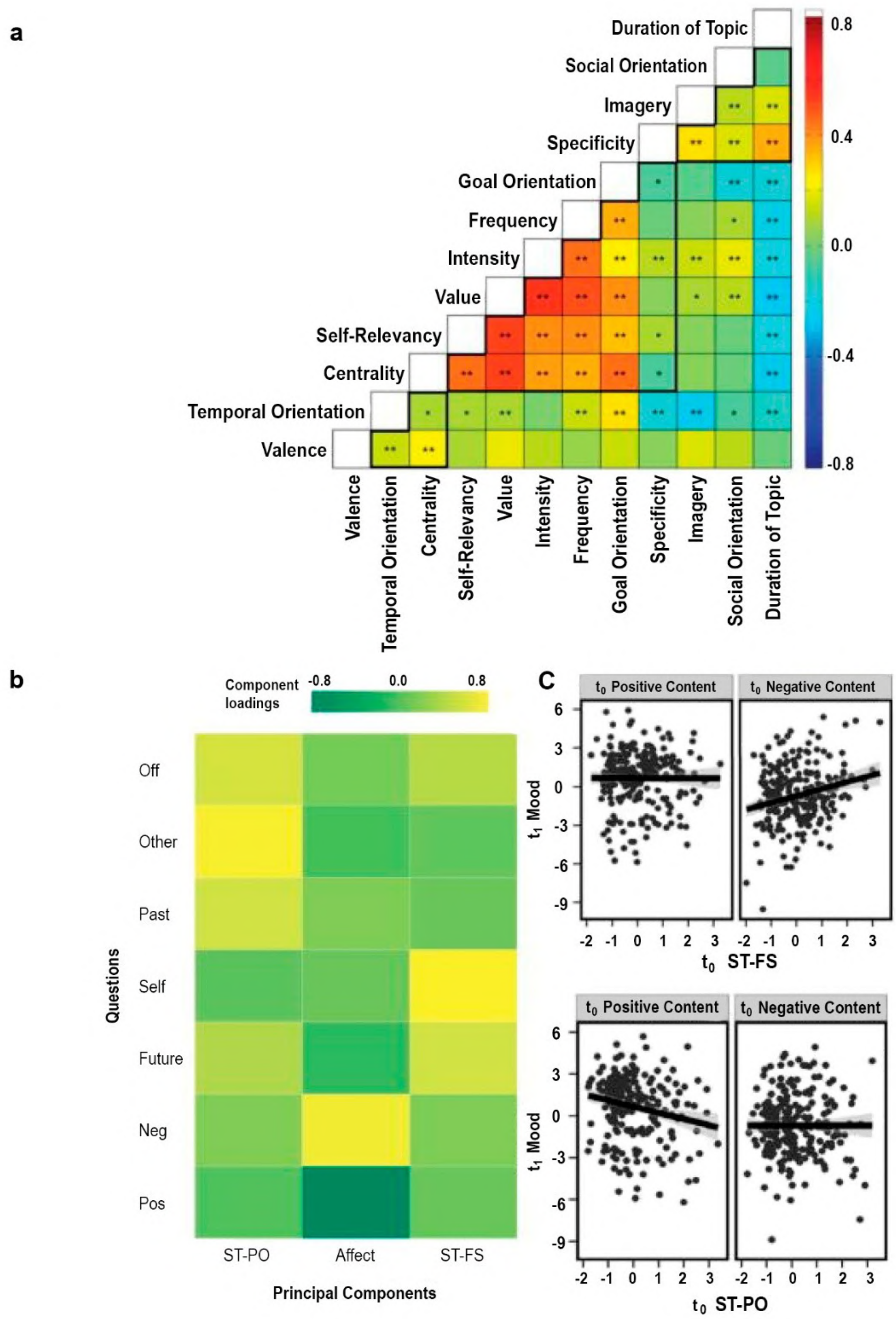

Figure 3.21. Heterogeneity of self-generated thoughts
A. Self-generated thoughts of 76 people experienced in daily life.
B. Decomposition of the content of task-unrelated self-generated thoughts while participants performed a non-demanding task. This revealed two different social thoughts:

a) social thoughts related to the past and others (ST- PO)
b) social thoughts related to the future (ST-FS)
A third type of thought (nonsocial emotional) was also identified (EMO)

C. Results of a lag analysis exploring the temporal relationship between each component from B. The co-occurrence of positive emotional content with thoughts about the past was followed by more negative mood. Negative mental content regarding the future led to a subsequent mood with a more positive tone.
(Source: Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, 1316(1), 29-52)

The content of self-generated thoughts can be related to the type of task that is usually performed, and changes over time. It has been shown, for example, that when you are involved with negative information, the number of negative and retrospective thoughts increases [164]. In the same way, it has been seen that social thoughts related to our past generate negative thoughts [165], while social thoughts related to one's future generate subsequent positive thoughts (Fig. 3.21). In addition, other studies have shown that thinking about yourself increases the number of thoughts related to the future [166].

3.5.3.5. DMN subsystems

The DMN plays an important role in the generation of self-generated thoughts, so it is convenient to know its functional and anatomical structure [167].

Recent studies using resting-state functional connectivity MRI (RSFC) and diffusion tensor imaging (DTI) have shown that the DMN is composed of several subsystems that interact with each other [168] (Fig. 3.22).

- *Medial temporal subsystem*

  This subsystem integrates the hippocampus, parahippocampal cortex, retrosplenial cortex (RSC), inferior posterior parietal lobe, and ventromedial PFC (vmPFC).

- *Medial dorsal subsystem*

  This subsystem integrates the dorsomedial prefrontal cortex (dmPFC), the junctional temporoparietal cortex (TPJ), the lateral temporal cortex (LTC), and the temporal pole (TP).

- *Core subsystem*

  This subsystem is the “functional hub” that enables the transfer of information between the other subsystems. Integrates the anterior medial prefrontal cortex (amPFC) and the posterior cingulate cortex (PCC).

As has been commented, the most complete identification of the component regions of the DMN has been carried out in an ambitious study, using clustering algorithms to resting-state activity from 1000 participants, dividing the cortex, cerebellum and the striatum, and grouping them into seven correlated networks of intrinsic activity [169].

This analysis was followed by a finer parceling (17 networks), identifying three bilateral subsystems similar to those previously indicated (Fig. 3.22), although with some important differences.

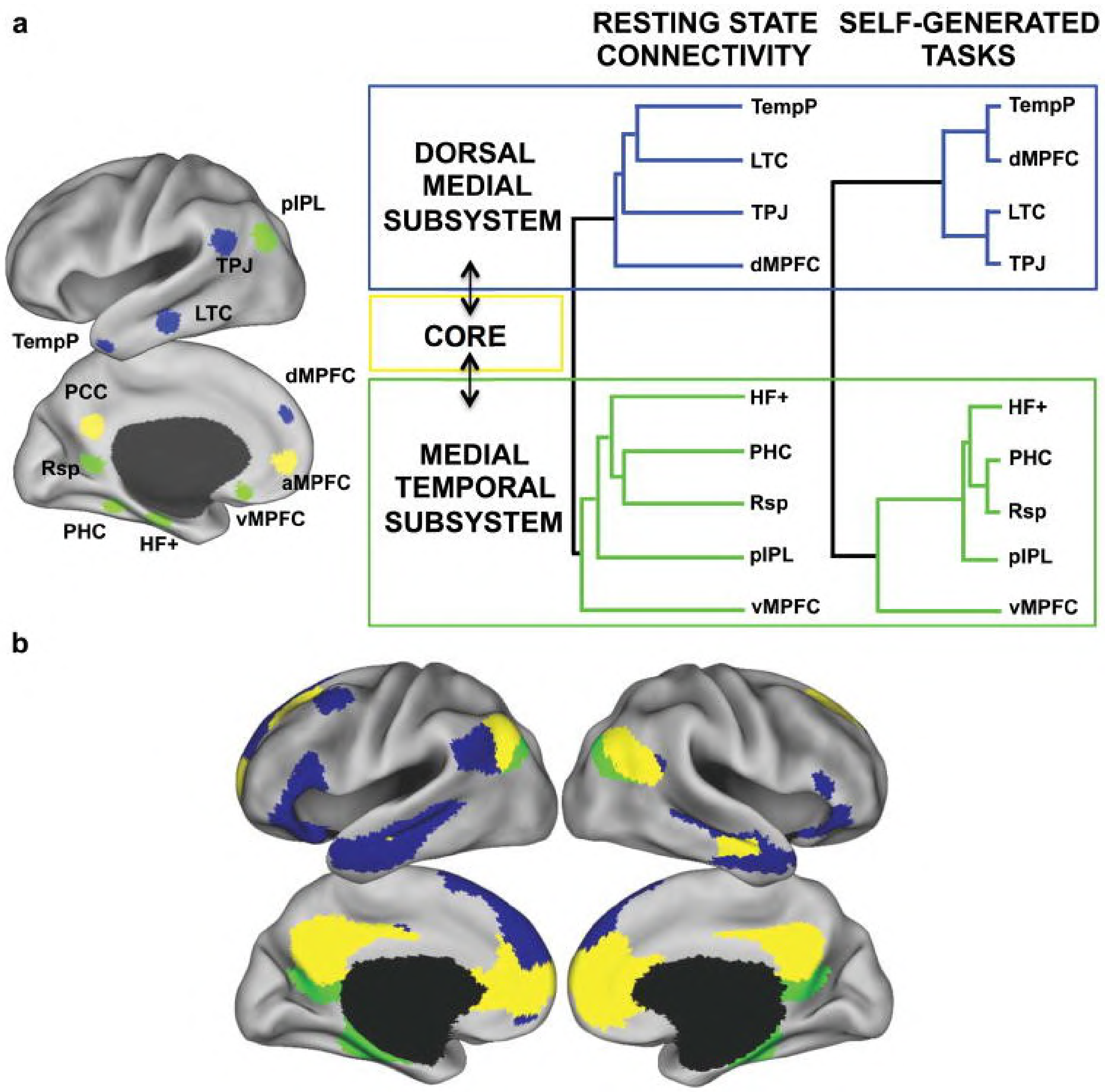

Figure 3.22. Heterogeneity of the DMN
A. Graph and clustering analysis of 11 DMN regions during passive rest and active self-generated tasks reveal the presence of different medial temporal and dorsal medial subnetworks that converge on the DMN core network (amPFC and PCC).
B. DMN components revealed by a whole-brain parcellation of resting-state fMRI data from 1,000 participants.
Both results are consistent.
(Source: Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, 1316(1), 29-52)

3.5.3.6. Analysis and functionality of the DMN subsystems

Since self-generated thoughts are heterogeneous in nature, and since DMN has a heterogeneous character, it could be thought that the different components of DMN could contribute to different aspects of self-generated thinking.

To answer this question, a large-scale meta-analysis was performed using *NeuroSynth65* to decode the functional properties of the three subsystems of the DMN (Fig. 3.22) [170]:

a. Medial temporal subsystem

It is associated with past and future autobiographical thought, with episodic memory (episodic, remember, memories, recall, etc.), and with contextual retrieval (Fig. 3.23).

b. Dorsal medial subsystem

It is associated with social cognition and mentalization (mentalizing, mental scenarios, personal cognition, social cognition, theory of mind, etc.), as well as the understanding of stories and semantic-conceptual processing (story, knowledge, language, comprehension, meaning, semantic, word, sentence, syntactic) (Fig. 3.23).

c. Core subsystem

It is associated with processes related to oneself (self-referential, personal, autobiographical, etc.), with emotional evaluation (the good, the bad, the positive, the negative, etc.) and with the social and mnemonic processes shared by the medial dorsal subsystem and medial temporal subsystem (mentalizing, recollection, retrieval, person, social, memories) (Fig. 3.23).

This study showed initial evidence on the functional differentiation between the different subsystems of the DMN, as well as the interactions between the DMN components.

The following sections summarize in detail the results of this study, consistent with other previous studies. And as a result, a detailed functional model of the DMN is proposed.

3.5.3.6.1. *Core subsystem* of the DMN

The *core subsystem* of the DMN is made up of the PCC and the amPFC [171].

- The PCC is a heterogeneous brain structure, with subdivisions characterized by different patterns of structural and functional connectivity [172]. The PCC can be broadly subdivided into ventral and dorsal components, with further subdivisions into the dorsal PCC [173]. The ventral PCC is functionally connected with the other regions of the DMN [174] and is activated in almost all self-generated tasks, such as self-referential processing tasks, episodic memory, autobiographical memory, conceptual processing, spatial navigation, future thinking, and theory of mind [175] (Fig. 3.23).

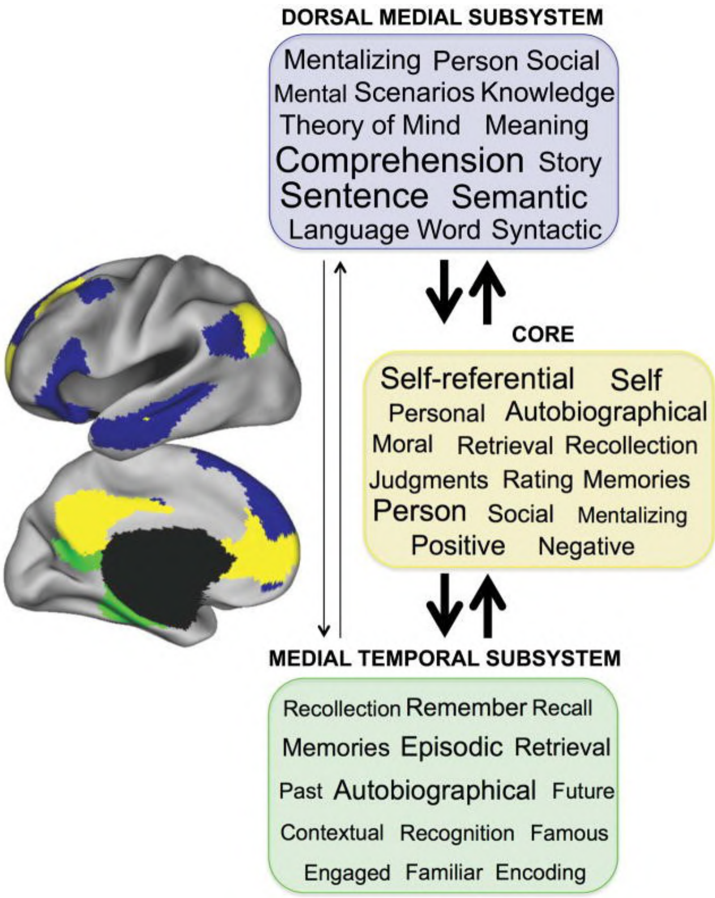

Figure 3.23. Decoding the functions of DMN components using automated fMRI meta-analyzes.
Automated meta-analytic software (NeuroSynth 65) has been used to compute the spatial correlation between each DMN component mask and every other meta-analytic map for each concept stored in database.
(Source: Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, 1316(1), 29-52)

The dorsal PCC is functionally connected to many other brain systems and has been linked to autonomic arousal and awareness [176], and the management of external changes and relevant stimuli [177].

The ventral PCC and the ventral dorsal PCC are anatomically strongly connected to each other and to the precuneus, located adjacently [178]. Therefore, the PCC is an integration zone that supports the bottom-up attention of the relevant information for behavior coming from both memory and perception [179].

The *core subsystem* is closely connected with other regions of the DMN such as the anterior lateral temporal cortex (LTC) and the angular gyrus (AG), which are activated by performing various types of tasks, such as theory of mind, memory retrieval, or semantic processing [180].

- The amPFC is strongly connected with the PCC, the *medial temporal subsystem* and *the medial dorsal subsystem*, the ventrally positioned limbic network (including the medial orbitofrontal cortex, OFC), and with other subcortical regions involved in autonomous arousal/regulation and affect [181]. The amPFC is generally involved in self-related processing, such as referring to oneself, in autobiographic memories, recovering any type of personal knowledge, visualizing future personal events, visualizing future mental states (Fig. 3.23) [182]. In general, we give great importance to our own personal information, considering it something very characteristic of our own identity, and this information involves the amPFC, especially in its ventral area [183].

The amPFC is also involved in making decisions that involve other loved and valued people, such as our family and friends [184], and close people [185]. AmPFC is linked to positive emotions and reward systems [186] and with negative emotions, especially when it is of personal importance, or when physical pain is anticipated (or evaluated) [187] or with social threats [188].

The amPFC has a strong connection with semantic, limbic and autonomic structures (including the lateral parietal cortex, LPC) for which it integrates the salient external and internal information (probably from the posterior cingulate cortex, PCC) with one's own current affective experience and with previous knowledge, both conceptual, as episodic. For this reason, the amPFC can make mental constructions, with a personal meaning, and that later can serve to update existing representations and to guide thoughts and behavior in long periods of future time [189].

3.5.3.6.2. *Medial temporal subsystem* of the DMN

The *medial temporal subsystem* includes the hippocampus, parahippocampal cortex, retrosplenial cortex (RSC), inferior posterior parietal lobe (PPL), and ventromedial PFC (vmPFC). This subsystem is directly involved in the simulation of the future and in the episodic/contextual recovery [190], as well as in various aspects of mental simulation, such as associative and constructive processes [191].

- The hippocampus (in the context of DMN) is involved in memory and imagination [192].
- The parahippocampal cortex is involved in spatial and scene recognition [193].
- The retrosplenial cortex (RSC) is involved in spatial navigation, and if it is damaged, what is called “topographical amnesia” can occur [194], (in the same way as angular gyrus lesions can alter the reminder aspects of episodic memory) [195].

In general, the medial temporal subsystem is involved in episodic future thinking and autobiographical memory [196].

Furthermore, within the *medial temporal subsystem*, RSFC alterations are related to the degree of spontaneous past and future thinking (during resting state) [197].

The *medial temporal subsystem* is also involved in scene construction [198], in episodic simulation, and in the integration of an object (or a person) in its environment (time and place) [199].

3.5.3.6.3. ***Medial dorsal subsystem*** of the DMN

The *medial dorsal subsystem* integrates the dorsal medial prefrontal cortex (dmPFC), the temporoparietal cortex junction (TPJ), the lateral temporal cortex (LTC), and the temporal pole (TP).

This subsystem is involved in mentalizing [200], and in thoughts related to the mental states of oneself and of other people [201]. It is also involved in the social and self-reflective aspects of autobiographical memory and future thinking [202].

One way to measure the theory of mind, or mentalizing, is to infer a person's false mental state [203]. This process involves external stimuli, as well as self-generated thoughts uncoupled from the physical world (due to the fact that people do not have quick perceptual access to other people's thoughts) [204].

In this sense, it has been shown that the *medial dorsal subsystem* is not activated when performing theory of mind social tasks that do not require internal or self-generated information [205].

Various regions of the *medial dorsal subsystem* (with the exception of the right TPJ) are also involved when people reflect on their own beliefs, desires, preferences, and emotions [206].

In the *medial dorsal subsystem*, there are functional differences in each of its component regions.

- The dmPFC is involved in social reflection [207].
- The right TPJ is involved in thinking about other people's beliefs [208].
- The LTC (including the left superior temporal sulcus, together with its adjoining areas in the direction of the angular gyrus, and the temporal pole) is involved in executive aspects of mentalization [209]. The anterior LTC plays a key role in processing [210] and can store various types of conceptual information and semantic knowledge of different entities and objects [211] supported by connections to ventral auditory and visual

processing streams [212]. The AG is strongly connected with the anterior LTC, the rest of the regions of the DMN, and with other regions involved in attention, perception, action, and spatial cognition [213]. The AG gyrus works as an intermodal center and allows internal information and perceptual information to become conceptual representations about entities, objects and events in their spatio-temporal contexts [214], in fact, lesions of the angular gyrus lesions can alter the reminder aspects of episodic memory.

These regions can collaborate in semantic and conceptual knowledge (including social knowledge), which is necessary in more complex social cognitive processes [215].

The *medial dorsal subsystem* is more intensely activated with social stimuli [216], so it is possible to deduce that people prefer social information over non-social information, and this perhaps is due to our evolutionary social nature [217].

3.5.3.6.4. Integrated activity of the three subsystems of the DMN

As a summary of the studies carried out, it can be said that the *core subsystem* of the DMN is involved in the representation of information that is personally relevant, the *medial temporal subsystem* allows the recovery of associative information to build coherent mental scenes, and the *medial dorsal subsystem* allows information related to oneself and others to be reflected in a metacognitive way, probably using stored conceptual knowledge [218].

Therefore, it can be concluded that the set of the three subsystems can support a large part of the content of self-generated thought, and that the DMN is mainly involved in the following tasks:

Core subsystem:

- Self processing [219].

Medial temporal subsystem:

- Scene construction [220].
- Constructive episodic simulation [221].
- Associative prediction [222].

Medial dorsal subsystem:

- Mentalization [223].

Finally, it should be noted that all the components of the DMN are involved in aspects of conceptual processing (storage, retrieval, and integration of conceptual knowledge).

[224]. And as is known, conceptual thinking is of great importance in the cognitive process since they are the basic components on which more complex self-generated thoughts are created, including future plans and autobiographical memories.

The existence of three subsystems within the DMN means that its general activity is structured in three different types of processes that interact with each other. This implies an additional complexity of the self-generated thoughts that can be generated, and this is of enormous importance in creative processes.

3.5.3.7. Functional relationship between the DMN with the ECN and DAN

The DMN is activated when no task is being performed and is also involved in the self-generation of internal thoughts. But it is also activated when certain tasks that require access to memory are performed, and it interacts dynamically with other neural networks (Fig. 3.24). Specifically, the DMN collaborates with the *Executive control network* (ECN) (to facilitate goal-directed cognition) and anticorrelates with the *Dorsal attention network* (DAN).

3.5.3.7.1. The DMN anticorrelates with the DAN

The *Dorsal attention nework* (DAN) is made up of the following brain regions [225] (Fig. 3.24):

- Posterior prefrontal cortex (PPC)
- Inferior precentral silcus (iPCS)
- Superior occipital gyrus (SOG)
- Middle temporal motion complex (V5/MT)
- Superior parietal lobule (SPL)

The DAN is involved with visuospatial processing, and when activated, the DMN is deactivated [226]. The deactivation of the DMN is necessary in order to have a greater capacity for processing information focused on the effective performance of cognitive tasks that require attention to external stimuli. In fact, several studies have seen that when self-generated thoughts arise, the processing of sensory information is reduced, a phenomenon known as *perceptual decoupling* [227].

The fact that DAN and DMN anticorrelate shows that the brain prioritizes and cares for the integrity of self-generated thoughts. When these thoughts are generated, perceptual inputs of attention are reduced, allowing self-generated thoughts to persist with minimal interruptions [228].

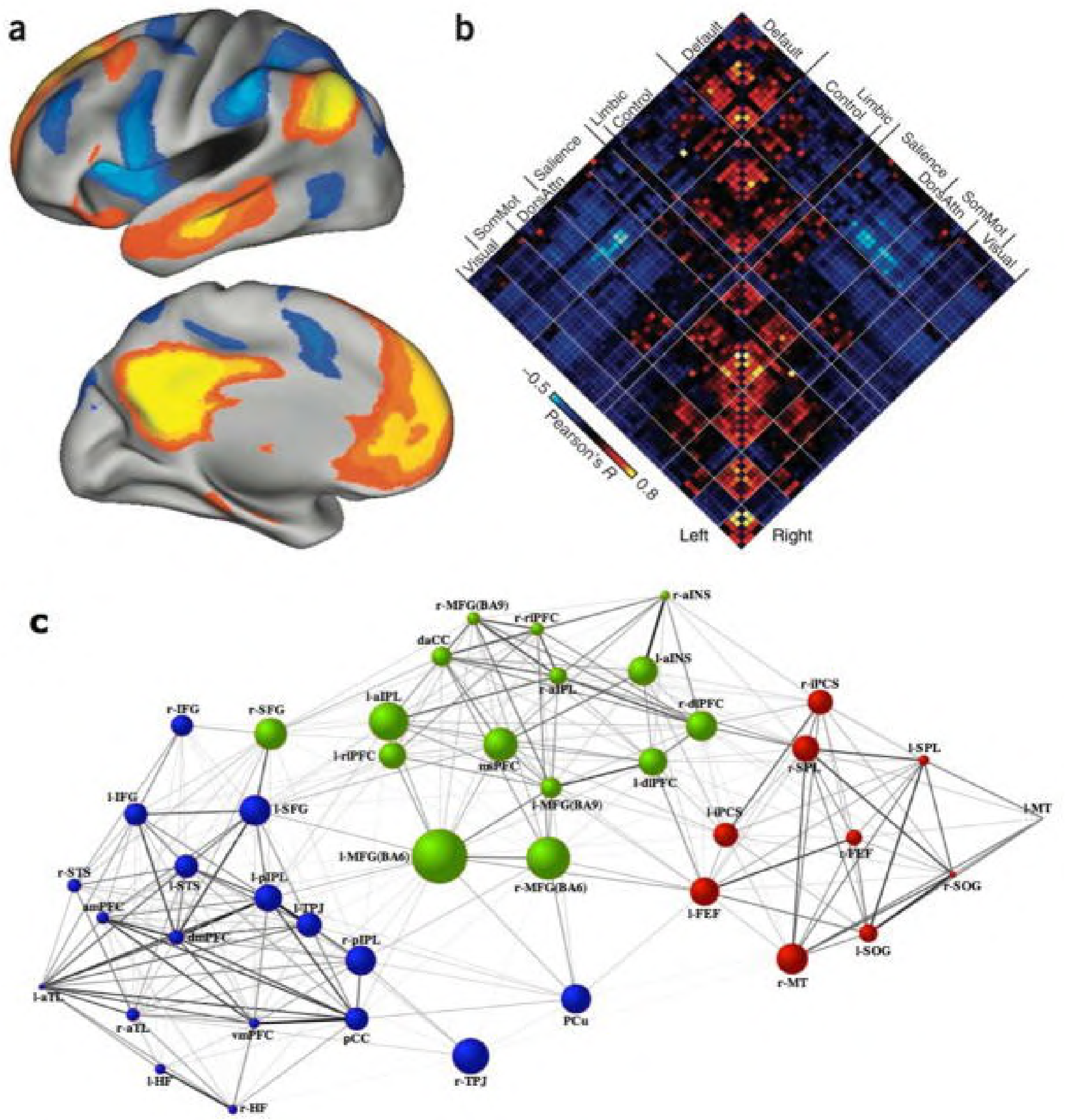

Figure 3.24. The DMN and large-scale network interactions examined using resting-state functional connectivity RSFC.

A. RSFC of the DMN, showing anticorrelation with the dorsal attention network DAN.

B. A correlation matrix shows the coupling architecture of the cerebral cortex measured at rest.

C. Interregional pairwise connectivity graph between the DMN (blue), DAN (red), and ECN (frontoparietal control network, also called FPCN) (green).

(Source: Andrews-Hanna, J. R., Smallwood, J. & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, 1316(1), 29-52)

Undoubtedly, the anti-correlation of the DAN and the DMN is a sample of the basic creative structure of the human brain, which prioritizes the generation and management of self-generated thoughts, over the management of the primary sensory information related to basic matters related to the here and now. The management of self-generated thoughts in a creative source, since such thoughts can suggest alternative paths in any human activity.

3.5.3.7.2. Interactive operation between the DMN and the ECN

Many higher order cognitive functions depend on top-down regulatory processes to ensure that goals are achieved. In this sense, the personal and social actions in which the DMN is involved also need a control system. This control is performed by the ECN.

At present, it is known that the ECN plays an important role in the executive control of attention [229].

As has been previously said, the ECN involves the following brain regions [230]:

- Dorsolateral prefrontal cortex (dlPFC)
- Inferior parietal lobe (IPL)
- Rostral prefrontal cortex (rPFC)
- Dorsal anterior cingulate cortex (dACC)
- Frontal operculum - anterior insula (FO/AI)
- Precuneus (PCu)
- Posterior inferior lateral temporal cortex (posterior LPFC)

So, the ECN is anatomically interposed between DMN and DAN [231], which suggests that it can play an important modulating role in the activation and deactivation of both networks, based on switching goal states. In fact, there is a high level of intrinsic functional integration between the DMN and the ECN [232]. On the other hand, these networks are not functionally associated with motor sensory systems [233], which suggests that they are involved in higher level cognitive processes.

The ECN is involved in externally directed tasks where task goals depend on stimulus. However, the ECN is also involved in the regulation of self-generated information (mnemonic, social and emotional), and it does so by varying its functional connectivity with the DAN or the DMN, respectively. For example, in visuospatial planning tasks, DAN and ECN are activated, while in autobiographical planning tasks, DMN and ECN are activated [234].

Several studies have been carried out that show the collaboration of the ECN with the DAN and DMN networks, evidencing what is called “flexible modulation hypothesis”.

1. On the one hand, studies have been carried out examining the brain activity during a problem-solving task, and it has been observed that the DMN and the ECN cooperate in various types of problem-solving tasks that require mental simulations [235]. For example,

in semantic processing tasks, several core regions of the DMN are activated, including MPFC and PCC, along with a region of the lateral prefrontal cortex linked to executive processing [236]. In autobiographical planning tasks, there is a coupling of the DMN and the ECN to imagine the steps necessary to achieve a certain personal goal, without imagining events associated with the achieved result [237]. Likewise, there is coactivation of the DMN and NEC during social working memory [238]. Finally, and especially important, is that the DMN and the ECN are involved in creative tasks [239].

All these tasks have in common the fact that internal information needs to be used, maintained, and evaluated to achieve a goal, which clearly suggests that these processes are a temporary evaluation of self-generated thoughts.

The dynamic interactions between the ECN and the DMN and DAN also show the participation of the ECN in certain types of self-regulation [240], such as regulation of emotions [241], memory suppression [242], and thinking unrelated to the task [243].

2. Analysis of RSFC MRI and graphs have also been performed to analyze in depth the relationships between the ECN with the DMN and DAN networks in the absence of task, to confirm the “flexible modulation hypothesis” (Fig. 3.24). The results practically coincide with the results of task-based functional magnetic resonance imaging: little positive connectivity has been observed between the DMN and the DAN, and on the other hand, a great connectivity has been observed between the DMN and the DAN with the ECN (Fig. 3.24).

Sliding-window correlation studies have also been performed that show that the relationship between DMN and ECN fluctuates dynamically [244].

Finally, there is evidence in behavioral studies that at least some types of self-generated thinking require executive resources, and that when performing tasks with a large component of working memory, the amount of self-generated thoughts is reduced [245], especially when performing future-focused tasks [246].

When performing not very demanding tasks, people with higher working memory create few self-generated thoughts unrelated to the current task [247]. On the other hand, when more demanding tasks are performed, people with greater cognitive control generate more self-generated thoughts not related to the task [248].

3.5.3.8. The need to jointly manipulate internal and external information

The DMN is strongly connected with other networks and therefore collaborates closely with them, although the details of this collaboration are not yet known. This collaboration allows certain complex cognitive processes that allow us to achieve complex goals that depend on both external sensory information and internally generated information. It is possible that the joint processing of internal information and external information is necessary to facilitate our proper behavior in the face of changing and complex situations in an increasingly complex environment.

Therefore, the anticorrelation between the brain's perceptual system and the internal thought management system helps the brain to focus on one task, excluding the other [249]. The ECN (as also does the SN) can mediate internally directed cognition and externally directed cognition, by maintaining a dynamic balance between DMN and DAN networks [250].

3.5.4. ***Triple network model*** in creativity

The first studies that tried to detect neurocognitive processes of creativity barely detected certain large-scale brain distinctions [251], as well as frontal versus parietal lobe participation in creative thinking [252].

However, more recent studies have detected the participation of two large-scale networks (ECN and DMN) and specific brain regions (hippocampus and parahippocampus) in the creative process. As seen in a previous section, the ECN and the DMN compete and collaborate with each other, based on the dynamic switching carried out by the SN. The contribution of these two networks, together with the MTL, in the human creative process is studied in detail below.

Executive control network (ECN)

The ECN is specifically activated during conditions of high cognitive control [253].

There have been many studies in which DLPFC and dACC have been shown to be activated by performing various types of creative tasks, such as generating creative stories [254], divergent thinking [255], piano improvisation [256], word association [257], the solving of insight problems [258], the formation of fluid analogies [259], and design of visual art [260].

It is known that when carrying out these creative tasks, the cognitive control carried out by these regions allows an analytical -and deliberate- mode of information processing, and in this way the evaluation of the suitability of novel ideas is possible [261] and select the most relevant creative ideas [262].

Therefore, the ECN network is involved in the creative activity evaluation process.

Default mode network (DMN)

The DMN (which includes the medial prefrontal cortex (MPFC), the posterior cingulate cortex (PCC)/precuneus, and the temporoparietal junction (TPJ) between its most prominent regions) is regularly activated during creative tasks [263].

Recent studies have shown that the TPJ increases its activity when performing various types of creative activities, such as in the generation of divergent thinking tasks [264], the generation of hypotheses [265], the formation of fluid analogies [266], and the generation of creative stories [267].

It is known that the MPFC [268], activates in the generation of creative stories. Further, the MPFC and the PCC/precuneus are activated in the resolution of insight problems [269]. It has also been proven that the DMN activates (while the ECN deactivates) in the improvisation of professional jazz pianists [270]. In general, it has been observed that when performing creative tasks, only parts of the DMN are activated, but not the DMN as a whole (with the sole exception of improvisation in jazz pianists).

In general, and based on the studies carried out, it can be said that the DMN is involved in two different ways in the process of generation and evaluation of creative processes.

- Since DMN is activated during conditions of low cognitive control [271] it may facilitate a freer associative mode of processing which, in the same way, may allow the generation of novel ideas [272], thus contributing to the generation of creative ideas.

- The DMN allows a creative evaluation of ideas since it is directly involved in the affective and visceroceptive evaluative processes observed in emotional processes. The DMN is activated during the evaluation of emotional reactions [273] and with the affective information generated internally [274], and therefore can generate reactions directly related to the most essential of people. In other words, DMN can create "visceral evaluation reactions" (intimate evaluation from our deepest being), as they are often referred to by creative people when monitoring their creative process [275].

Medial temporal lobe (MTL)

The hippocampus and the parahippocampus (two regions of the MTL), are involved in the creative process. The hippocampus increases its activity during visual art design [276] and in divergent thinking [277].

The MTL memory network is involved with associative processing [278] and with the memory retrieval process [279]. Furthermore, recent studies show that the MTL activates in the creation of semantic and episodic associations, and in recovering these

associations [280]. It is also involved when mental simulations of past events and possible future events are carried out, which require the recombination of stored information [281].
Therefore, this cooperative and associative capacity of the MTL suggests that it is especially important for creative thinking, since it allows generating new ideas by making associations of previous ideas.

Summarizing, and based on the studies carried out, three networks are involved in the process of generating and evaluating ideas of the creative process:

- MTL memory network, that contributes to associative processes allowing the generation of creative ideas.
- DMN, that has a dual role. Contributes to the generation of creative ideas due to its low level of information control. It also contributes to the evaluation of ideas since it is involved in the affective and visceral evaluation process.
- ECN, that contributes to the process of analytical evaluation of creative activity.

3.5.5. Context-dependent prioritization of off-task thoughts by the DLPFC

When the sensory information available is not demanding, human beings tend to wander and generate thoughts of greater personal relevance. On the other hand, when humans carry out a certain task, they do not generate so many internal thoughts. Recent studies have shown that the dorsolateral prefrontal cortex (DLPFC) is responsible for prioritizing off-task thinking [282]. The activity of the DLPFC is high both when "on-task" performing demanding tasks and "off-task" performing non-demanding tasks. It was also evidenced that people who increase self-generated thoughts (not related to a certain task) when external demands decrease, show a lower correlation between neural signals linked to external tasks and DLPFC, as well as less cortical gray matter in the regions sensitive to these external signals relevant to the task.

Therefore, it can be concluded that humans give priority to daydreaming when environmental demands decrease, and this cognitive prioritization task is performed by the DLPFC.

3.5.5.1. *Context regulation hypothesis*

The human brain has evolved to prioritize self-generated thoughts, not related to the sensory signals of each moment, in order to deal with issues of greater relevance than simply responding to the specific demands of a certain ongoing task.

Self-generated thoughts can be positive or negative. Positive self-generated thoughts are generally generated when we do not perform a task (or when it is trivial), they are not related to external input, and they are useful in the short or long term, such as those that include a delay in gratification [283], creative problem solving [284] or the refinement of personal goals [285].

On the other hand, negative self-generated thoughts are usually generated when performing externally demanding tasks, they cause worse executive control and can be the cause of poor performance when performing the current task [286].

The existence of self-generated thoughts in opposite situations may seem strange, however it is common and obeys what is called as *context regulation hypothesis*. This hypothesis determines a reduction in self-generated thoughts when external demands are high, and an increase in self-generated thoughts, with personally relevant information, when external demands lack a compelling goal.

Several functional magnetic resonance imaging (fMRI) studies have been conducted to understand how people create self-generated thoughts when task demands are low. According to previous neuroimaging studies, the objective-motivated prioritization process depends on the *Salience network* [287]. This network is important to influence the maintenance of tasks [288] in various types of contexts, such as listening to music [289], empathy and theory of mind [290], or pain [291]. The wide range of contexts in which the *Salience Network* influences human cognition suggests that it could be important in the process of context regulation.

3.5.5.2. Left DLPFC is responsible for prioritizing self-generated thoughts in low demand situations

Previous studies suggested that the DLPFC prioritizes task-relevant information in a context-dependent manner [292], monitoring internal and external signals, and emphasizing those with greater relevance to current objectives [293]. This allows us to explicitly prioritize processes like daydreaming, rather than less compelling events in the here and now. However, and although the ability to imagine different situations and places is very important [294], not adequately suppressing self-generated thoughts is also a major source of problems in various types of activities, such as at work [295], in the school [296], or while driving [297].

Taking into account these precedents, a study has recently been carried out with the final aim to find out whether the ability to prioritize personally relevant self-generated thoughts during periods of low external demand depends on a general domain neurocognitive process [298].

This study combined multiple neuroimaging methods and by conducting two experiments it was demonstrated that the left DLPFC was the region responsible for prioritizing personally relevant information in low demand situations (Figs. 3.25 and 3.26). The studies were conducted in low-demand situations in which individuals prioritize personally relevant thoughts, and two experiments were performed [299].

- Experiment 1 showed that the left DLPFC was activated and associated with off-task thinking when task demands are lower and with on-task thinking when demands are higher. It is important to highlight the activation of the parietal region of the DAN, positively associated with on-task thought in both tasks.
- Experiment 2 showed that the ability of an individual to generate off-task thoughts in the low-demand condition was related to the degree of uncoupling of the neural signals that arise from the regions of the posterior DAN (involved in external task focus), of the lateral DMN signals.

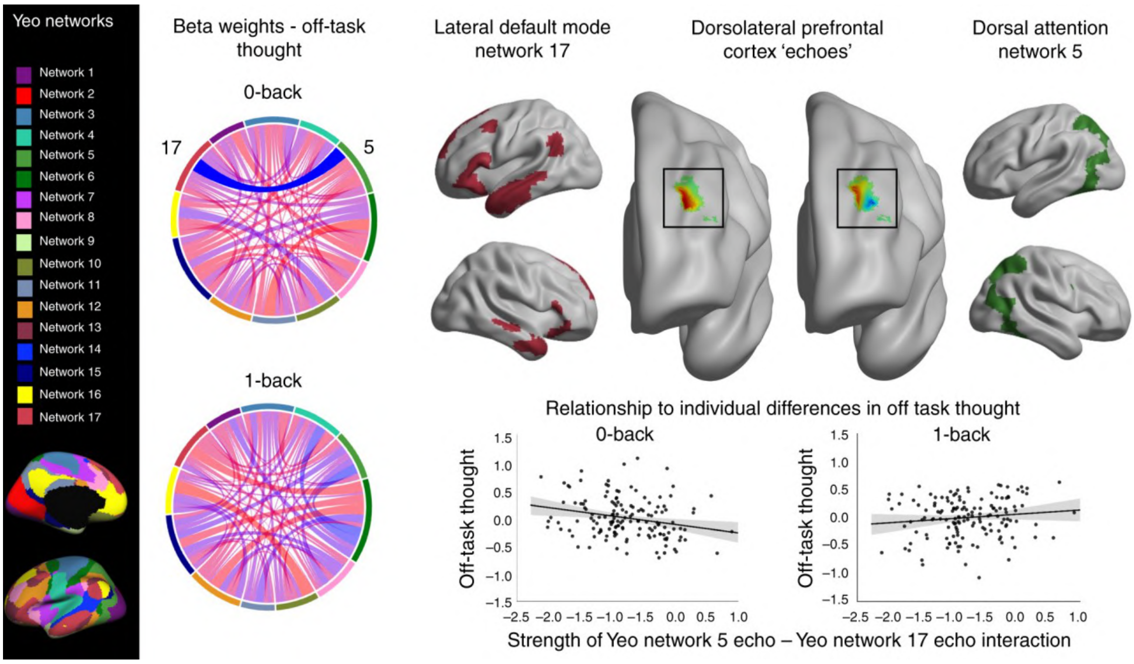

Figure 3.25. Segregation between echoes of the DAN and lateral temporal regions of the DMN relate to off-task thoughts in the 0-back condition.
(Source: Turnbull, A., Wang, H. T., Murphy, C. et al. (2019). Left dorsolateral prefrontal cortex supports context-dependent prioritisation of off-task thought. *Nature Communications*, 10, 3816)

As a result of these experiments, two important conclusions were drawn from the study:

- When off-task thinking is high, the increase in neural activity within the left DLPFC is linked to the appearance of an increase in personally relevant off-task thought
- Individuals exhibiting this ability show a greater separation of functional signals between those linked to the task (posterior DAN) and the lateral regions of the DMN.

Therefore, the study reinforces the hypothesis that the DLPFC oversees prioritizing cognition that matches the demands of a particular context.

This study also dispelled some doubts regarding whether executive control suppresses [300] or facilitates off-task thinking [301], since it demonstrated that focusing on a task, or imagining different people, times and places, depends on neural processes shared by the left DLPFC. DLPFC helps prioritize off-task thinking by reducing processing of task-relevant signals [302]. This is further supported by the fact that DLPFC lesions prevent patients from ignoring external sensory input [303]. Therefore, this study suggests that DLPFC may contribute to the decoupling of attention from external sensory stimuli, which is necessary for efficient processing of self-generated information [304] and is a fundamental mechanism that enables the enormous potential of the human creativity.

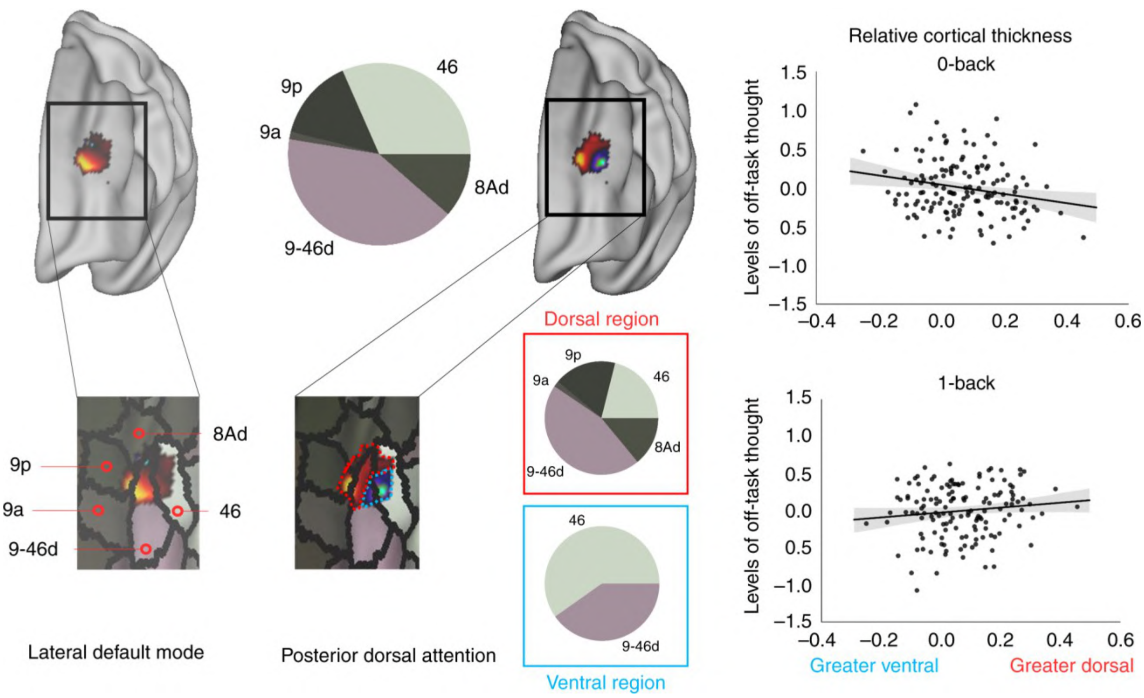

Figure 3.26. The structure of the left DLPFC supports individual differences in prioritizing off-task thoughts.
(Source: Turnbull, A., Wang, H. T., Murphy, C. et al. (2019). Left dorsolateral prefrontal cortex supports context-dependent prioritisation of off-task thought. *Nature Communications*, 10, 3816)

The study also showed that while the left DLPFC oversees the process through which off-task thought is prioritized in a context-appropriate way, the DMN is in charge of detailing the thinking experience [305]. In fact, and although previous studies had already shown that the DMN is involved in the level of detail in the current thinking patterns [306], this study shows that the DMN is involved in defining the characteristics of how a personal experience is represented, including its subjective detail.

3.5.6. *Triple network model* and its relationship with diseases

As mentioned in previous sections, many large-scale ICN networks have been identified in the human brain, but three of them are especially important in higher cognitive function in general, and especially in the creative process. Therefore, they are often referred to as "core" neurocognitive networks, and usually is also called as *triple network model*. These networks are the *Executive control network* (ECN), the *Default mode network* (DMN), and the *Salience network* (SN) [307] (Fig. 3.27).

ECN and SN usually increase their activity in cognitive tasks driven by external stimuli. The DMN decreases its activity during tasks in which it is not necessary to make use of self-referential memory and independent of external stimuli, instead it increases its activity in the absence of external tasks, or in tasks in which it is necessary to make use of self-referential memory [308].

The *triple network model* proposes that these three central neurocognitive networks have a joint and coordinated participation and are fundamental for higher cognition, and as a consequence their activation and participation abnormalities are very important in many psychiatric and neurological disorders (Fig. 3.28).

The basic characteristics of these three networks are briefly summarized below, as well as their relationship to certain cognitive dysfunctions in psychopathology. The knowledge of these dysfunctions provides additional knowledge about the functionality of these three fundamental networks, as well as their relationship with the great human creative capacity.

Psychopathologies associated with the Executive control network (ECN)

The ECN is mainly centered in the frontoparietal area (for this reason it is often called as *frontoparietal network*), and specifically it is anchored in the dlPFC and the lateral PPC [309].

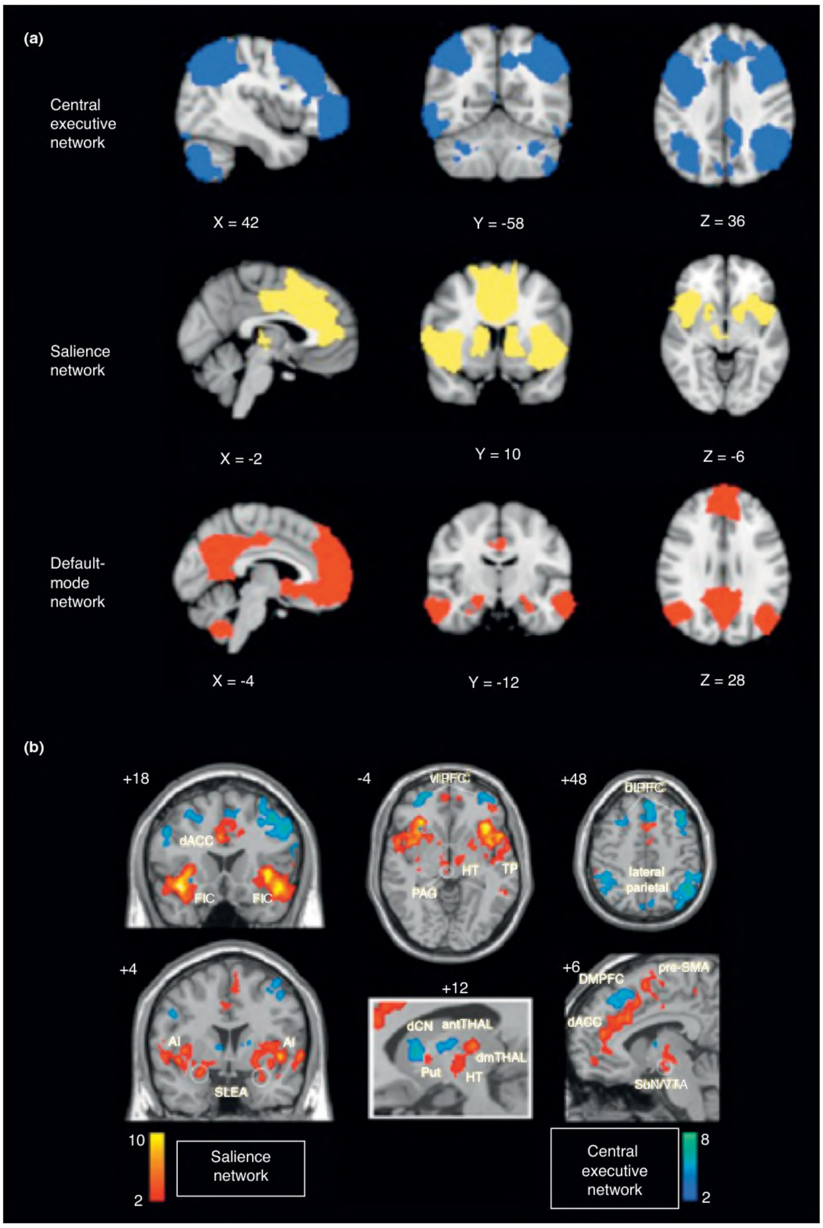

Figure 3.27. Triple network model. Three core large-scale networks.
A. The ECN, SN and DMN. The frontoparietal ECN anchored in the dlPFC and the PPC, is involved in working memory and attention tasks. The SN is anchored in the FIC and dorsal dACC and features extensive connectivity with subcortical and limbic structures involved in reward and motivation. The SN is involved in the detection of salient external inputs and internal brain events. The DMN is anchored in the PCC and medial PFC and is important for self-referential mental activity.
B. The ECN and SN are both coactivated during a wide range of cognitive tasks but have distinct patterns of intrinsic cortical connectivity in the dorsomedial prefrontal cortex (DMPFC) dACC, dlPFC, vlPFC and lateral parietal cortex and subcortical connectivity in the anterior thalamus (antTHAL), dorsal caudate nucleus (dCN), dorsomedial thalamus (dmTHAL), hypothalamus (HT), periaqueductal gray (PAG), putamen (Put), sublenticular extended amygdala (SLEA), SuN / VTA and the temporal pole (TP)
(Source: Menon, V. (2011). Large-scale brain networks and psychopathology: a unifying triple network model. *Trends in Cognitive Sciences*, 15 (10), 483-506)

ECN nodes that show strong intrinsic functional coupling also show strong coactivation when performing various types of cognitive tasks, such as manipulating information in working memory, rule-based problem solving, and decision-making aimed at achieving certain objectives [310].

Some psychiatric disorders are associated with certain deficiencies in ECN [311]. For example, working memory deficits in patients with schizophrenia have been focused on the dlPFC and PPC regions, which are part of the ECN [312]. ECN disruption is generally associated with all major psychiatric and neurological disorders, such as depression, Alzheimer's, frontotemporal dementia, schizophrenia [313], and autism. All these studies have focused on activation deficits in the dlPFC and PPC regions, and not from a network perspective, that is, the connectivity deficits of the entire ECN have not been studied.

Psychopathologies associated with the Default mode network (DMN)

DMN is usually deactivated when performing cognitive tasks as a consequence of external stimuli [314]. It is anchored in the PCC and mPFC and includes nodes in the medial temporal lobe (MTL) and the angular gyrus (AG).

The DMN is involved in various types of functions. The PCC, hippocampus, and AG are involved with retrieval episodic memory [315], autobiographical memory [316], and semantic memory related to internal thinking [317]. On the other hand, mPFC nodes are involved with self-related and social cognitive processes [318], value-based decision making [319] and emotion regulation [320].

Intrinsic functional connectivity abnormalities within the DMN are associated with all major psychiatric disorders, including dementia, schizophrenia, epilepsy, anxiety, depression, autism and the ADHD attention-deficit/hyperactivity disorder [321].

Psychopathologies associated with the Salience network (SN)

The SN is involved in detecting, integrating, and filtering autonomous and emotional information [322]. It is anchored in the dorsal anterior cingulate (dACC) and the frontoinsular cortex (FIC).

The SN, and specifically the AI, is a comprehensive center for managing dynamic interactions between other large-scale networks involved in externally oriented care and self-related processes. Furthermore, SN plays an important role in dynamic cognitive control and saliency detection [323]. The triple network model is based on the correct functioning of the SN, and in particular the AI, to perform a correct switching of networks, activating the ECN when relevant external stimuli are detected, and deactivating the DMN. When the AI detects a salient stimulus, it facilitates the processing of the task-related information by initiating the appropriate transient control signals. These signals involve areas of the brain that mediate attention, working memory, and higher-order cognitive processes, and at the same time deactivates the DMN.

The first type of neurological disorder observed is generated because of an abnormality in the normal functioning of the SN, making an inappropriate assignment of saliency to external stimuli or internal mental events [324].

The deficiencies in the functioning of the SN may be the following:

- Upstream faulty detection of salient events
- Defective interaction of the anterior and posterior insula to modulate reactivity to salient stimuli
- Sending of aberrant control signals to other large-scale brain networks
- Damaged functional coupling with the ACC that facilitates access to the motor system

Recent studies show that AI must have the correct activity to generate the proper warning signals to initiate brain responses to salient stimuli, but in the case of anxiety the AI can be hyperactive and send too many signals, and in the case of autism it can be little active and send few signals [325]. In other words, in the case of anxiety, too much attention is paid to socially relevant signals, while in autism little attention is paid to relevant signals.

The triple network model predicts that dysfunction in one core network may affect the other two networks, with clinical manifestations that may transcend the primary deficit. Therefore, a dysfunction of the SN can cause dysfunctions in the other two core networks. For example, in the case of patients with chronic pain (associated with a dysfunction of the SN, they also suffer from depression, anxiety and alterations in decision-making, which are due to abnormalities in the functioning of the DMN [326].

Similarly, a deficiency in DMN activity has been observed in depressed patients [327]. This deficiency is due to the inability to free oneself in the management of internal mental processes to attend to salient task-relevant external stimuli, as observed in depression [328]. An extreme case is schizophrenia patients, in whom structural and functional deficits have been observed in the three central networks [329].

Within the triple network model, in addition to the previous insula AI and the fronto insular cortex FIC, there are two other regions especially associated with psychological dysfunctions: the amygdala (which plays a fundamental role in the detection of biologically important affective signals such as fear), and the nucleus accumbens/ventral tegmental area (which is important for reward prediction).

3.6. Neurocognitive bases of the essential processes of creativity

The general creative process basically consists of two stages. One stage aims to create new ideas, and another stage aims to evaluate them, in order to know if they are novel and valuable [330].

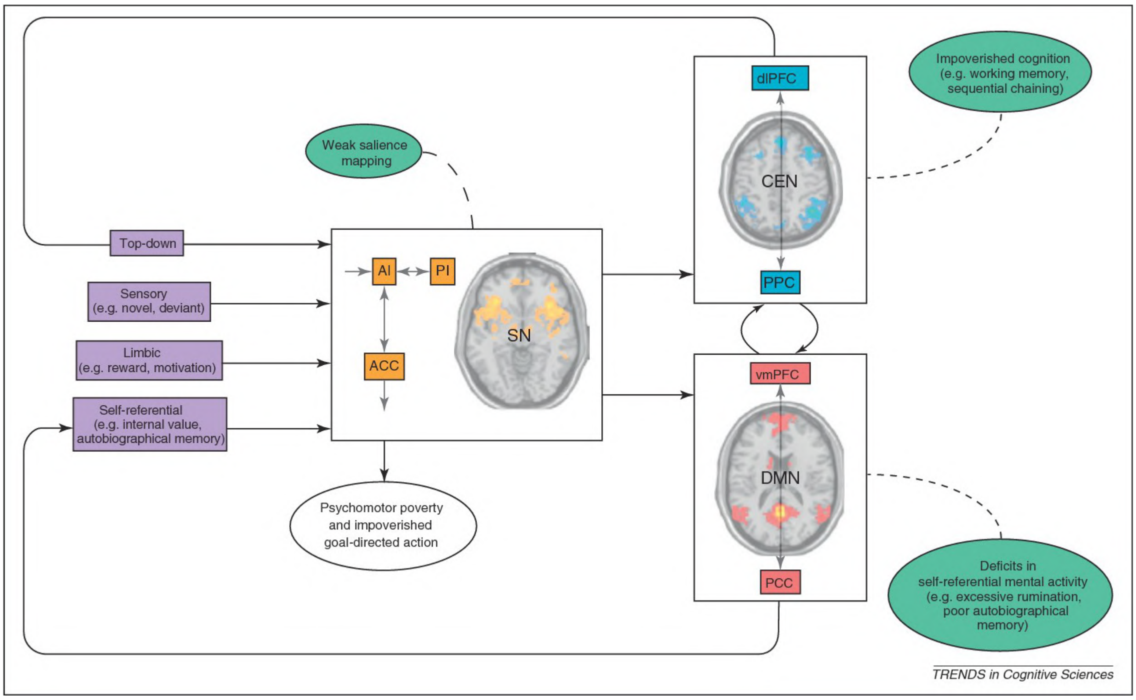

Figure 3.28. Triple network model of major psychopathology. Aberrant intrinsic organ psychiatric and neurological disorders. The model proposes that weak salience detection of goal-relevant external stimuli and internal mental events from the SN plays a major role in psychopathology.
(Source: Menon, V. (2011). Large-scale brain networks and psychopathology: a unifying triple network model. *Trends in Cognitive Sciences*, 15 (10), 483-506)

To create new ideas, the process of human imagination is fundamental, in which one can create objects, entities or events that do not exist, but that could exist in the future. To create new objects, entities or non-existent events, it is essential to be able to mix the information that one has about existing objects, entities or events, in order to alter their characteristics, or intermix them with each other. Therefore, the semantic representation that can be made of them is important.

Once certain objects, entities or events have been created, it is necessary to evaluate them properly. This evaluation can be of various types, from a general objective evaluation to a very intimate and personal evaluation. Finally, there is a process of self-evaluation of the ideas generated based on their contemplation, in order to check the relevance of the work that is being performed, and its ability to move.

In this section, the neurocognitive bases of these essential processes of creativity are studied in detail.

3.6.1. Neurocognitive bases of imagination and future planning

Creativity involves the future creation of something that does not yet exist. Therefore, in the creative process, although in a blurred and ambiguous way, future plans must be made, in the same way as people project their personal goals. When imaging and planning for the future, two different processes must be carried out [331]:

- *Process simulation*

  The *process simulation* is the process of visualizing the steps that must be taken to obtain a certain goal

- *Outcome simulation*

  The *outcome simulation* is the process of visualizing the effects that are obtained once a certain goal has been reached

As is known, creative activity is very complex, and it is the result of several different processes. One of these processes consists in the visualization of the steps to follow, and in the visualization of the achievements that are intended to be achieved [332].

On the one hand, the necessary steps that must be carried out to achieve a certain objective must be visualized, and on the other hand, the desired result must be visualized, to experience the pleasure of the possible associated rewards (recognition, personal achievement, money, etc.).

For example, imagine that you want to make a completely new sculpture. Within the creative process, the two mentioned processes must necessarily be considered. On the one hand, the stages to be carried out must be visualized. You must visualize what material to use and how to get it; sketches should be made on paper showing different points of view of the final 3D shape (initially poorly defined and incrementally detailed during the creative process); it must be visualized where to start the sculpture and how to continue; it must be visualized what to do in case of possible incidents. In addition, in each of these stages the desired objective must be visualized. At the beginning of the process, the visualizations will necessarily be fuzzy and poorly defined, but throughout the creative process, the visualizations will be more and more defined. On the other hand, the objectives to be achieved must be visualized, seeking the pleasure that being able to achieve it implies. In each stage, the result of what is being achieved must be compared with the visualizations of desired results…. If they both resemble, the creator feels pleasure and continues on that path. On the other hand, if what is being achieved distances from what is visualized and desired, the creator does not obtain pleasure, feels uneasiness, and is forced to look for another way (hoping to obtain pleasure as a result of having achieved something similar to what is visualized) [333].

Therefore, it is convenient to study the neurocognitive bases of process simulation, and outcome simulation, in order to improve human creative capacity, and to be able to design an artificial computational system that emulates human creative capacity.

3.6.1.1. Process simulation and outcome simulation

Process simulation and outcome simulation have been extensively analyzed and have completely different effects [334].

a. *Process simulation*.

In a recent study [335] it was seen that when students visualize the steps they must take to finish a project, or to obtain a good grade (*process simulation*), they were much more successful than when they visualized themselves once the goal was reached (*outcome simulation*). Students who visualized the process to obtain a goal began to be more orderly, they began to study earlier, they spent more hours studying, and they were less anxious, and consequently they obtained better grades on exams and on assignments.

This type of study has been repeated in different situations, and the same results have always been obtained, the *process simulation* is more effective than the *outcome simulation* in order to achieve a specific objective [336].

b. Outcome simulation

The simulation of desired future outcomes allow for the visualization of the desired future goals, and therefore allow to experience beforehand the affective impact of those goals, and the value of the reward [337]. This characteristic of outcome simulations has been shown to decrease *temporal discounting*, which is the tendency not to expect future rewards, and instead desire immediate rewards [338]. When people envision future events associated with rewards, they tend to outgrow *temporal discounting*, and are more willing to expect a delayed but greater reward. It has also been shown that imagining future personal events favors their achievement [339].

3.6.1.2. Neurocognitive bases of process simulation and outcome simulation

Some neuroimaging studies of episodic *process simulations* of future events have been performed [340], it has been seen that the DMN is part of a functional network together with regions of the ECN, as in the case of the dorsolateral prefrontal cortex (dlPFC) [341]. In another study, several people were analyzed as they imagined the steps necessary to achieve their goals in life, and it was observed that the DMN is coupled with the *frontoparietal control network* (ECN) (which includes the rostrolateral prefrontal cortex (rlPFC), medial frontal gyrus (MFG), anterior insula / frontal operculum (AI/FO), dorsal anterior cingulate cortex (daCC), precuneus (PCu) and anteroinferior parietal lobe (aIPL)) [342].

On the other hand, some studies related to *outcome simulations*, have also been carried out. First, it has been observed that the vmPFC (a region of the DMN) is linked to self-referential processing [343], and for this reason collaborates directly in the simulation of *future outcomes*. Other studies have linked the rostral mPFC in the ability to experience the imagined and desired future outcomes, especially if they are associated with some type of reward [344]. In the affective and reward system, in addition to the mPFC, several brain regions are included, such as the nucleus accumbens (NAcc), the amygdala, the anterior cingulate cortex (ACC), the insula (I), and the thalamus [345].

Based on these previous investigations, an fMRI study of the activation patterns for *process simulations* was recently carried out in which the participants had to visualize the steps they had to take to achieve a certain objective (put them into a coherent sequence and imaging themselves going through these steps, keeping in mind the goal), and for *outcome simulations*, during which the participants had to imagine a set of events and rewards as a consequence of having achieved this goal [346].

The results of the study showed that during *process simulations* the seed nodes of the ECN and DMN (pCC, aIPL and dlPFC) behave as a network and are connected to a distributed network of regions included in the ECN and the DMN (including MFG, IFG, rlPFC, PCu and PHG) (Fig. 3.29). These studies reinforce the evidence that ECN and DMN are coactive during goal-directed simulations that require cognitive control [347].

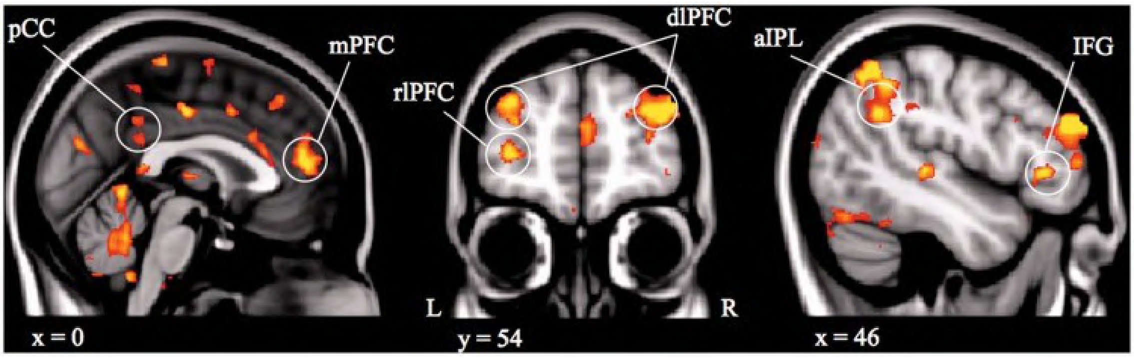

Figure 3.29. Regions activated in the seed PLS analyses of *process simulations*.
(Source: Gerlach, K. D., Spreng, R. N., Madore, K. P., & Schacter, D. L. (2014). Future planning: default network activity couples with frontoparietal control network and reward-processing regions during process and outcome simulations. *Social Cognitive and Affective Neuroscience*, 9(12), 1942-1951).

These results fit with the previous hypothesis that ECN regulates the activity of DMN and DAN (dorsal attention network), and that it is activated by external sensorial stimuli [348]. Based on the obtained results, it can be speculated that the ECN could control the DMN, protecting it from distracting external stimuli and supporting the creation of the simulation of complex internal plans.

On the other hand, the results of the study showed that during *outcome simulations* activity is increased in the mPFC (a main node of the DMN) [349], and the amygdala (related with emotion processing) [350] (Fig. 3.30). The mPFC is activated in response to self-referential processing [351], which includes thoughts about personal future goals [352].

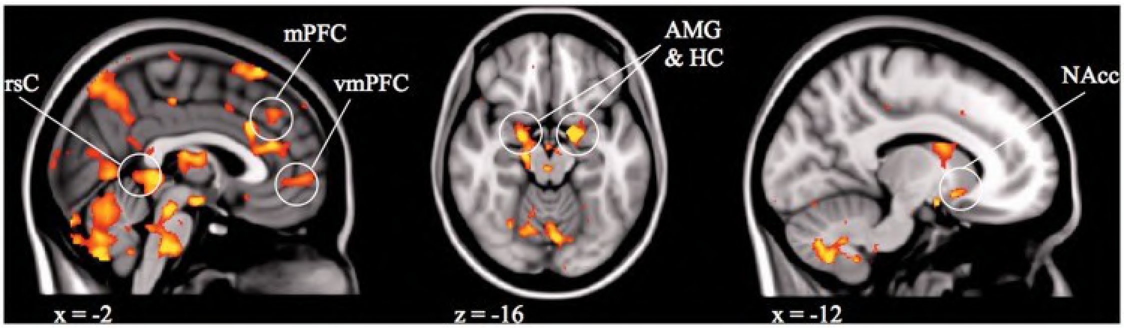

Figure 3.30. Regions activated in the seed PLS analyses of *outcome simulations*.
(Source: Gerlach, K. D., Spreng, R. N., Madore, K. P., & Schacter, D. L. (2014). Future planning: default network activity couples with frontoparietal control network and reward-processing regions during process and outcome simulations. *Social Cognitive and Affective Neuroscience*, 9(12), 1942-1951).

MPFC activity is significantly correlated with bilateral amygdala activity during *outcome simulations*, and the three seed regions (pCC, aIPL, and dlPFC) are also connected to a distributed network that integrates other regions of the DMN (e.g., vmPFC, HC, rsC) and regions involved in anticipating and evaluating rewards and outcomes (including ACC, NAcc, MFG, caudate, and medial thalamus) [353]. The activation of the mPFC is related to the imagination of positive events and goals that, in turn, promote positive actions [354], and to the evaluation of possible rewards and outcomes [355].

Other regions of this functional network, such as the ACC, the amygdala, and the hippocampus, can be activated when participants imagine possible rewards, thereby reducing the *reward delay discounting* [356]. It is also known that vmPFC is involved in anticipating future consequences and deciding the objectives to be reached [357], which is aligned with its recruitment during outcome simulations.

Therefore, the DMN and the regions of the *reward system* can be activated together in order to generate simulations of the desired future outcomes, which facilitates decision-making on future goals.

Finally, it should be noted that several behavioral studies of *process simulations* and *outcome simulations* have suggested that both types of simulations can help us achieve our goals, although they do so in different ways [358]. *Process simulations* can help us make plans to achieve certain goals by establishing the exact steps necessary to achieve them. On the other hand, *outcome simulations* can help us choose beneficial long-term goals, such as the ability to make future decisions in the context of *temporal discounting* [359] is extended to the choice of personal goals.

3.6.2. Neurocognitive bases of *idea generation* and *evaluation process*

A large number of methodological and psychological studies have suggested that the creative process, although very complex and includes an enormous amount of details, generally consist of two basic components [360]:

a. Idea generation process
b. Idea evaluation process

In the same way, when artists and creatives define their own creative process, they always refer to two general processes [361]:

- Recurring sequential process based on the realization of approximate sketches of their ideas and
- Process of criticism of those ideas to refine the next cycle of evaluation and test

Therefore, and among many other components, the creative process seems to have a double process of trial and error, and innumerable methods have been proposed to improve its effectiveness throughout history. However, it has recently been proposed that understanding the neurocognitive process of human creativity could improve its efficacy. For this reason, studies have recently begun to identify the networks and regions involved in the creative process.

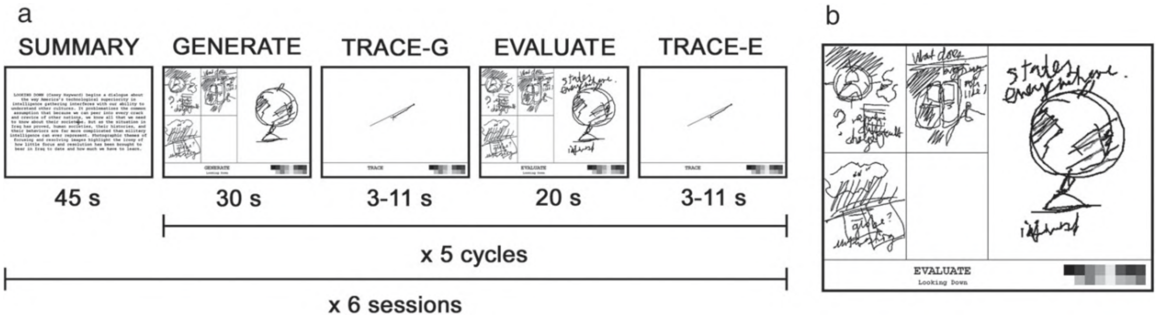

Figure 3.31. a. Schematic of experimental paradigm. b. Screenshot of an evaluate trial.
(Source: Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage*, 59(2), 1783-94)

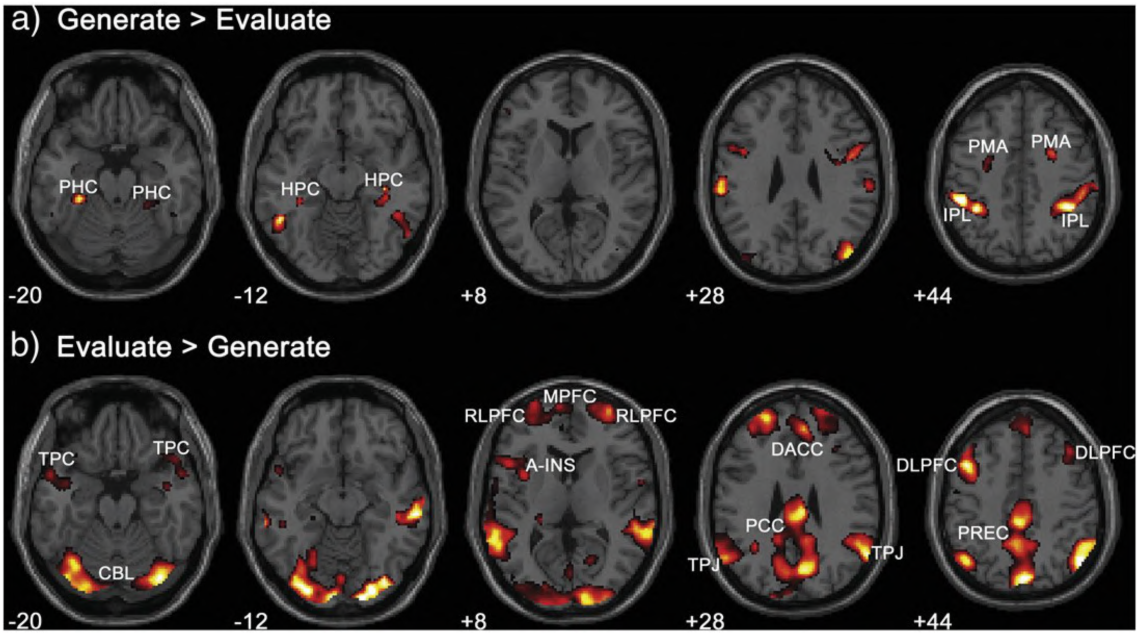

Figure 3.32. Brain maps for creative generation and evaluation processes.
a. Idea generation is associated with activation of the hippocampus (HPC) and parahippocampus (PHC) in the medial temporal lobe, as well as the inferior parietal lobule (IPL) and premotor area (PMA). Activations were also observed in the left inferior frontal gyrus (IFG), bilateral superior parietal lobule (SPL), bilateral fusiform gyrus, bilateral middle temporal gyrus (MTG), and left cerebellum.
b. Idea evaluation is associated with activation of the ECN (DLPFC and dACC) and DMN (MPFC, PCC/precuneus, and TPJ), as well as the RLPFC, cerebellum (CBL), temporopolar cortex (TPC), and left anterior insula (A-INS). Activations were also observed in the supplementary motor area, bilateral IFG, bilateral SPL, bilateral MTG, bilateral lingual gyrus, bilateral middle occipital gyrus, and bilateral cuneus.
(Source: Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage*, 59(2), 1783-94)

In order to identify which specific regions are activated differentially both in the process of generating ideas and the process of evaluating ideas, a recent study has been carried out [362] (Fig. 3.31).

The study consisted of analyzing the brain activity of 15 people, with fMRI, while they made creative designs using a drawing tablet. This study therefore used an approach closer to the real activity of designers and creatives, since in previous similar studies the participants were only asked to imagine their creative designs [363].

3.6.2.1. Brain regions involved in the idea generation process

In the idea generation process, an increase in MTL activity was detected (Fig. 3.32, Table 3.2), specifically in the hippocampus and parahippocampus.

In the process of generating ideas, greater activity was also detected in the bilateral inferior parietal lobe (IPL), in the premotor area (PMA), in the superior parietal lobe (SPL), in the left inferior frontal gyrus (IFG), in the middle temporal gyrus (MTG), in the fusiform gyrus, and in the left cerebellum.

Region	*MNI coordinates*						
	L/R/M	*BA*	*x*	*y*	*z*	*Voxels*	*Z value*
Frontal							
Premotor area	L	6	−26	−2	56	271	4.30
Premotor area	R	6	28	2	52	185	4.45
Inferior frontal gyrus	L	45	−50	38	12	35	3.69
Parietal							
Superior parietal lobule	L	7	−28	−52	64	22	3.21
Superior parietal lobule	R	7	32	−48	64	32	3.01
Inferior parietal lobule	L	40	−48	−36	44	601	5.22
Inferior parietal lobule	R	40	40	−42	44	851	4.72
Temporal							
Hippocampus	L	–	−32	−40	−4	80	4.40
Hippocampus	R	–	36	−26	−12	99	3.92
Parahippocampus	L	36	−30	−34	−20	71	4.35
Parahippocampus	R	36	34	−38	−16	74	3.65
Fusiform gyrus	L	37	−50	−52	−12	64	4.28
Fusiform gyrus	R	37	40	−68	−4	161	4.42
Middle temporal gyrus	L	19	−30	−80	36	121	3.64
Middle temporal gyrus	R	19	46	−76	24	165	4.34
Subcortical							
Cerebellum	L	–	−14	−72	−48	55	3.58

All activations were significant at $p<.05$ FDR-corrected and $k>20$.

Table 3.2. Activation peaks during the creative generation process.
(Source: Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage*, 59(2), 1783-94)

3.6.2.2. Brain regions involved in the idea evaluation process

In the idea evaluation process, a greater activation was detected in the ECN, including the dACC, and the DLPFC (Fig. 3.32, Table 3.3).

Region	*MNI coordinates*						
	L/R/M	*BA*	*x*	*y*	*z*	*Voxels*	*Z value*
Frontal							
Dorsal ACC	M	24/32	8	44	28	40	3.94
Medial frontal gyrus (MPFC)	M	10	−8	64	4	88	3.27
Superior frontal gyrus (RLPFC)	L	10	−22	54	28	1170	4.19
Superior frontal gyrus (RLPFC)	R	10	32	58	16	1073	4.19
Middle frontal gyrus (DLPFC)	L	9	−44	14	44	382	4.51
Middle frontal gyrus (DLPFC)	R	9	42	26	44	183	3.20
Inferior frontal gyrus	L	47	−32	56	−4	168	3.24
Inferior frontal gyrus	R	47	22	58	0	39	3.48
Inferior frontal gyrus	R	45	48	22	0	37	2.79
Inferior frontal gyrus	L	45	−60	20	0	36	3.14
Supplementary motor area	M	6	−2	12	68	141	3.03
Parietal							
Precuneus	M	7	0	−32	44	773	4.35
Posterior cingulate cortex	M	23/31	4	−30	24	1035	4.50
Inferior parietal lobule (TPJ)	L	39/40	−68	−38	0	96	4.09
Inferior parietal lobule (TPJ)	R	39/40	66	−40	4	469	4.34
Superior parietal lobule	L	7	−44	−66	48	563	4.36
Superior parietal lobule	R	7	50	−66	44	1906	5.02
Temporal							
Temporopolar cortex	L	38	−32	6	−40	70	3.30
Temporopolar cortex	R	38	54	8	−28	287	3.60
Middle temporal gyrus	L	22	−66	−32	−8	3219	4.54
Middle temporal gyrus	R	22	56	−30	−8	739	4.68
Occipital							
Cuneus	L	19	−28	−88	−12	2720	4.76
Cuneus	R	19	24	−88	−8	12111	5.23
Middle occipital Gyrus	L	18	−22	−94	24	705	3.88
Middle occipital Gyrus	R	18	18	−94	−8	39	5.06
Lingual gyrus	L	17	−8	−94	−12	752	4.48
Lingual gyrus	R	17	14	−92	4	124	4.40
Subcortical							
Anterior insula	L	–	−36	6	8	215	3.46
Cerebellum	L	–	−34	−84	−12	39	4.58
Cerebellum	R	–	36	−80	−16	355	4.66

All activations were significant at $p<.05$ FDR-corrected and $k>20$.

Table 3.3. Activation peaks during the creative evaluation process.
(Source: Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage*, 59(2), 1783-94)

In the process of evaluating ideas, a greater activity was also detected in the DMN, including the MPFC, the TPJ, PCC/precuneus, the rostro-lateral PFC (rlPFC), the temporopolar cortex, the cerebellum, and the left anterior insula. Increased activity was also detected in IFG, supplementary motor area, SPL, MTG, lingual gyrus, median occipital gyrus, and cuneus.

Therefore, this study reinforced the hypothesis that the MTL is especially involved in the generation of creative ideas, and instead the DMN and the ECN are involved in the evaluation of creative ideas.

3.6.2.3. Neurocognitive process of idea generation during creative thinking

Previous studies linked MTL with general memory processing, and specifically with the spontaneous reactivation of memory [364]. Likewise, it has been observed that MTL is related to spontaneous mental processing in resting conditions [365]. In addition, the MTL has a constructive-associative function that allows you to create thoughts and generate new ideas.

This set of properties suggests that the MTL may be more active during the formation and recovery of semantic associations, especially in the parahippocampus [366]. Although the MTL is activated both in the processing of past events and in the processing of future events [367], it has a greater activation in the simulation of future events, especially in the hippocampus [368], which clearly suggests that MTL is involved in the generation of visualizations of novel ideas or images. In fact, imagining novel and/or fictional scenes has been shown to activate the same regions of the MTL as simulating future events [369]. MTL is also involved with the creation of mental simulations, which in turn are the basis of theory of mind and spatial navigation tasks [370]. On the other hand, the parahippocampus is capable of creating new associations (or accessing old associations) that the hippocampus soon afterwards mixes with other information to build episodic simulations [371].

According to these studies, it can be concluded that the MTL carries out an associative process of ideas (of various types and with different levels of abstraction) in order to generate new ideas, and to restructure previous ideas [372], which is consistent with an agreed psychological description of the creative process [373]. Additionally, there are several studies that involve the PFC with the generation of creative ideas [374], with the resolution of insufficiently specified, or poorly structured, problems [375], and with the resolution of well-defined and structured problems [376].

3.6.2.4. Neurocognitive process of analytical evaluation of ideas during creative thinking

Analytical evaluative processing usually involves the ECN, the cerebellum, and the RLPFC.

ECN is frequently related to cognitive control functions [377]. Therefore, the fact that the process of evaluating ideas activates the ECN implies the need to perform a top-down control in creative evaluation, which suggests that a commitment to a high level of cognitive control that can facilitate an analytical processing.

The evaluative process activates the dACC (region of the ECN) that is usually involved in processes of attention focusing, and attention shifting and error detection. These functions of the dACC essentially form the basis for a more general conflict monitoring and detection process that signals the need for greater cognitive control [378] (Fig. 3.33).

In this sense, the DLPFC (another region of the ECN involved in the evaluative process) can perform the necessary cognitive control [379] to select the most appropriate solution [380] based on their integration and assessment of the relevance of the dACC entries, other prefrontal areas, memory regions, and association cortices [381].

Analytical evaluation processes activate different combinations of regions within the ECN. In previous studies, these networks have been named differently, although they are all part of the ECN.

For example, the lateral PFC, the dACC and the lower parietal lobe (IPL) make up a frontoparietal control subnetwork, which integrates information from two opposing systems and regulates their activity (one system process external information and the other stores internal representations) [382].

DLPFC and IPL also form an executive control subnetwork that directs attention and control processing in the posterior sensorimotor regions [383].

The DLPFC, IPL and precuneus create another control subnetwork that performs the top-down control [384] together with a cingulo-opercular network that maintains the objectives of the task [385].

The cerebellum is also habitually activated during creative evaluation. The cerebellum can mediate the activity of dlPFC and IPL and optimize performance by transmitting error-related information [386]. Therefore, the current results clearly suggest that analytical processing (analytical evaluation) is an essential part of creative evaluation.

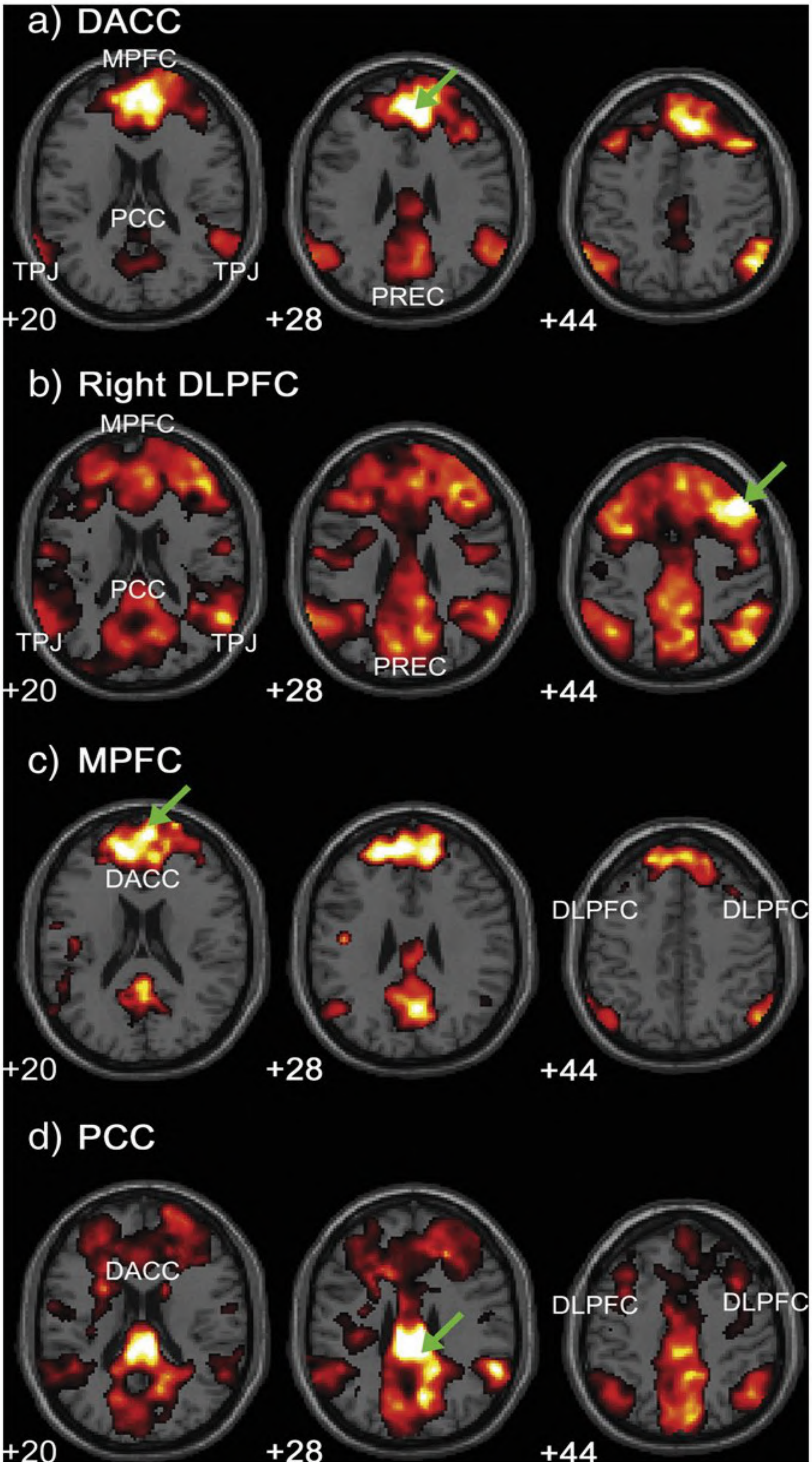

Figure 3.33. Functional connectivity maps of ECN and DMN regions during task performance. Activity in the ECN, including the (a) dACC and (b) right DLPFC, was highly correlated with activity in DMN regions, such as the MPFC, PCC/precuneus, and bilateral TPJ.
(Source: Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage*, 59(2), 1783-94)

The analytical evaluation process of the creative process also involves the rostro-lateral PFC (rlPFC), although it does not belong to the ECN network. Recent studies show that the rlPFC performs a higher order meta-cognitive function that allows evaluating and integrating the results of previous stages of cognitive processing [387]. Therefore, the activation of the rlPFC during the creative evaluation process enables a metacognitive evaluative processing of the design process. This metacognitive function includes judgments regarding progress toward the goal, as well as the appropriateness of the final creative result.

The RLPFC is activated during metacognitive processing in various domains, such as complex reasoning [388], spontaneous thinking [389], complex reward processing [390], multitasking activity [391], moral decision making [392] and memory retrieval [393].

3.6.2.5. Neurocognitive process of affective and visceroceptive evaluation of ideas during creative thinking

The evaluation process of the design process has a visceroceptive component, since it also involves the DMN. The DMN integrates sensory information and processes it taking into account very personal and intimate information (usually called “visceral information”) to make decisions [394].

In addition to being activated when tasks are not being performed, the DMN is also activated in various visceroceptive and affective evaluative processes, such as the evaluation of the emotional reactions of oneself and of others [395] and the attribution of the emotional mental state of others [396]. A region of the DMN, the MPFC, is involved in the evaluation of internally generated affective information [397] (Fig. 3.33).

Based on recent studies, it has been proposed that the DMN has a general functionality that corresponds to the evaluative processing of internally generated affective information [398]. It is an inferential processing of information retrieved from memory (knowledge rules) and integrated with external sensory information [399].

The integration of information can be carried out in the TPJ since it is one of the association areas of the brain, which processes information from multiple sensory and limbic areas [400].

Another region of the DMN, the PCC/precuneus can also integrate the information of the association cortices (TPJ) and memory regions (MTL), and can also serve as an interface between the MPFC and TPJ to represent the relevant information generated internally [401]. The MPFC can make inductive inferences based on internal affective information in order to infer conclusions that guide behavior.

Finally, in the creative evaluation process, the temporopolar cortex (TPC) and the anterior insula (AI) are also activated, integrating highly processed sensory information with interoceptive-autonomous information. The anterior insula (AI) is part of the *Salience network* (SN) [402], and processes detailed representations of transitory internal states (visceral or emotional) [403]. Finally, the temporopolar cortex (TPC) can combine complex perceptual information with visceral emotional information from the anterior insula and amygdala [404].

Therefore, the fact that the DMN and the *Salience network* are activated implies that the evaluation process has a “visceral” component. In fact, creative people claim that when they create, they continually pay attention to their "gut reactions" [405]. In short, the DMN and the SN jointly provide an “affective and visceroceptive evaluation process” during the creative process.

3.6.2.6. Coactivation of ECN and DMN in the creative process

The evaluation of the creative process activates the ECN and the DMN. Although it is possible that different networks are activated at different times during the evaluation process, functional connectivity analysis suggest that the two networks are not completely independent.

At the beginning of research on large-scale networks, it was thought that the DMN and the ECN were activated in the opposite way, so it was thought that the DMN (task-negative network) is deactivated when the ECN (task-positive network) is activated, and vice versa [406].

However, more recent studies have shown that both networks are activated jointly by performing various activities such as autobiographical planning [407], movie viewing [408], mind wandering [409], or narrative speech comprehension [410].

Similarly, recent studies on the neurocognitive bases of creativity have shown that certain regions of the DMN and the ECN are activated together, such as the ACC, the PCC/precuneus and the TPJ during the resolution of problems [411] and DLPFC, ACC, PCC/precuneus, and TPJ during a fluent analogy task [412].

Therefore, the creative *evaluation process* within the design process can allow the combination and integration of cognitive and affective evaluation processes, as well as deliberate and spontaneous types of evaluative thinking. Thus, creative evaluation can be an expanded and more effective type of analytical evaluation and is capable of linking processes that usually do not work together.

3.6.3. Neurocognitive bases of creative “inner self evaluation”

Throughout the creative activity, a double process is always generated.

a. On the one hand, and as seen in the previous section, a generation-and-test process is generated, in which certain solutions are proposed and after they are evaluated.

b. At the same time, a closely related, but different, feedback process is generated between the entity that is being created (in its different evolutionary stages), and the author's expectations.

This process becomes even more complicated when the entity to be created has a visual component. In this case, the contemplation of the result is important for its proper evaluation, but it also has a much higher purpose, because in the contemplation a kind of "coupling" or emotional "resonance" is sought between the author and the creative artwork that is being made (in any of its stages, but especially in the later ones). This emotional "coupling" between the artwork and the author is essential, as it will probably also occur when other people contemplate it.

In general, the contemplation of a certain visual artwork can generate certain psychological and emotional reactions in some people, but not in others. Certain artworks may seem very emotive to some people, while they may seem indifferent to others. This means that there must be some kind of "resonance", or "coupling", between a certain visual creative artwork, and some people. This phenomenon also occurs throughout the creative design process with a great visual component. Contemplating the result of each stage throughout the creative process must provide the necessary "resonance" (a kind of emotional "coupling") between the work and the author, so that the creative process goes one way or another, regardless of the evaluation process that runs in parallel (therefore this type of "coupling" could be seen as a kind of emotional evaluation).

It is therefore necessary to know the neurocognitive mechanisms of this “resonance” phenomenon, in order to better understand the effects of the contemplation of works of art, and consequently to improve the creative process.

In this sense, a study has recently been carried out in which this "resonance" activity in the visualization of works of art has been associated with the activity of the DMN [413] (Fig. 3.34).

3.6.3.1. The DMN and self-referential mental processing

Until very recently it was believed that the DMN represented a "task-negative" network that usually activated in an anticorrelated manner from "task-positive" networks such as the sensory-semantic pathways, the *Executive control network* (ECN) and the dorsal attention network (DAN) [414]. However, recent studies have shown that DMN is also activated when certain tasks are performed [415].

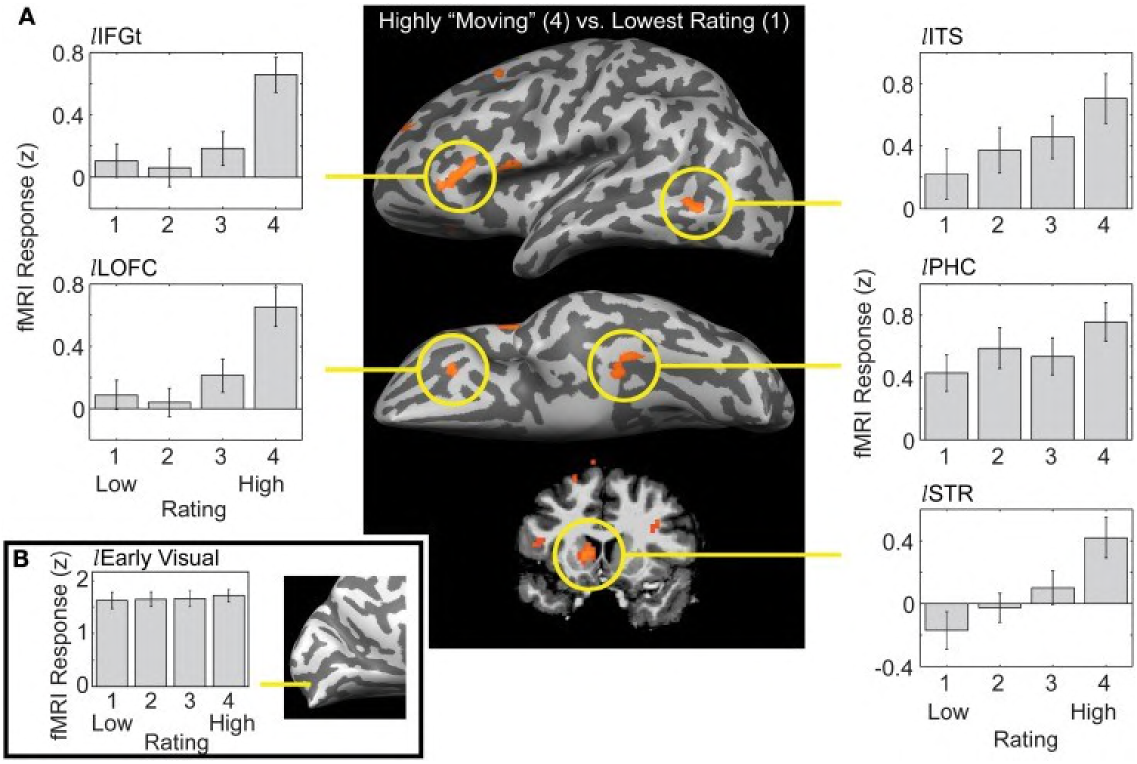

Figure 3.34. Distinct patterns of response to artworks as a function of their ratings in a distributed network of brain regions.
A. Center. Brain analysis contrasting trials on which observers rated artworks as highly moving
Right-side. Linear increase with rating was observed for the activation loci in occipitotemporal cortex and some subcortical loci
Left-side. Nonlinear, step -like response pattern was observed in the previous activation loci. Responses did not differ for images rated 1, 2, or 3, but were significantly elevated for images rated 4
B. Extensive portions of early visual cortex were strongly activated by all paintings, but the magnitude of fMRI response did not differ by rating.
(Source: Vessel, E. A., Starr, G. G., & Rubin, N. (2013). Art reaches within: aesthetic experience, the self and the default mode network. *Frontiers in neuroscience*, 7, 258)

In this study on aesthetic impact, it was also found that DMN is activated under certain circumstances. It was found that when images considered as unimportant for the observer (rated 1, 2 and 3, out of 4) were viewed, the DMN remained deactivated (Fig.

3.35). On the other hand, when images that were considered very important and suggestive for the observer (rated as 4 out of 4) were contemplated, an important activation of the DMN regions was observed, and a complete activation of the MPFC (Fig. 3.35). Initially this seems confusing and requires a detailed analysis.

Recent studies have shown that the DMN (specifically the ventral MPFC) is activated in affective decision-making processes, which include the evaluation of the emotional salience of external stimuli, and the evaluation of the value of future rewards [416].

In the same way, the anterior and dorsal areas of MPFC are activated when making self-relevant moral decisions [417], when performing tasks that involve self-knowledge, such as making judgments about oneself (or relatives and friends), and when performing theory of mind tasks, which require evaluating the way others see life [418]. It has also been observed that the posterior cingulate cortex (PCC) and the medial temporal lobe (MTL) regions are activated when performing tasks that involve retrieving autobiographical memories, and when planning, or simulating, the future [419].

Because of this evidence, it can be said that DMN is especially involved in self-referential mental processing [420]. This process usually occurs in our daily lives, and this can happen spontaneously (for example, in the type of mind wandering during periods of rest), or in response to certain external stimuli that force us to use certain self-referential information, related to the self (both automatically and intentionally). And perhaps this is the process that occurs when strongly moving artworks are observed.

3.6.3.2. Intense aesthetic experience. *Poiesis*, *aisthesis* and *catharsis*

The impact of the contemplation of artworks varies for each person, and sometimes it is a strongly moving, pleasant and intimate experience. Many people actually claim that their artistic preferences are part of their inner self, or their own identity. Whether it's musical themes, symbols, paintings, novels, or movies, people feel strongly involved with certain artworks. In fact, they show it in their social media profile, they get tattoos, they put posters in their room, and they usually reference them when they try to define their personality.

In general, certain artwork can provide three types of moving and pleasant experiences to the people who contemplate them [421]:

Poiesis. It is the moving and pleasant experience provided by the contemplation of certain works of art made by oneself.

Aisthesis. It is the moving and pleasant experience that the contemplation of certain works of art made by other people provides.

Catharsis. It is the emotional and deeply pleasant experience, derived from the aesthetic contemplation (usually of artworks made by others), and which is capable of leading us to a change in convictions, or to the liberation of the mind.

The most deeply moving experience is the *catharsis*, which although it is rare, many people experience, even though they cannot define it in detail. Usually, people who experience some of these experiences, and especially *catharsis*, define it as a deep experience in which they feel "coupled" to the artwork.

There are hardly any studies that have analyzed the neurocognitive causes of this “coupling” between personal identity and specific artwork, and currently there are only speculations or tangentially related works.

Some researchers have proposed that some artwork "resonate" with some people's sense of self, to such an extent that it has physiological consequences that are strongly perceived [422]. In some way, the neural representations of the external stimuli (derived from the contemplation of specific artwork) can access the neurocognitive substrates related to the self, that is, the regions of the DMN. This access allows the representation of the artwork to interact with the neuronal processes related to the self, alter them, and even join them (to shape the future representation of the self).

This hypothesis was generated because of the results obtained in the fMRI analysis of neuronal activity as a response to the contemplation of artwork [423]. Participants should rate from 1 to 4 how moving they found the images of different artwork (previously unknown). In a first stage, immediately after the presentation of the artwork (Fig. 3.35), the activity of the MPFC (the region most associated with evaluations of personal relevance) was reduced when observing them. Therefore, the DMN deactivated as a result of external stimuli. But immediately afterwards, the activity of the MPFC increased (it was liberated from its suppression) only in the case of highly moving artwork, while it remained inactive in the other cases. This type of MPFC activity is very similar to what occurs when a highly relevant stimulus to oneself is perceived (such as hearing one's name or seeing oneself in a photo) [424]. However, one might wonder about the fact that artwork, many of them never seen before, generates this same activation pattern of the DMN.

Based on the studies carried out so far, it is not possible to give an answer to this behavior. However, this hypothesis provides a coherent explanation for the results obtained based on the different hypotheses made about the artwork.

A work of art, in any of its variants (visual art, graphic art, music, architecture, literature, etc.) has a very personal character. In fact, the intense aesthetic experience often brings a sense of intimacy, and of connection with the artwork that seems to emerge from within us. The nerocognitive basis of this phenomenon is undoubtedly because of the moving images activate the DMN (and specifically the MPFC) related to the most intimate self-referential activity of our self.

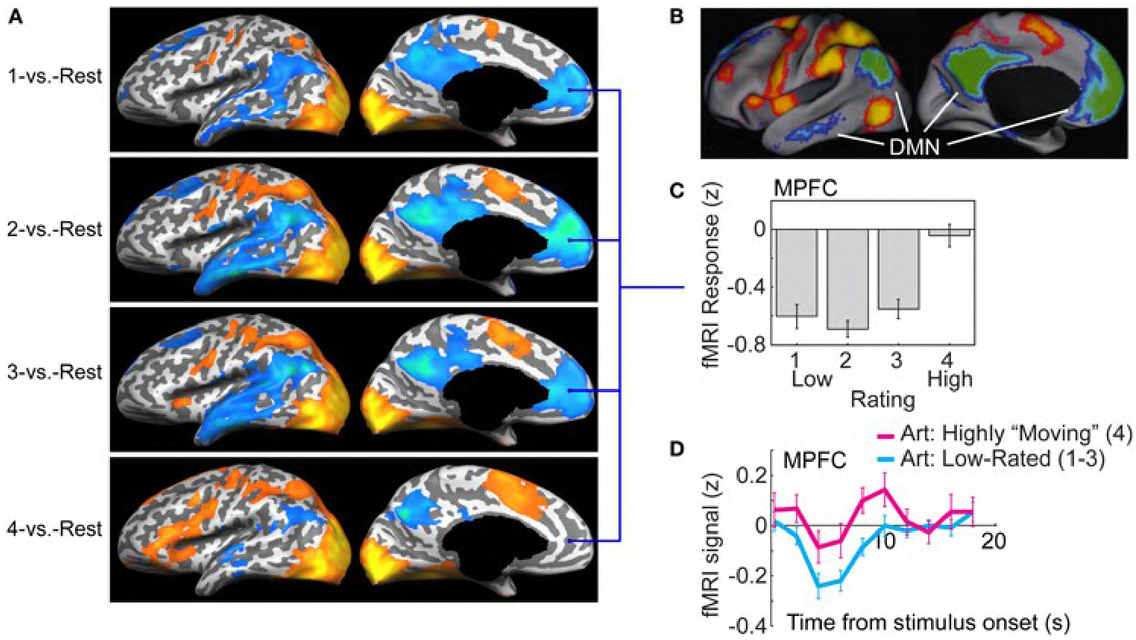

Figure 3.35. The DMN deactivation during task performance is alleviated when viewing highly moving artworks.

A. Lateral and medial views are overlaid with statistical maps comparing fMRI responses during task (viewing and rating of artworks) versus rest periods.

B. The spatial pattern of deactivation during the lower-rated trials (1–3) closely resembles the activation pattern of the DMN.

C. Average fMRI response in the MPFC region of interest (ROI) was markedly and uniformly below rest for trials rated 1, 2, or 3, but was not different from rest for the highest-rated trials (4).

D. fMRI signal timecourse in the MPFC for the lower-rated trials, and the highest-rated trials.

(Source: Vessel, E. A., Starr, G. G., & Rubin, N. (2013). Art reaches within: aesthetic experience, the self and the default mode network. *Frontiers in neuroscience*, 7, 258)

The "resonance" that occurs between certain artwork and the sense of the self generates an intense and intimate aesthetic experience, which is different from self-referential emotions (such as shame, guilt, or pride) [425].

In addition, this intense aesthetic experience is often bidirectional, that is, the observer not only feels connected to the artwork but also feels that the artwork somehow understands the observer. In some cases, the observer of the artwork feels that its author understands what he feels, by exposing their most intimate thoughts and feelings. This explains the intimate connection that many people feel with their favorite artists, even if they do not know them personally [426]. For example, we can listen to a certain song by happenstance, which catches our ear, instantly we feel identified, and immediately coupled with it. The same can happen with a drawing, a painting, a sculpture, a movie, a book, or any creative artistic manifestation.

Therefore, in self-referential emotions the relationship with others focuses on valuation, but in intense aesthetic experience the relationship with others, through the artwork, focuses on a sense of understanding, acquired knowledge and of meaning. In fact, the extraction of meaning is one of the main factors of the aesthetic experience [427]. In general, one of the ways to extract meaning from artwork is done by appealing to information related to oneself, but there is another more intense way when the DMN is activated. Although the DMN is only activated by means of artwork with great personal relevance, which is a fundamental characteristic of the intensely moving aesthetic experience.

3.6.3.3. The neurocognitive bases of *aesthetic catharsis*

Based on recent studies, it is known that certain artwork activate the DMN and therefore are capable of generating a deep and emotional impact by "coupling" with the observer. However, the process by which observers feel this coupling is not yet known. Nevertheless, two plausible hypotheses can be formulated.

- *Direct activation of the DMN*. Researchers based on their own studies [428] have created the speculative, but convincing hypothesis that people, through some type of neural signal, become aware (with a some delay) of the activation of the DMN when they observe artwork that they find very moving, and decide their emotional responses when they detect that signal.

This hypothesis is consistent with the results of several studies in which it has been observed that the MPFC and the PCC (two main regions of the DMN) are activated when the available information is relevant to oneself, and even if the previous evaluation of this relevance has not been required [429]. Therefore, people are more likely to rate certain artworks as "very moving" when they are able to activate a certain sense of personal relevance in them.

- *Pre-evaluation of the ECN, prior to the activation of the DMN*. Given the limited temporal information provided by fMRI methods, an alternative hypothesis can be established. It is possible that when artworks are observed, a previous evaluation by the ECN is carried out, and as a consequence of this evaluation the DMN is activated. In fact, a recent MEG study has been carried out evaluating the aesthetic impact on observers, and it has been observed that regions of the medial frontal cortex and regions of the posterior and temporal cortex are activated. But this activation has been detected 1 second after highly moving artworks have been shown (window of 1000-1500 ms) and not before (window of 250-750 ms) [430]. The results of this study reinforce the hypothesis that DMN is activated (released from suppression) by observing highly moving artworks, but only after an initial perceptual and semantic analysis, but fast enough that it can be used to select the answers.

It should be emphasized that there are no references to the existence of other experiences in which there is a coactivation of the DMN and the sensory system driven by stimuli, as has been observed for highly moving aesthetic experiences. However, it must be considered that if an artwork can modify our inner self identity, it is possible that other stimuli can also do the same. In other words, our own identity can be influenced by the environment in which we live, and therefore the DMN could be activated much more than what was believed up to now. Therefore, it is possible that there may be many more events capable of generating a “coupling” between external stimuli and internal processing related to oneself.

Therefore, our daily life may be structured by switching between periods in which ECN (and other task-positive networks) is activated and the DMN (task-negative) is deactivated, and vice versa. But these periods are punctuated by significant moments in which “coupling” is detected in our brain between the outside world and our internal representation of the self, allowing task-positive and task-negative networks systems to co-activate, interact, influence and reshape each other.

3.6.4. Neurocognitive bases of the semantic process

Semantic memory allows us to remember the meaning of concepts, and in a complementary way allows great flexibility to interweave them and create new concepts. This semantic flexibility allows the creation, for example, of complex linguistic processes with a high cognitive level, such as humor, irony, and metaphors. To achieve these processes the language system must process and have access to multiple alternate meanings for any entity, or object, including those that are not related, or whose relationship is rare. In this way, linguistic semantic creativity occurs by associating concepts that are apparently unrelated, or distant, and in doing so creates a meaningful linguistic expression. This creative process can also be obtained in a conceptual and graphic way, in various fields of human knowledge.

Semantic associations create a semantic memory network, the structure of which greatly influences the brain creative level. In fact, there are several definitions of the creative process as a combination of remote associations that create novel and valuable results. [431]. From this definition, it can be inferred that the more elements that can be remembered during the semantic creative process, the more likely it is to generate unusual associations or solutions, and the greater the number of possible novel ideas. So, within the creative process, the semantic management of information is essential.

When you want to create certain entities or objects, it is essential to know the meaning that should be provided. In addition, by slightly altering its meaning (the type and quantity of its attributes), new entities and previously non-existent objects can be created [432]. For this reason, it is important to know the way in which the human brain is able to encode concepts and manipulate them semantically. That is, the neurocognitive bases of the semantic process.

3.6.4.1. Cross-modal semantic representations

It was traditionally accepted that concepts are encoded in the brain as representations distributed through various regions. This means that each generated concept is associated with a certain verbal or sensorimotor experience [433].

There is currently a consensus that semantic memory (conceptualization) is similar, but has been expanded, since it is assumed that additionally there are cortical regions that are essential to integrate and refine the “raw information” generated by the sensorimotor and verbal regions, and transform it into coherent, complete and refined cross-modal semantic representations [434]. Until now, two of these regions had been identified, which act as interfaces: the middle temporal gyrus (MTG), and the anterior temporal lobe (ATL).

- *Middle temporal gyrus, MTG*

It has been known that the MTG is a nucleus for integration of auditory and visual information [435].

- *Anterior temporal lobe, ATL*

It is assumed that together with the modaly-specific regions (those that encode the information of the same type of sensory stimulus), the areas of the ATL also contribute fundamentally in the creation of semantic memory especially its ventral zone (vATL) [436]. Recent rTMS research has also shown that the ATL regions are involved in verbal and non-verbal semantic processing [437], and they form a cross-modal center of representation in which several specific sources of information are integrated [438].

3.6.4.2. Multimodal sematic model

The anterior temporal lobe (ATL) is composed of several regions (fusiform gyrus (FG), temporal pole (TP), inferior temporal gyrus (ITG), middle temporal gyrus (MTG) and superior temporal gyrus (STG), and only recently has it been possible to explore the contribution of each of them in semantic processing (verbal and non-verbal).

In a recent study [439] the activation of each region of the ATL induced by a semantic task was analyzed, which varied according to the type of stimulus (verbal and non-verbal).

The study had three fundamental results in relation to the integration of different sources of information as a basis for semantic representation (Figs. 3.36 and 3.37):

- The MTG integrates auditory and visual information since it is interposed between the visual and auditory processing flows [440].
- The ATL, through its multiple connections with various modality-specific sources [441], generates cross-modal representations and is the nucleus that generates coherent concepts [442].
- The AG and the PFC also show significant multimodal activation. Previous studies had suggested that these regions are not in charge of coding semantic representations, but rather they perform a "semantic control", that is, they manipulate the brain semantic knowledge database to generate an appropriate behavior [443]. These studies support previous works in which it was shown that the lateral PFC could collaborate in the semantic control process [444].

Based on these recent studies, it is clear that semantic memory is generated based on a transmodal hub. Classic neurocognitive paradigms assume that modality-specific regions interact directly to generate multimodal concepts [445]. The *hub-and-spoke* theory of semantic representation is based on this classic paradigm, and proposes that, in addition to the multiple modality-specific sources of information, an ATL hub adds a transmodal representation coding [446].

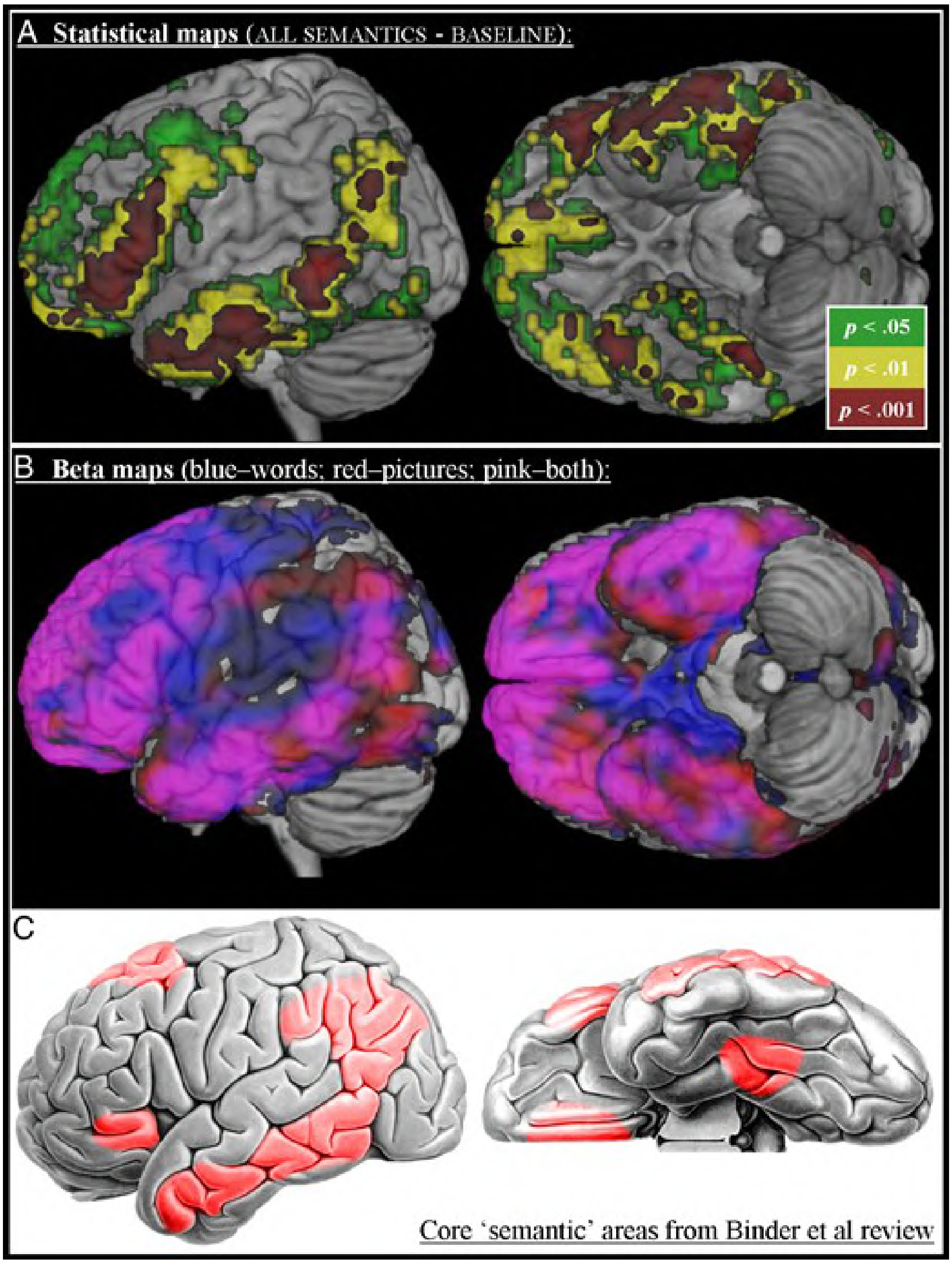

Figure 3.36.
A. Statistical maps of activated regions for the contrast all semantic-control tasks at different statistical thresholds
B. Beta maps of the positive beta values for the pictures-baseline (red) and words-baseline (blue) (areas in common in pink)
C. Core semantic areas based on the independent meta-analysis of semantic tasks
(Source: Visser, M., Jefferies, E., Embleton, K. V., & Lambon Ralph, M. A. (2012). Both the middle temporal gyrus and the ventral anterior temporal area are crucial for multimodal semantic processing: Distortion-corrected fMRI evidence for a double gradient of information convergence in the temporal lobes. *Journal of Cognitive Neuroscience*, 24(8), 1766-1778)

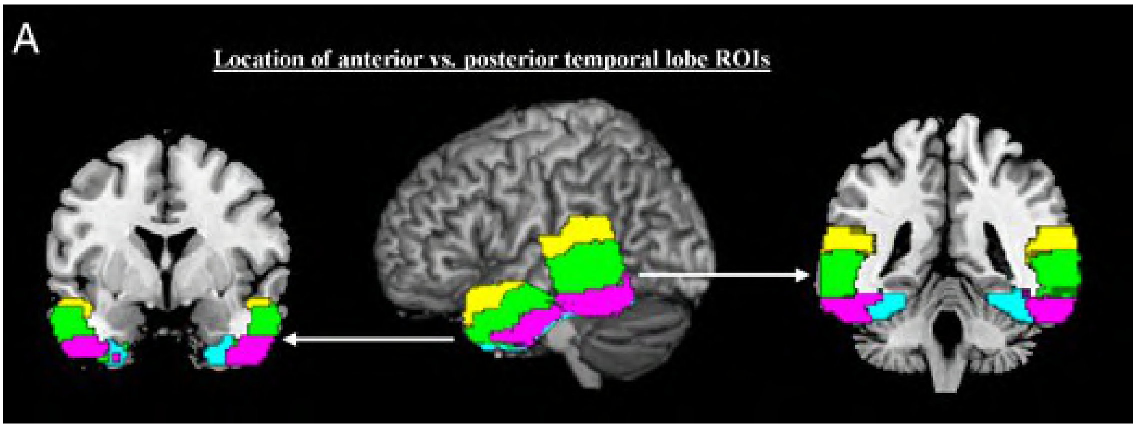

Figure 3.37. ROIs in the posterior and anterior parts of the temporal lobe referring to superior (yellow), middle (green), inferior (purple), and fusiform (cyan) regions (regions defined by Marsbar analysis).
(Source: Visser, M., Jefferies, E., Embleton, K. V., & Lambon Ralph, M. A. (2012). Both the middle temporal gyrus and the ventral anterior temporal area are crucial for multimodal semantic processing: Distortion-corrected fMRI evidence for a double gradient of information convergence in the temporal lobes. *Journal of Cognitive Neuroscience*, 24(8), 1766-1778)

3.6.4.3. Semantic functions of the cross-modal semantic center

Within this proposed semantic model, conceptual knowledge is created through a combination of transmodal and modality-specific representations [447]. Logically, the modality-specific information is a basic source for the construction of concepts, but it is insufficient, since the different “attributes” (characteristics of objects) are combined in complex and non-linear ways when forming a concept [448].

In this context, the cross-modal center can provide two important "semantic functions”:

- It allows for correct mappings between the modality-specific "attributes" and a certain relevant concept.
- It allows for cross-modal representations that provide the basis for making semantic generalizations taking into account conceptual similarities, rather than superficial similarities (which constitute the central function of semantics) [449].

To reinforce this hypothesis, recent studies showed that, when this cross-modal center of representation is damaged (for example, due to *semantic dementia*), errors of excessive generalization are made (strange components are accepted in a group, for example, a wolf is accepted as a type of dog) and sub-generalizations (the atypical components of a group are rejected, for example, a Chihuahua is rejected as if it were not a dog) to a certain concept [450].

Notes 3

[1] Mesulam, M. M. (1998). From sensation to cognition. *Brain* 121, 1013-1052

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CHAPTER 4

The fundamental role of the DMN in the creative process

Chapter 4. The fundamental role of the DMN in the creative process

As seen in the previous section, there are three large-scale networks that continuously iterate among themselves and play a fundamental role in the human cognitive system: *Default mode network* (DMN), *Salience network* (SN) and *Executive control network* (ECN).

Collaboration between these three networks has also been seen to play a fundamental role in human creativity, and one of them has a fundamental role: the DMN. This network is currently the most investigated since, based on the use of new technologies, it turns out its functionality is much more complex than was initially thought. Initially it was thought that it was activated only activated in the absence of external tasks, but today it is known that it is activated when certain tasks are performed. In addition, it is currently known that its topographic structure is not accidental, and plays a fundamental role in human cognition, since its main nodes are located at a maximum topographic distance from the primary sensorimotor unimodal networks. In the same way, it has been seen that it is located at one end of the main gradient, with the greatest possible distance from the sensorimotor unimodal networks.

In this chapter, a reflection is made on the latest studies carried out regarding the functional and topographic structure of the DMN that have a fundamental role in human creativity.

4.1. Improved and recent model of the DMN

As seen in the previous chapter, since the DMN was first discovered, many studies have been carried out, and as a consequence, the most important regions of the DMN located in the cortex have been identified: the ventromedial and lateral prefrontal cortex, posteromedial and inferior parietal cortex, and the lateral and medial temporal cortex [1].

Subsequently, some regions that belong to the DMN have also been identified. For example, certain subregions of the cerebellum [2], and the striatum [3] are functionally connected with the cortical regions of the DMN.

Similarly, seed-based functional connectivity studies have also shown that the DMN is connected to various subcortical structures, including the amygdala [4] and the striatum [5].

In recent studies, it has also been shown that the thalamus is structurally and functionally connected to the DMN regions [6].

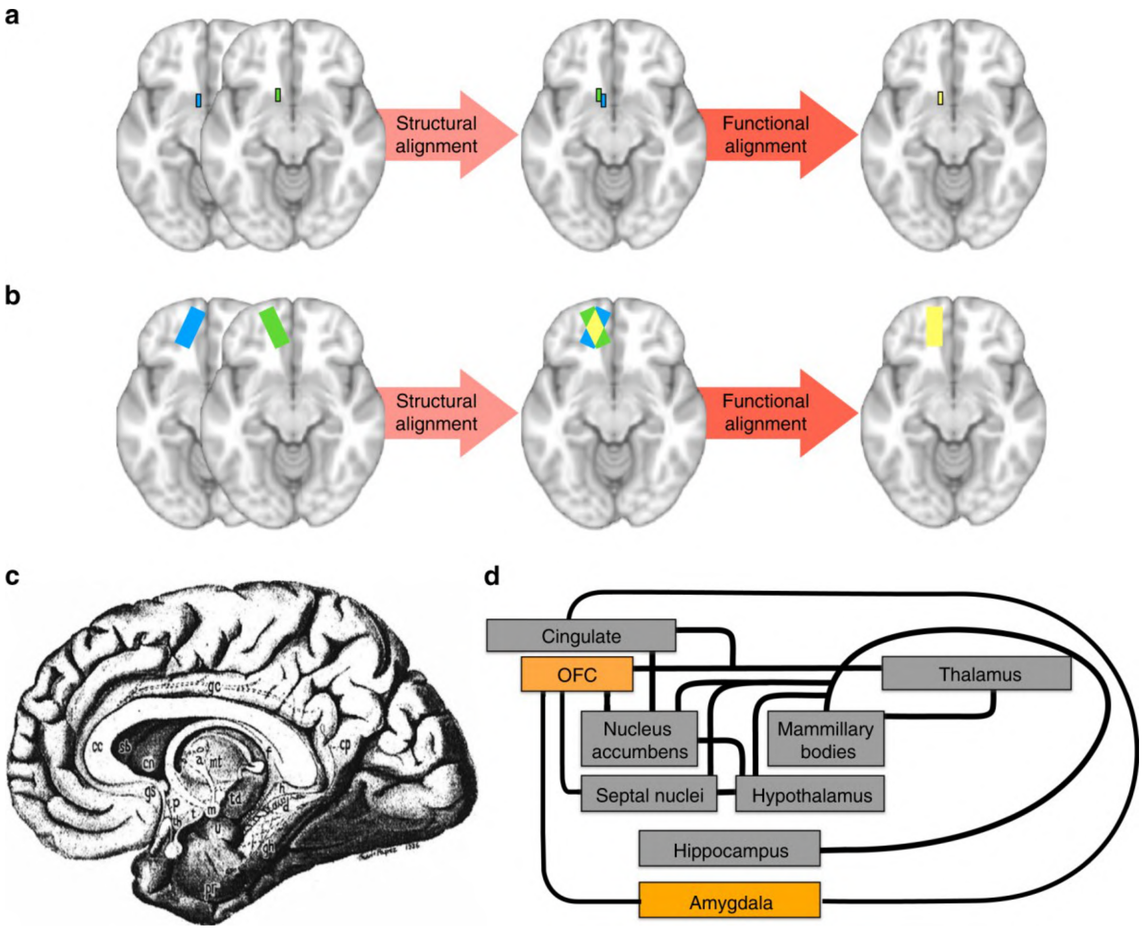

Figure 4.1. Alignment of brain images (between several subjects) and block diagram of the limbic system.
(The blue and green rectangles represent the same functional area of two different people. The yellow rectangles illustrate the overlap of the two functional areas after alignment).
A and B. In the structural alignment there may be a complete misalignment of small functional areas, (or a partial misalignment of large functional areas), due to functional-anatomical variability (or the lack of accuracy of the method).
C. Limbic system, as originally described by Papez
D. Block diagram of the limbic system.
(Source: Alves, P. N., Foulon, C., Karolis, V. *et al.* (2019). An improved neuroanatomical model of the default-mode network reconciles previous neuroimaging and neuropathological findings. *Communications Biology*, 2, 370)

However, until a few years ago it wasn’t possible to accurately identify the subcortical components of the DMN. The problem is that although the DMN is a fairly cohesive network [7], its smaller regions cannot be detected, especially when the MRI does not have enough contrast [8]. Therefore, it is possible that the functional areas of different people cannot be overlapped when structurally aligned brain images are averaged in cluster analysis [9] (Fig. 4.1).

In addition, some parts of the DMN such as the nucleus basalis of Meynert, the mammillary bodies, or the anterior thalamic nuclei can have great variations in shape, position and size among individuals, and therefore can be misaligned when using current methods of structural registration [10].

To solve the problem of detecting small regions or variable shape/position, researchers began to use functional alignment methods to perform more precise mapping of resting-state functional connectivity [11].

In this sense, in a recent study a very precise and complete map of the DMN has been made, in which several subcortical regions belonging to the DMN have been identified (many of which had previously gone unnoticed) [12]. In this study, a functional alignment of individual DMN maps based on resting-state fMRI (rs-fMRI) was performed to build a more complete DMN model, including the contribution of subcortical structures. To identify the anatomy of the DMN, the structural connectivity of this model was explored using tractography imaging techniques.

As a result of this study, DMN connectivity maps obtained from structural and functional alignments were created (Fig. 4.2). Of course, and as expected, both maps include previously identified regions of the DMN: posterior cingulate cortex (PCC) and retrosplenial cortex (RSC); ventromedial, antero-medial, and dorsal prefrontal cortex (PFC); temporal pole (TP); middle temporal gyrus (MTG); hippocampus and parahippocampal cortex; tonsil and posterior parietal cortex (PPC).

Twenty-four regions of interest (ROI) were defined, previously obtained in the functional space, and which coincided with the previous anatomical definitions of the DMN [13]. To these twenty-four ROIs were added another nine regions that could only be identified after functional alignment. These ROIs include the ventral lateral prefrontal cortex (VLPFC), the thalamus, the basal forebrain, the midbrain, and the caudate nucleus, resulting in a total of 33 ROIs (Table 4.1). The strength of association determined by the Pearson correlation between the ROI rs-fMRI time series (i.e., functional connectivity) was greater with alignment in functional space, compared to structural space (Fig. 4.3)

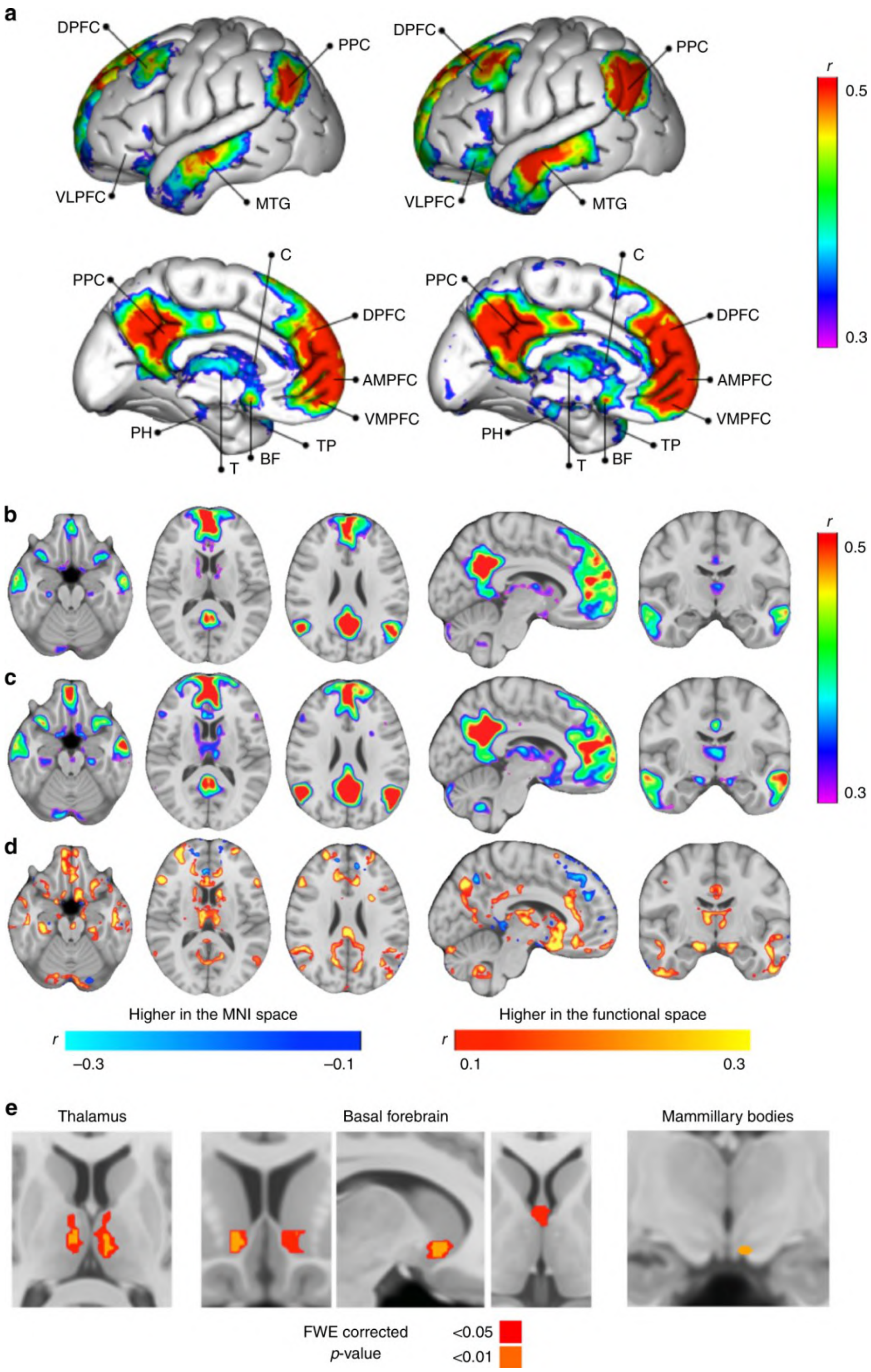

Figure 4.2. Structural and functional map of the DMN.
A. Left part corresponds to the alignment of the structural space. Right part corresponds to the alignment of the functional space.
B. Structurally aligned DMN in brain sections
C. Functionally aligned DMN in brain sectoions
D. Subtraction of the structurally and the functionally aligned DMN maps
E. Statistical comparison between structurally and functionally aligned DMN
(Source: Alves, P. N., Foulon, C., Karolis, V. *et al.* (2019). An improved neuroanatomical model of the default-mode network reconciles previous neuroimaging and neuropathological findings. *Communications Biology*, 2, 370)

Region of interest	*Voxels*	*MNI (X)*	*MNI (Y)*	*MNI (Z)*
Cortical components:				
Left ventro-medial prefrontal cortex	2267	−11	55	−5
Right ventro-medial prefrontal cortex	2673	11	53	−6
Left antero-medial prefrontal cortex	2243	−10	50	20
Right antero-medial prefrontal cortex	2144	10	50	19
Left dorsal prefrontal cortex	3818	−20	31	46
Right dorsal prefrontal cortex	3084	23	32	46
Left posterior cingulate cortex	2484	−5	−50	35
Right posterior cingulate cortex	2224	7	−51	34
Left posterior parietal cortex	2448	−46	−64	33
Right posterior parietal cortex	1733	50	−59	34
Left middle temporal gyrus	2406	−58	−21	−15
Right middle temporal gyrus	2170	59	−17	−18
Left temporal pole	348	−38	17	−34
Right temporal pole	318	43	15	−35
Left ventrolateral cortex	706	−36	23	−16
Right ventrolateral cortex	487	37	25	−16
Left retrosplenial cortex	845	−6	−55	12
Right retrosplenial cortex	638	6	−54	13
Subcortical components:				
Left parahippocampal region	355	−24	−30	−16
Right parahippocampal region	287	26	−26	−18
Left amygdala	66	−15	−9	−18
Right amygdala	58	17	−8	−16
Left caudate	303	−11	12	7
Right caudate	266	13	11	9
Left cerebellar hemisphere	906	−26	−82	−33
Right cerebellar hemisphere	1500	29	−79	−34
Left cerebellar tonsil	184	−6	−57	−45
Right cerebellar tonsil	278	8	−53	−48
Left thalamus	382	−7	−14	8
Right thalamus	305	7	−11	8
Left basal forebrain	456	−7	12	−12
Right basal forebrain	351	7	9	−12
Midbrain	65	−1	−22	−21

Table 4.1. Regions of interest of DMN
MNI coordinates represent the centre of gravity of each region
(Source: Alves, P. N., Foulon, C., Karolis, V. *et al.* (2019). An improved neuroanatomical model of the default-mode network reconciles previous neuroimaging and neuropathological findings. *Communications Biology*, 2, 370)

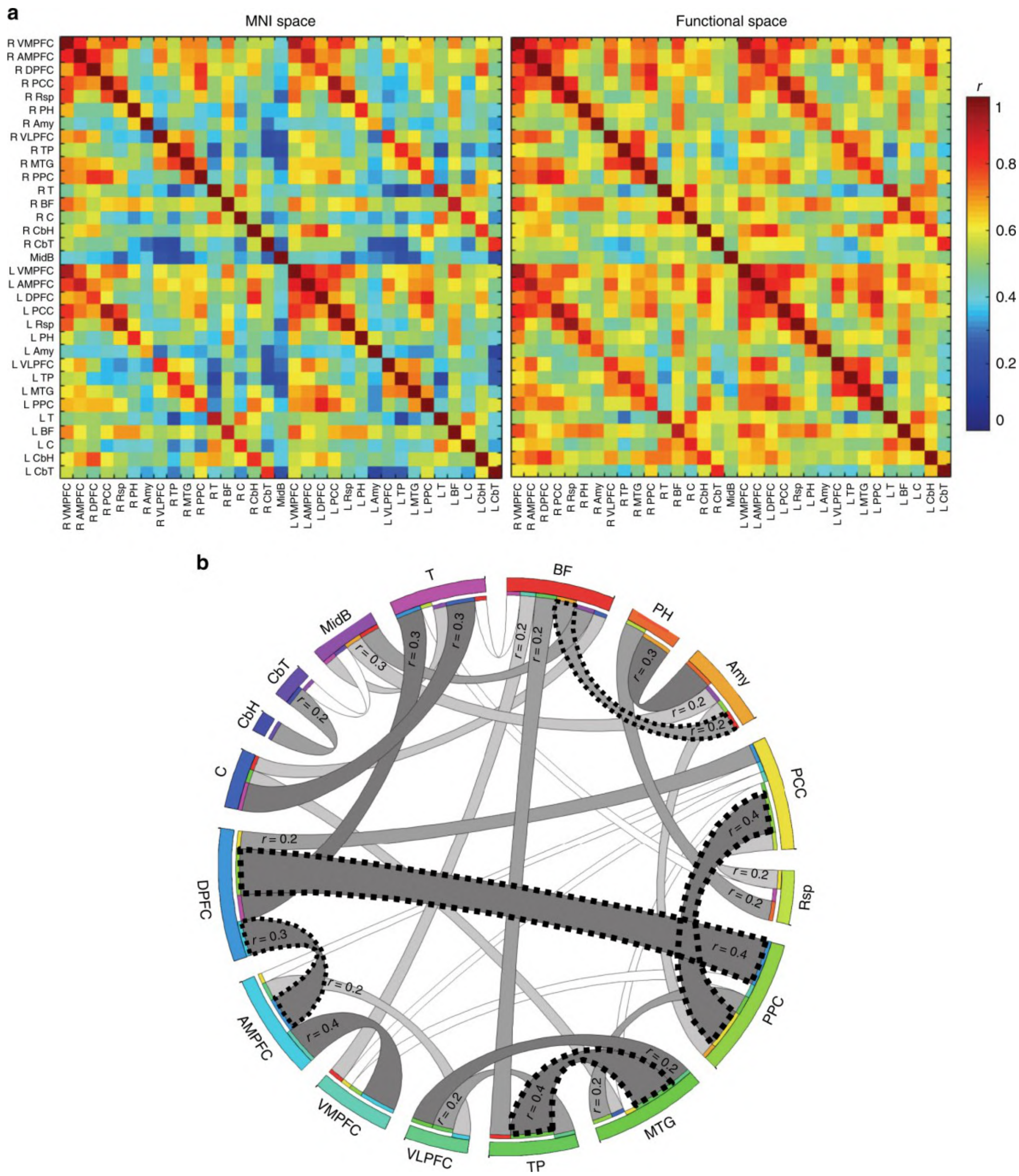

Figure 4.3. Functional connectivity.
A. Matrices of the Pearson's correlations between rs-*f*MRI time series of the ROI in structural space and functional space.
B. Graph representation of the partial correlations between ROI in the functional space
(Source: Alves, P. N., Foulon, C., Karolis, V. *et al.* (2019). An improved neuroanatomical model of the default-mode network reconciles previous neuroimaging and neuropathological findings. *Communications Biology*, 2, 370)

As a result, three important discoveries were made in this study [14]:

- A higher correlation of functional connectivity and sharper anatomical structure was achieved when registering the DMN maps in a functional space.

- It was confirmed that the anterior and mediodorsal thalamic nuclei, and the basal forebrain belong to the DMN (Figs. 4.2, 4.3, 4.6).
- Detailed maps of the structural connectivity underlying the functional connectivity were made (Fig. 4.5).

All these findings made it possible to make a more complete neurobiological model of the DMN (Figs. 4.3, 4.5, 4.6).

The difference between alignment in functional space and structural space (Fig. 4.3) was characterized by an increase in the strength of connectivity between all pairs of nodes, including many subcortical areas previously not considered to be part of the DMN.

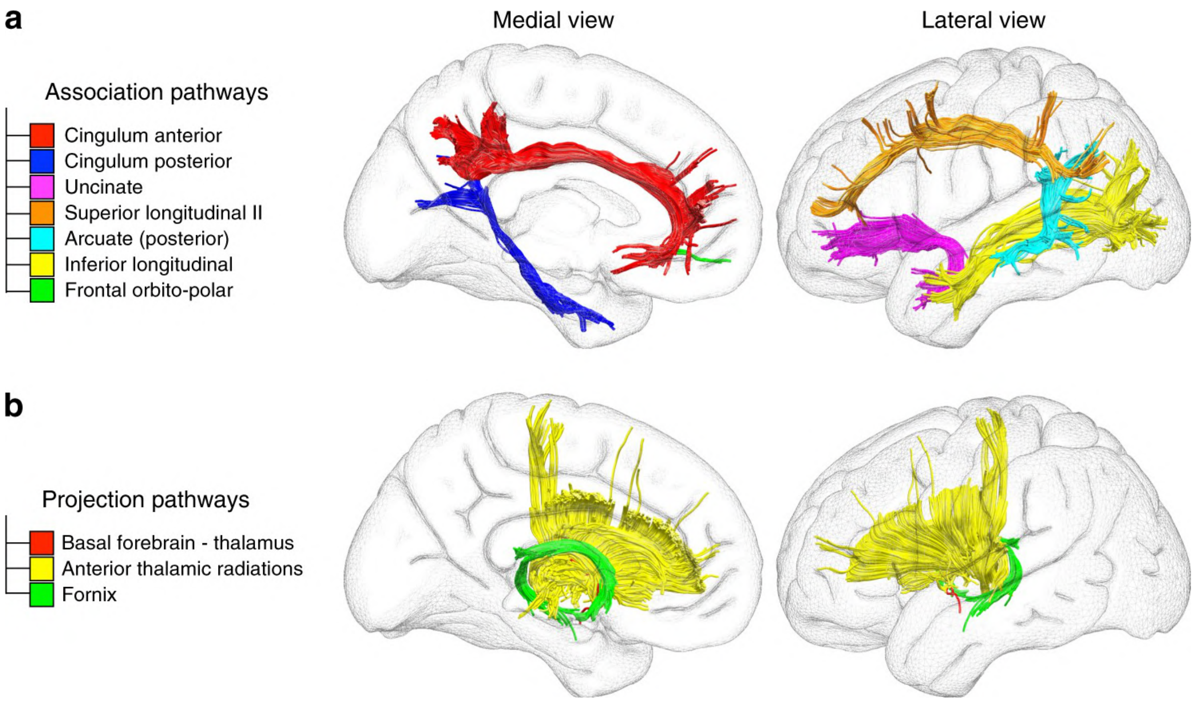

Figure 4.5. Structural connections of DMN.
a. Association pathways connecting the regions of the DMN.
b. Projection pathways mediating the connections between subcortical and cortical regions of the DMN (Source: Alves, P. N., Foulon, C., Karolis, V. *et al.* (2019). An improved neuroanatomical model of the default-mode network reconciles previous neuroimaging and neuropathological findings. *Communications Biology*, 2, 370)

Maps of the DMN in functional space showed regions previously not considered to be part of the DMN, such as the anterior and mediodorsal thalamic nuclei and the basal forebrain. On the other hand, the tractography analysis revealed the structural connectivity of these new DMN regions with the other regions of the network. It especially revealed that the cingulum connected the basal forebrain (BF) with the medial prefrontal cortex (MPFC), the retrosplenial cortex (RC), the posterior cingulate cortex (PCC), and the hippocampus and parahippocampal regions (PH) [15].

This study also revealed that the fornix connected the basal forebrain (BF) (the nuclei of the medial septum) with the hippocampus and parahippocampal regions (PH) [16]. The anterior thalamic views connected the thalamus with the medial and ventrolateral prefrontal cortex (M+VLPFC) [17] and finally some of the most medial fibers that connect the basal forebrain with the thalamus, probably corresponded to the mammillothalamic tract of Vicq D'Azyr [18].

Finally, the application of graph theory [19] in structural connectivity provided a complete structure of the DMN (Fig. 4.6), and revealed the importance of the thalamus and the basal forebrain in the DMN [20].

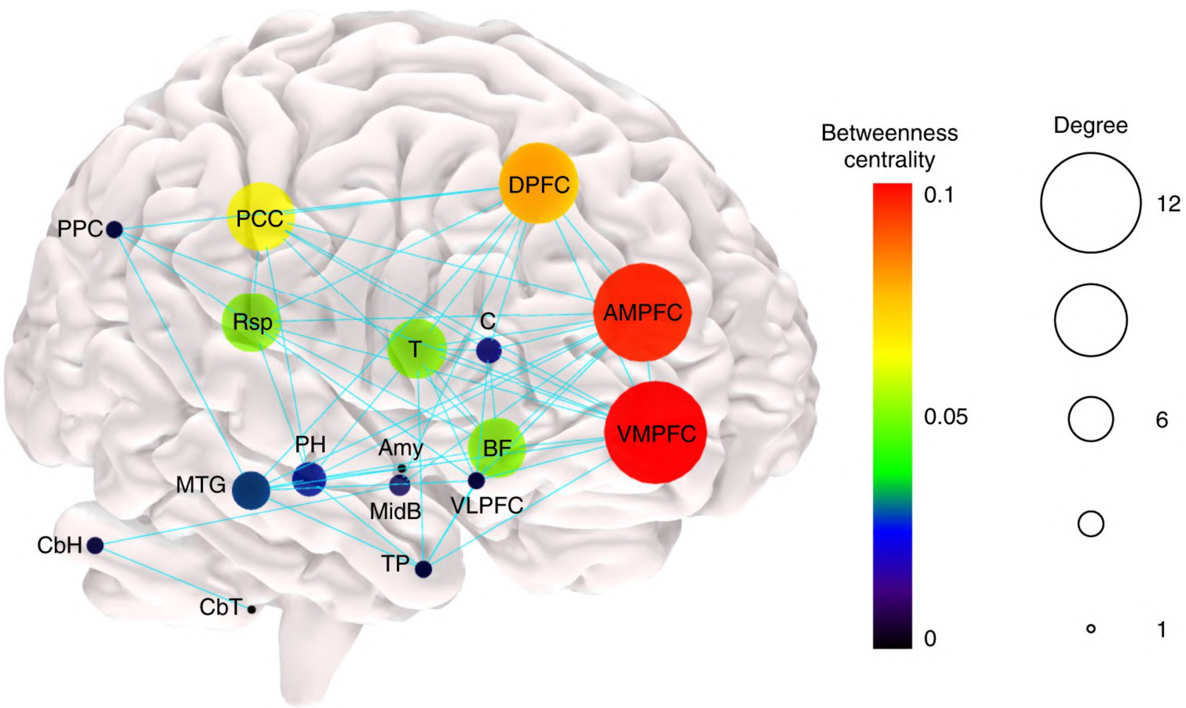

Figure 4.6. Graph theory analysis of structural connectivity.
(Node size represents node degree, node colour represents node betweenness centrality, and represent structural connection.
(Source: Alves, P. N., Foulon, C., Karolis, V. *et al.* (2019). An improved neuroanatomical model of the default-mode network reconciles previous neuroimaging and neuropathological findings. *Communications Biology*, 2, 370)

Therefore, the study shows that the thalamus and the basal forebrain (BF) have a high centrality within the DMN and perhaps provide its high level of integration [21], along with previously known central regions, such as the medial prefrontal region and the posterior cingulate cortex (PCC) and retrosplenial cortex (Rsp) [22].

As a consequence, the DMN is currently considered to be composed of the following regions:

AMPFC	anteromedial prefrontal cortex
Amy	amygdala
BF	basal forebrain
C	caudate
CbH	cerebellar hemisphere
CbT	cerebellar tonsil
DPFC	dorsal prefrontal cortex
MTG	middle temporal gyrus
MidB	midbrain
PCC	posterior cingulate cortex
PH	parahippocampal region
PPC	posterior parietal cortex
Rsp	retrosplenial cortex
T	thalamus
TP	temporal pole
VLPFC	ventrolateral prefrontal cortex
VMPFC	ventromedial prefrontal cortex

4.1.1. Implications of the integration of subcortical zones for the functionality of the DMN

The integration of subcortical nodes increases the previously accepted functionality of DMN. As it is traditionally known, DMN decreases its activity when performing tasks that require attention based on external stimuli [23]. On the other hand, it is currently known that the DMN is activated when executing certain tasks related to autobiographical, episodic and semantic memory, mind wandering, perspective taking or future thinking [24].

In this context, the inclusion of the basal forebrain (BF) and the anterior and middorsal thalamus in DMN implies certain additional functional characteristics:

- Justify the role of the DMN in memory processes [25], since both the anterior and mediodrosal thalamus, as well as the basal forebrain, constitute connection points of the limbic system [26].

- The basal forebrain produces acetylcholine [27], which has an important neuropharmacological effect on memory processes.

- DMN is associated with the mesolimbic dopaminergic pathway through its connection with the ventromedial prefrontal cortex (VMPFC) and the midbrain (MidB), so there is a clear relationship between DMN and emotional modulation [28].

The nucleus accumbens is involved in the integration of affect, and in the regulation of emotions [29], and constitutes an outlet for dopaminergic projections. On the other hand, the nucleus accumbens also receives glutamatergic inputs from the hippocampus and the prefrontal cortex (PFC), which are regions of the DMN [30]. This association with the mesolimbic dopaminergic pathway has been reinforced by functional connectivity studies, which show that the ventromedial prefrontal cortex (VMPFC) and the midbrain (MidB) have large partial correlations with the basal forebrain (BF) [31].

Consequently, it can be concluded that DMN could have an important role in the integration of the cholinergic and dopaminergic systems dedicated to memory and emotion.

Several complementary studies reinforce this. For example, functional gradients along the cortical surface have been studied and it has been seen that the DMN is at the opposite end of the sensorimotor areas in a spectrum of connectivity differentiation, and it has also been seen that the regions of the DMN are separated the greatest distance and are equidistant from the unimodal cortical areas [32]. This study suggests that the DMN behaves like a neural relay for cross-modal information. In parallel, it can be speculated that the basal forebrain and thalamus may act as a relay at the subcortical level, integrating functional networks (related to primary functions) and brain stem inputs to associative areas [33]. In this regard it should be remembered that the basal forebrain and thalamus are phylogenetically older than many cortical structures (especially the regions of the DMN) [34].

4.1.2. Establishment of a new functional paradigm of the DMN

By using new technologies and new analysis methods, the prevalent perception on DMN over the past decade is being modified [35].

It was commonly known that the DMN deactivated during tasks [36], and also that its activity increased when it was not performing tasks [37], and this generated an initial idea that emphasized task-negative functions of the DMN [38].

However, recent studies are painting a new picture, one in which DMN increases its activity by performing tasks in which cognition and behavior must utilize the memory of related previous experiences.

For example, it has been proven that the DMN increases its activity (in conditions in which it should remain deactivated) on at least the following occasions:

- When the decisions to be made depend on the information that has been generated in a previous trial [39].
- When task-relevant stimuli should make use of long-term memory [40].
- When the context of a certain task is retrieved from memory [41].
- When a certain action rule has already been coded that can be used in subsequent actions [42].
- When performing very demanding semantic memory or working memory tasks (under conditions where activity in DMN was previously believed to decrease), connectivity between the DMN and task-positive networks may increase, indicating that the regions of the DMN continues to collaborate on cognition [43].

Therefore, these studies show that DMN is also activated when certain tasks are performed. As a consequence, it seems that the activity of the cortex takes place through a gradient of large-scale networks: from the primary sensorimotor networks, to the transmodal regions that make up the DMN [44].

4.1.3. DMN as high level transmodal integrative neural network

As seen in the previous chapter and based on recent research a new functional paradigm of brain functioning seems to be maturing. This paradigm involves several scales of neural networks, from unimodal networks (involved in direct sensory response activities), to transmodal networks (with an activity less related to input sensory information) [45], which enables neural signals from the DMN to integrate neural signals from other brain regions, allowing it to make top-down predictions to lower levels of the network hierarchy (which has a direct relationship with the creative potential of the brain, as will be seen later) [46].

This integrative function of the DMN is facilitated by its topographic location, that allows it to encode relatively abstract representations by integrating signals from regions lower in the hierarchy.

Therefore, it appears that the DMN supports neural contexts that reflect more integrated patterns of cognition, including those that are carried out when performing any tasks [47].

4.1.4. DMN supports the level of detail in experience while performing tasks

All this evidences force a reconsideration of the role of the DMN when performing tasks. In fact, several experience samplings studies have been carried out recently that show the contribution of DMN to ongoing thoughts during the active maintenance of information relevant to the task in working memory [48].

Previous functional magnetic resonance imaging (fMRI) studies indicated that DMN activity increases when thoughts unrelated to the task being performed are generated [49]. However, recent research indicates that ongoing thinking has a more complex structure than previously thought [50]. The complex structure of these thoughts can be detected using the multidimensional experience sampling technique (MDES), which describes patterns in experience derived from multiple features of self-reported data[51]. This technique reveals characteristics that are usually task-negative, such as off-task thoughts about oneself in the future, as well as components that describe emotions or abstract properties of the experience, such as its level of detail [52]. Furthermore, these previous studies combining fMRI with experience sampling failed to manipulate the demands of the ongoing task, making it difficult to identify DMN activity in ongoing thoughts during active task states.

In a recent study [53] a combination of techniques (self-reports and fMRI) was used in order to redefine the role of the DMN in cognition (Fig.4.7).

The technique of *Representational similarity analysis* (RSA) was used in this study to examine the relationships between experience patterns and neural activity [54]. An RSA technique was chosen because of its ability to mask psychological states [55].

This study showed that the DMN is responsible for making representations of task-relevant information in working memory [56]. In fact, the study showed that during periods of active maintenance of working memory, the DMN kicks in, providing the level of detail in ongoing thinking [57].

The DMN integrates information from lower regions in the cortical hierarchy to form a representation of the ongoing neurocognitive context [58].

Likewise, it has been discovered that the cortex is structured in a specific spectrum of regions that go from the unimodal regions of the cortex (such as the visual and motor cortex) to the most extensive regions with more transmodal functions (and the most extensive is the DMN) [59].

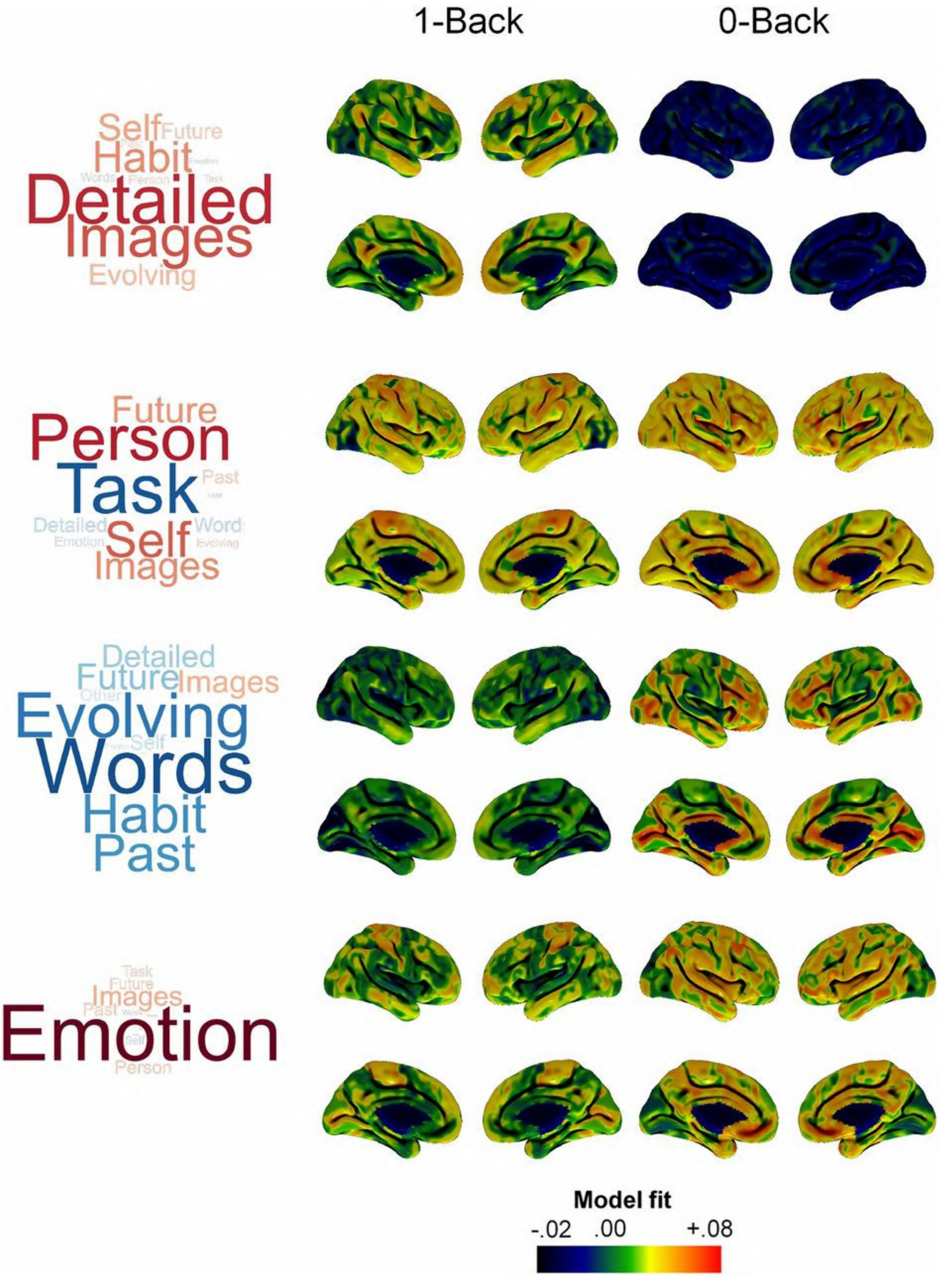

Figure 4.7. Relationship between neural activity and four dimensions of experience.
Left: The groups of words describe 4 dimensions of the experience.
Right: The brain images show the correlation values of the average RSA model.
(Source: Sormaz, M., Murphy, C., Wang, H., Hymers, M., Karapanagiotidis, T., Poerio, G., Margulies, D. S., Jefferies, E., & Smallwood, J. (2018). Default mode network can support the level of detail in experience during active task states. *Proceedings of the National Academy of Sciences*, 115(37), 9318-9323)

In this spectrum, as we move away from the unimodal cortex, neural activity encodes detailed thought patterns during periods of maintenance of working memory. This suggests that the DMN is involved in making detailed cognitive representations through interactions with lower regions of the cortical hierarchy. Furthermore, DMN plays a fundamental role in detailed experiences in working memory processes during memory recovery [60] and is involved in the level of specificity of the information [61], or in the detail level of the information [62].

4.2. Topographic identification of the DMN and its relationship with creativity

There are very few studies that analyze the reason why the different brain regions are located exactly where they are located, and in which parallels are formulated between functionality and topographic location. It is possible that the topographic location of the different brain regions is underestimated, and the studies have focused both on the structure and functionality of each region, as well as on the structure and functionality of the different large-scale networks that have been identified with over time and based on a sequential set of studies.

However, as awareness grows for the enormous complexity of some large-scale networks, such as the DMN considerable interest has been shown in the topographic study of these structures. The DMN has a varied set of functionalities that apparently have little in common, and their study found a way out. For this reason, this network has been analyzed from different points of view, hoping that some of them will shed more light on its functionality. A network that continues to be called “Default mode network”, but to which, without a doubt, its name should be urgently changed, since its functionality is extraordinarily more varied and important than the one initially attributed to it.

In this section, a topographic study of the DMN is carried out and based on this, very important conclusions are drawn, and the doors are opened in the delimitation of a new functional paradigm of this network. In fact, the topographic structure of the DMN also has an important relationship with its role in creative processes.

4.2.1. Importance of the topographic structure of the DMN

The relationship of DMN with memory processes suggests that it is involved in many of the characteristics that are said to make us human, such as our “sense of identity” [63]. In addition, other studies have linked DMN to conceptual processing [64], or our sense of self [65]. Based on this previous research, and further new research [66], the heterogeneous activity of the DMN is currently thought to be due to its spatial and physical location in the cortex [67]. Specifically, it is thought that the contribution of DMN to cognition is closely related to its physical and functional distance with the motor and sensory regions [68].

The mechanisms of human evolution have favored and rewarded the cortex to expand considerably [69], and in doing so, cortical regions have been created that are less restricted by external input of information than motor and sensory regions, that are directly involved with action and perception [70].

Based on this restructuring of the cortex during its evolutionary expansion, it is possible that the different regions of the DMN assumed a more complex and abstract functionality, and less influenced by external events, than the primary cortical regions more restricted by these external events [71]. This fact is consistent with other investigations that show that the cortical zones less restricted by external events are also the natural end point of processing streams, responsible for encoding increasingly abstract characteristics of external input, and that allow for behavior control in an increasingly complex way [72].

Therefore, knowledge of the topographic location of the DMN provides at least three important indications on its role in the human cognitive process:

- The topographic structure of the cortex explains why regions with very similar functions are located precisely where they are located.
- The increase in the physical distance between the different regions of the DMN and the sensorimotor areas explains why the DMN usually works in a way unrelated to external events.
- The location of the DMN at the end of the processing flows that begin at the periphery of the cortex, provides an adequate structure so that it can be involved in various higher order and more abstract cognitive processes (such as episodic memory, semantic memory, social cognition, etc.).

4.2.2. Structure of the DMN

DMN was detected for the first time using fMRI techniques when measuring brain activity when performing tasks (Fig. 4.8,b), although the greatest advances in the definition of its structure and functionality were made using the resting-state fMRI technique (Fig. 4.8,a).

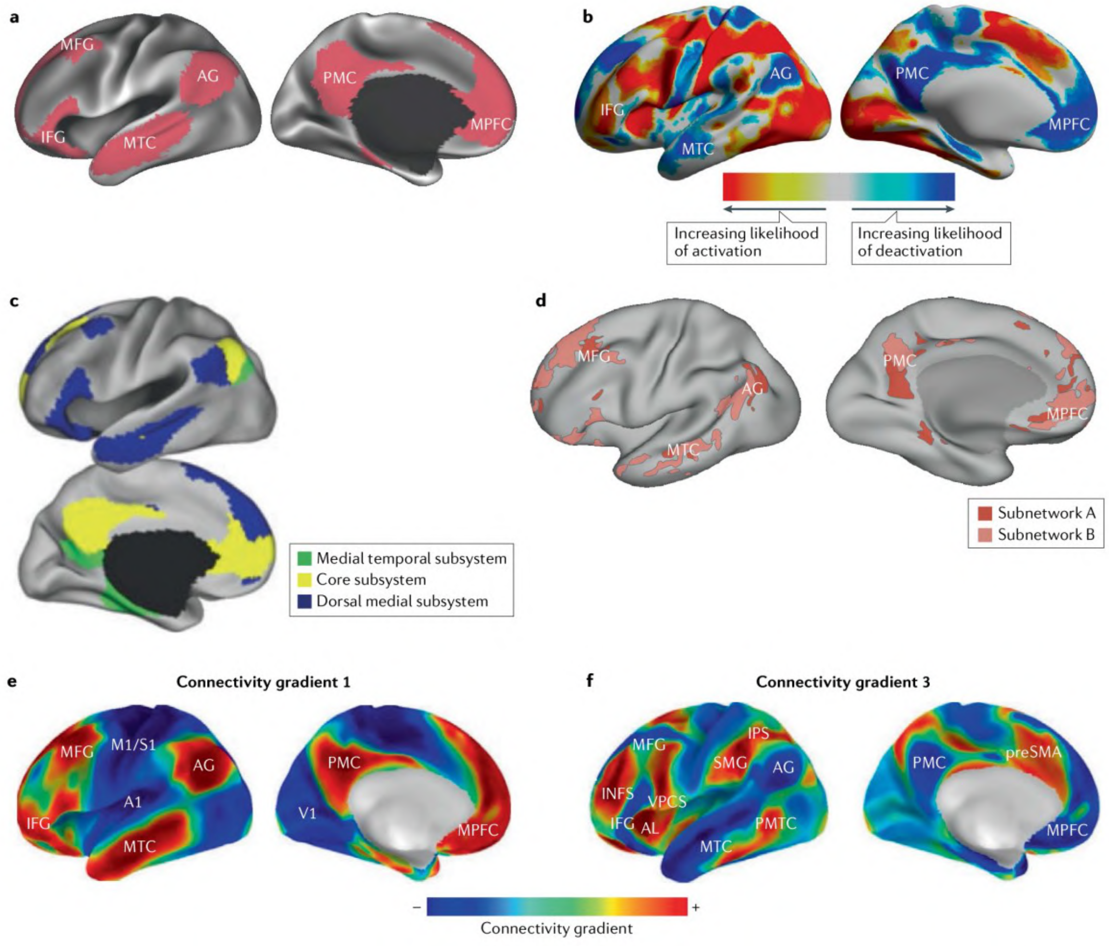

Figure 4.8. Map of the DMN.

A. Default mode network (DMN) (pink color).

B. DMN. Analysis of patterns of brain activation (defined as greater activity during tasks relative to baseline) and deactivation (defined as greater activity during baseline than during tasks) using data from the available analyses included the *Human Connectome Project*. Regions more deactivated by tasks include DMN regions, such as the posteromedial cortex (PMC), medial temporal cortex (MTC), medial prefrontal cortex (MPFC) and angular gyrus (AG).

C. The DMN has also been divided into "subsystems" and "subnetworks". Group analyses, in which brain activity is averaged across many individuals, highlighted three *subsystems*, based on statistical groupings of the observed brain activity at rest.

D. Intensive scanning of single individuals highlights two distinct yet adjacent networks with a complex interdigitated structure, based on patterns of correlated brain activity.

E. *Connectivity gradient 1*. Regions with warmer colours include the hubs of the DMN, and regions in cooler colours include the sensorimotor cortex (M1/S1), auditory cortex (A1) and visual cortex (V1). This indicates that, for this *connectivity gradient 1*, the DMN's activity differs to the maximum from that of unimodal regions.

F. *Connectivity gradient 3*. Many of the regions that are recruited during goal-orientated cognition (such as the intraparietal sulcus (IPS), supramarginal gyrus (SMG), ventral precentral sulcus (VPCS), intermediate frontal sulcus (INFS) and anterior insula (AI)) are located towards one end of the *connectivity gradient 3*, whereas regions of the DMN are located towards the other.

(Source: Smallwood, J., Bernhardt, B. C., Leech, R., Bzdok, D., Jefferies, E., & Margulies, D. S. (2021). The default mode network in cognition: a topographical perspective. *Nature Reviews Neuroscience*, 22, 503-513)

Using this technique (in which the temporal correlation between neuronal activity in different brain regions is measured) it was shown that the different regions of the DMN display a coordinated temporal activity at rest [73], which is precisely what defines a large-scale network [74].

Furthermore, and as seen in the previous chapter, by means of measurements of the activity at rest (carrying out an analysis at the group level) it could be seen that the DMN was composed of three spatially different “subsystems” [75] (Fig. 4.8,c,d):

- *DMN Dorsal medial subsystem*, anchored in the lateral temporal cortex, the dorsal prefrontal cortex, and the parietal cortex
- *DMN Temporal medial subsystem*, anchored in the temporal parietal cortex and the medial lateral cortex
- *DMN Central subsystem*, anchored in the parietal cortex and the frontal cortex

However, high-resolution recent studies of people during rest [76], and during tasks [77], showed a different structure of the DMN.

These studies suggested that the DMN consists of two separate and juxtaposed "sub-networks" [78] (Fig. 4.8,d). Unlike the three subsystems described above, these two subnets are equally spatially distributed, and each subnet includes the same set of regions, organized in a complex and interdigitated manner. The interdigitation of both subnets could allow the integration of temporal and spatial information [79], which in turn serves as the basis for some high-level cognitive functions of the DMN.

DMN is also related to other neural networks in a very complex way. In a generalized way, the DMN shows patterns of activity opposite to other regions that are activated when performing tasks, although sometimes it also shows relatively low correlation patterns [80]. Recent studies of multivariate approaches have shown that the neuronal activity of some regions of the DMN, such as the posteromedial cortex PMC, contains signals that are related to neuronal functioning in various regions outside the DMN [81]. These observations therefore suggested that DMN is also activated when goal-directed activities are performed [82].

The set of these observations has led to a new account of brain functionality [83] that has been formalized based on the application of a new technique called *cortex-wise decomposition*, linked to the analysis of principal components, to measures of brain activity and its connectivity [84]. These new techniques provide generate a set of representations of the distribution of brain activity in the cortex, each describing unique patterns of variation in brain activity observed at rest. These representations are often called *connectivity gradients* and are based on covariance patterns within a data matrix. In turn, these gradients can be classified based on the percentage of variance that each principal component shows with the initial data. In each of the gradients, the clustered brain regions located at one extreme have similar temporal fluctuations, but different from the clustered regions at the other extreme (which also are "clustered" because they have similar temporal fluctuations).

Using this new technique at rest, it was observed that two of the three connectivity gradients explained properly the variation in activity (and therefore provide more information on the organization of neuronal function in the cortex), involve the DMN [85] (Fig. 4.8,e,f).

- The first gradient created (unimodal - transmodal) showed that the DMN is the network least like the unimodal networks of the cortex. Therefore, the visual, auditory, somatosensory and motor cortex is located at one extreme of this gradient and the DMN at the other extreme [86].
- The third gradient created (task unrelated - task related) showed that the regions of the DMN were located at one extreme, while the frontal parietal network (ECN) [87], that coordinates external task states was located at the other extreme [88].

The analysis of the connectivity gradients therefore provides very valuable information on some important characteristics of the role of the DMN in cognitive processes, and creativity.

4.2.3. The role of the DMN in higher order cognition

The first investigations on the role of DMN in cognition were based on its relationship with memory [89]. These investigations showed that DMN activity increases in various circumstances, such as when thinking about oneself [90], in social cognitive processes [91], when imagining events in the future or in the past [92], or when creating spatial scenes in the imagination [93].

All these activities are related in one way or another to human creative activity, so from the beginning the relationship between DMN and creativity began to be suspected. Additionally, experience sampling studies also showed that self-generated thoughts were related to the activation of the DMN, such as, for example, thinking about oneself or thinking about other people, as well as episodic representations of events that are not related to external sensory events [94]. The most active region in the self-generated episodic and social cognition processes is the MPFC [95], that is central node of the DMN and a center of task deactivation [96].

All these experiences are related to human creative activity, which is why from the beginning the relationship between DMN and creativity began to be suspected.

In the same way, it is important to note that these types of experiences appear in periods of awake rest, but decrease when external tasks are performed [97], which is also related to creativity.

Research activity on DMN has increased recently and it has been shown that it is related in several additional facets of human cognition [98], such as the following:

- Empathic attitude [99]
- Affective processing [100]
- Moral judgment [101]
- Aesthetic judgment [102]
- Watching movies, and narrative comprehension [103]
- Space navigation [104]
- Decision-making based on rewards [105]

Thus, the DMN is involved in several different types of cognition, and no specific functionality can be attributed to it. However, it is important to note that all these activities are included in the structure of the design process, so they represent new evidence of the relationship between DMN and creative activity, and especially graphic creative activity.

Given that the DMN is involved in several different aspects of cognition, without apparent relationship, the investigations also focused on finding the activities in which the different regions that compose it are involved. For instance:

- There is evidence that the angular gyrus (AG) and pontine micturition center (PMC) (regions of the *central subsystem* of DMN), support the recovery of autobiographical information [106].
- A *semantic network* [107] has been identified, anchored in the middle temporal cortex (MTL) and the left angular gyrus (AG) (regions of the *medial dorsal subsystem* of the DMN), that uses long-term knowledge, and is involved in making us the sense of the world.
- A *mentalizing network* has been also identified [108] that includes the right angular gyrus (AG), and the medial prefrontal cortex (MPFC) (regions of the *central subsystem* of the DMN) and is involved in social cognition.

However, knowledge of the functionality of the different regions of the DMN is not very helpful, as these regions also have several functions and are apparently poorly related to each other.

Therefore, and recently, studies are being carried out on determining the “general contribution” of DMN in cognitive processes.

One of the most important studies that has been carried out consists of a meta-analysis of the functional profile of the DMN regions, using the large amount of information available in the *Neurosynth* database [109]. As expected, the result showed that the DMN regions were involved in a large variety of apparently different domains (linguistic, episodic, emotional, and social).

Only two regions (right angular gyrus (rAG), and the left middle temporal cortex (lMTL) had more specific functional profiles, since they are only involved in two of these domains. In contrast, other regions, such as the MPFC have a more generic cognitive profile and were involved in all the domains indicated above. Therefore, it was demonstrated that the DMN has a general functionality, which allows it to be involved in several higher order cognitive processes [110].

4.2.4. Meta-functionality of DMN

The undivided analysis of its different component regions did not shed any light on determining a differentiated activity of the DMN, so the investigations were focused on a different path.

Now the objective is to look for more abstract and more general patterns of activity of the DMN, which could have their different and heterogeneous patterns of activity in common.

It was intuited that more generic and higher-order activity patterns must exist which are able to support the different and heterogeneous activities of DMN. And for this reason, they could be called “DMN meta-functionality patterns”.

The studies carried out up to now shows three “meta-functionalities” of the DMN.

a. *Delayed Matching*. The functionality of the DMN may vary depending on the way in which cognitive processes emerge within the temporal structure of the current task.

Several studies have been carried out in which a *delayed matching* had to be carried out, in which the location or shape of the pieces had to be memorized [111]. In these studies, probes were placed intermittently to remember the presence or location of an element in previous exercises.

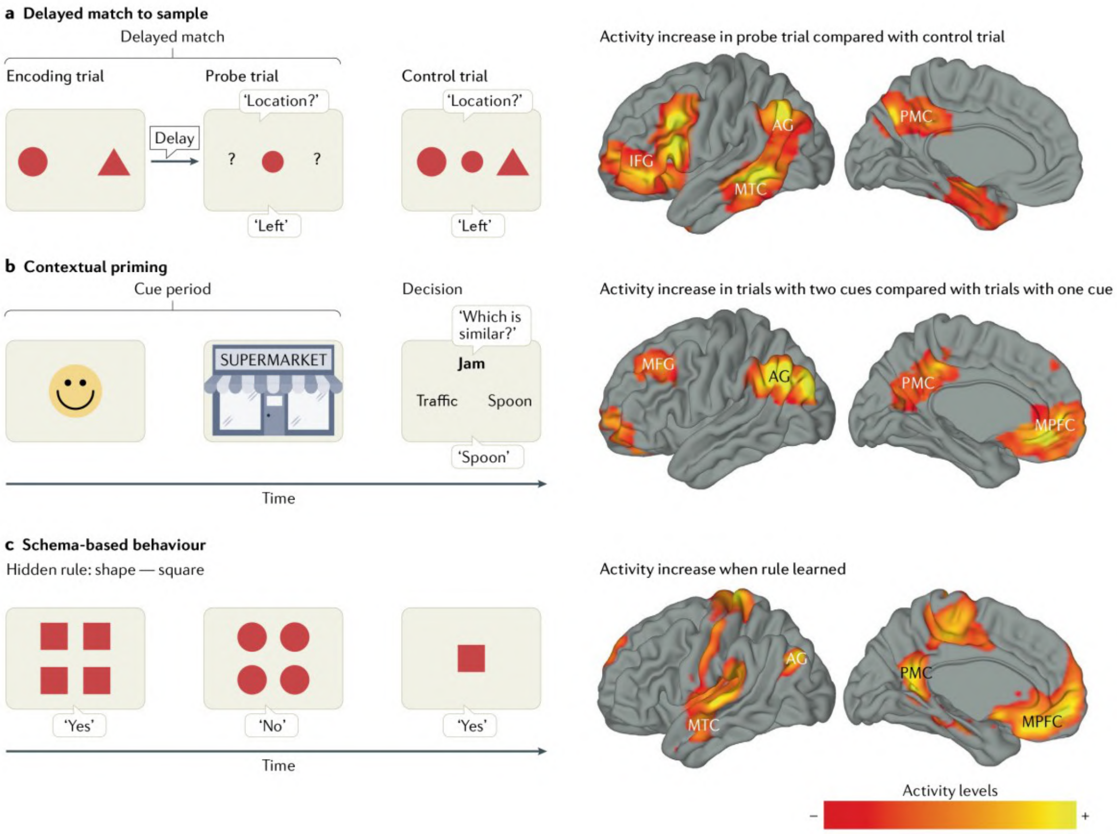

Figure 4.9. DMN activity is sensitive to the temporal structure of cognition during a task.
DMN activity can be related when prior experience contributes to the external task completion (regions in red and orange show significant activation).
A. Regions of the DMN with greater activity during *delayed match*: regions of parietal cortex (posteromedial cortex (PMC) and angular gyrus (AG)), frontal cortex (inferior frontal gyrus (IFG)) and temporal cortex (middle temporal cortex (MTC)).
B. Regions activated when simple associative judgements following *contextual priming* are performed: regions of parietal (AG), temporal (MTC) and prefrontal (mid- dle frontal gyrus (MFG) and medial prefrontal cortex (MPFC)) regions.
C. In a *schema-based decision-making* when participants have learnt the hidden rule and can use this information to guide decision-making, brain activity increases in the regions of the DMN: frontal (MPFC), parietal (AG) and temporal (MTC).
(Source: Smallwood, J., Bernhardt, B. C., Leech, R., Bzdok, D., Jefferies, E., & Margulies, D. S. (2021). The default mode network in cognition: a topographical perspective. *Nature Reviews Neuroscience*, 22, 503-513)

During these investigations it was observed that the parietal cortex (PMC and AG), the temporal cortex (MTC) and the frontal cortex (IFG) (*medial central* and *dorsal* *subsystems* of the DMN) had greater activity when decisions were based on information from previous tests, than when decisions were made based on current sensory information [112] (Fig. 4.9,a). In these studies, it was observed that people who showed greater connectivity in these regions performed the task better [113].

In these studies, a greater activity was also observed within a region of the PMC associated with self-reports, which shows a greater focus on the relevant details of the task [114]. These results are consistent with other investigations in which it was observed that the DMN is associated with the level of detail when performing certain tasks [115].

Therefore, the *delayed matching hypothesis* suggests that DMN is activated when decisions are made based on previous experiences, and not based on immediate sensory information.

b. *Contextual modulation*. The DMN can vary its pattern of neural activity depending on the previous experience

Several studies have been made about word associations [116], in which participants must make decisions to choose semantically ambiguous words (for example, whether the word "nails" is related to the fingers of the hand, or to carpentry). In some tests, obviously the choice of the participants was shown images linked to the intended association (for example, images related to the human body, or images related to construction). During decision-making, when both types of images were shown, the activity in the frontal cortex (MPFC and middle frontal gyrus) and in the parietal cortex (angular gyrus and PMC) increased, compared to the activity observed when they were shown only one type of images. These regions that increased their activity belong to the *central* and *dorsal-medial subsystems* of the DMN [117] (Fig. 4.9,b).

Therefore, the *contextual modulation hypothesis* establishes that the activity of the DMN can vary depending on the previous experiences, even when the information on which the decision is made is the same.

c. *Schema-based decision-making*.The DMN increases its activity when internal rules are used to perform tasks

Several studies have been carried out in which the participants had to perform a classification task, in which they needed to use a rule that could change at any time [118] (Fig. 4.9,c). These studies showed that when the rule was changed, the activity of the DMN was considerably reduced when making decisions. Instead, DMN activity increased when participants learned the rule and used it when making decisions.

In these studies, it was observed that two regions of the DMN were especially activated, the parietal cortex (PMC and angular gyrus) and the frontal cortex (MPFC). These regions belong to the *central subsystem* of the DMN.

Therefore, the *schema-based decision-making hypothesis* suggests that the activity of the DMN can be influenced by previous experience, although the stimuli in which the decisions must be made are the same.

As a result, together these three types of investigations show that the DMN is also activated in the performance of tasks, and that its activity can vary significantly.

- During *delayed matching*, DMN activity is high when decisions and choices are made based on previous experiences.
- During *contextual modulation*, DMN activity increases when decisions are consistent with various characteristics derived from the immediately preceding information.
- During *schema-based decision-making*, the DMN activity increases when rules generated based on accumulated feedback from previous activities related to the task are used.

All these studies are definitive evidence that the DMN is involved with memory processes [119], and also show that the DMN is involved in situations associated with the *multiple demand system* [120], including working memory, perceptual matching and rule-based classification. This new vision of the DMN involved in an abstract form of objective-oriented external cognition, reinforces also the relationship between the DMN and the executive control process.

Therefore, in certain situations the activity of the DMN is opposite to the activity of the ECN, although in other situations they collaborate in a very effective way.

To try to answer these questions, another new line of research has now been opened trying to see the relationship between the topography of the DMN and its functionality.

4.2.5. Consistency of the topographic structure of the DMN with previous hypotheses on the cortical organization

The DMN is activated in the absence of tasks, and also when certain tasks are performed. For this reason, and in order to define in more detail the functionality of the DMN, its topographic structure has been studied in recent years [121].

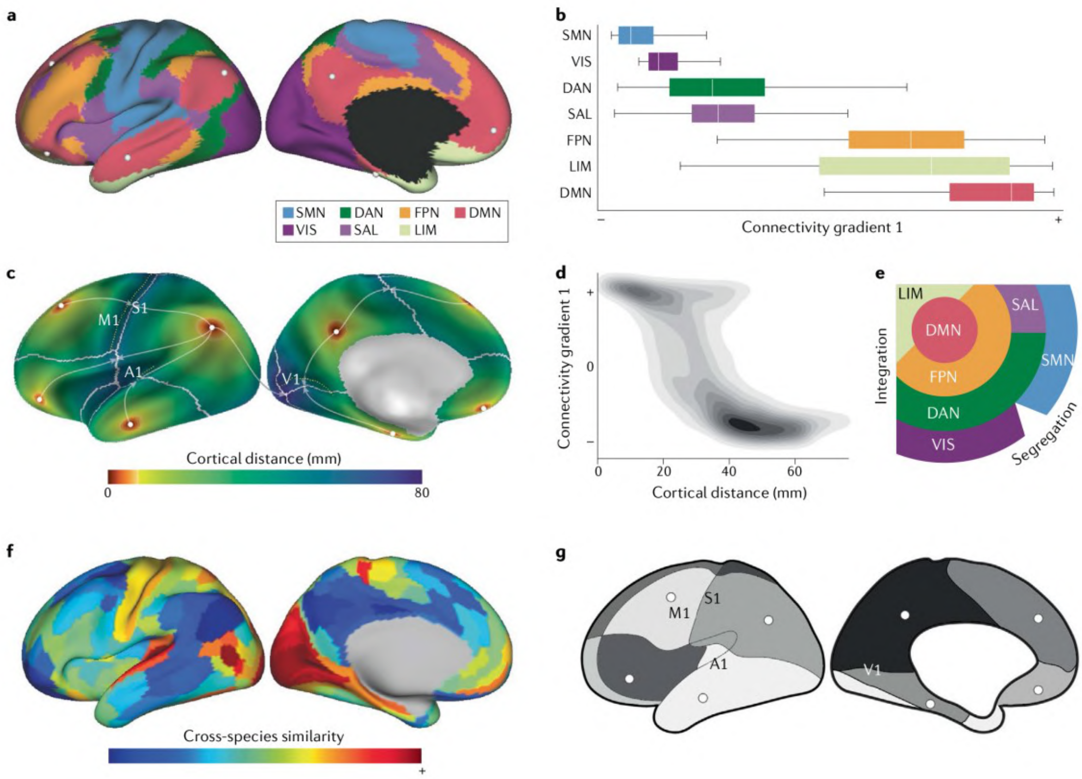

Figure 4.10. DMN Topography. The default mode network (DMN) has been shown to be functionally and spatially distant from primary sensory and motor networks.

A. The DMN as large-scale brain network.

B. Networks organized along the first *connectivity gradient 1*.

C. The centers of the regions that make up the DMN are most distant from regions of unimodal sensory cortex (primary auditory cortex (A1), primary motor cortex (M1) and primary somatosensory cortex (S1))

D. Distance measure against *connectivity gradient 1* reveals that both metrics are correlated. This indicates that the functional and physical separation between the DMN and primary systems are related phenomena.

E. The location of the DMN at the end of processing streams (part b) suggests that it may correspond to the hypothesized functional integrative centre of the cortex. The images illustrate how the DMN can be thought of as the end of multiple processing streams that originate in sensorimotor cortex, and thus the functional core of the brain.

F. Results of an analysis comparing the similarity of whole brain patterns of functional connectivity in macaques and humans.

G. Based on the spatial location of the peaks of *connectivity gradient 1*. DMN divides the brain into mutually exclusive 'cortical fields', each defined by the convergence of a specific set of sensory/motor streams towards a region of the DMN at the centre of each field.

(Source: Smallwood, J., Bernhardt, B. C., Leech, R., Bzdok, D., Jefferies, E., & Margulies, D. S. (2021). The default mode network in cognition: a topographical perspective. *Nature Reviews Neuroscience*, 22, 503-513)

It was previously known that the DMN is a very robust network, since the set of its regions (located far apart from each other) show stronger connections with each other than with other regions of the cortex [122]. This strong connection is supported by the structural system of the white matter of the cortex [123], and due to the dispersion of its nodes, it is related to various states of distributed neuronal activity [124].

Gradient studies have also been carried out [125], which place the DMN at the transmodal extreme of a first connectivity gradient (unimodal - transmodal), which organizes all neural systems along a spectrum that goes from the unimodal cortex to the transmodal. That is, the DMN is the network that is the most separated from the primary visual cortex and primary motor cortex (Fig. 4.10,a,b).

This functional organization corresponds directly to the topography of the cortex, since the different regions of DMN are located at the maximum possible distance from the nuclei of unimodal systems [126] (Fig. 4.10,c).

In this way, the position of the brain regions within the first connectivity gradient (unimodal - transmodal) is directly related to the physical distance that separates them from the sensorimotor nodes [127] (Fig. 4.10,d). Consequently, and from a topographic point of view, the different regions of the DMN are strongly interconnected, and are located at the maximum possible distance from the unimodal systems (both in terms of physical distance and in terms of activity similarity).

These topographic features of the DMN suggest that its regions are strongly functionally interconnected, and furthermore are separated at the maximum possible distance from the sensory and motor nodes of the cortex. This topographic evidence is consistent with two current consensus hypotheses on the structure and organization of the cortex.

a. *Consistency with the Mesulam hypothesis.*

The structure and location of the DMN is consistent with the hypothesis of the influence of cortical organization on the integration of information in the human brain.

This hypothesis was proposed by Mesulam [128] who created a topological scheme to describe how cortical connectivity is the basis of the balance between processing flows and integration [129]. In this topological hypothesis, peripheral unimodal sensorimotor systems support concrete relationships between neural function and behavior and enable simple stimulus-response behaviors. Instead, the progressive integration of neural signals from unimodal regions to transmodal networks allows the encoding of general (and invariant) characteristics that allow abstract higher-order cognition.

Several *axonal tract tracing* studies with primates have confirmed the basic characteristics of this hypothesis, since they show that sensorimotor signals converge locally before ending up in the association cortex [130]. Similarly, several human studies have shown that large-scale networks are organized, in an orderly way, along the cortical surface from the unimodal regions to the DMN [131].

Therefore, these investigations suggests that the DMN is located at the end of the processing streams that are anchored at cortex (Fig. 4.10,b,e).

b. *Consistency with the Tethering hypothesis.*

The structure and location of the DMN is consistent with the evolutionary hypothesis of mammalian cortical expansion.

The evolutionary hypothesis of cortical expansion, commonly called *tethering hypothesis* [132], suggests that by expanding the cortex in the regions of the association cortex, these regions were freed from the limitations of sensory hierarchies. This allowed diverse functional associations to be created between these regions, especially in humans.

According to this hypothesis, a study has recently been carried out that suggests that the regions of the DMN are the ones that have changed their functionality the most throughout evolution [133] (Fig. 4.10,f). This study also suggests that the anterior-posterior functional axis of the DMN (which is evidenced, for example, in the strong temporal correlation between the activity of the MPFC and the PMC) may have been created in recent evolutionary development [134].

4.2.6. Implications of the location of the DMN to explain its functionality

Knowing the topographic structure of the DMN regions can help to understand their role in cognition and behavior. In this sense, three major discoveries have been made.

a. *The distributed and interconnected structure of the DMN may explain the fact that it is involved in many different aspects of cognition.*

It has now been accepted that different forms of complex thinking are based on various sets of distributed processes. In this sense, for example, *semantic memory* [135] and *episodic memory* [136] have a “hub and spoke” structure, in which the central regions interact with the radial regions frequently distributed in the sensorimotor cortex. It has also been proposed that social cognition is based on a set of highly distributed regions and that it involves several neural systems [137]. Similarly, it has been proposed that emotion involves distributed systems, including those involved in perception and language [138].

These forms of higher-order cognition can depend on the DMN structure because its privileged and distributed location allows it to encode information about brain activity from across the cortex.

In fact, the recent studies carried out, at rest, show patterns of neuronal activity of the DMN through the cortex with a high level of precision [139]. All this shows that the DMN contains information from across the cortex, and this is very useful when cognition depends on the coordination of several different regions, distributed throughout the cortex.

b. *The topography of the DMN may explain the fact that it is often involved in abstract forms of experience.*

Several studies have been carried out that directly show that the DMN manipulates generic and abstract information, shared by all the regions related to it [140]. Information processing flows (such as the ventral visual flow) are organized so that the regions involved respond to increasingly abstract characteristics of cognition as the information passes along the flow [141]. Because the DMN is located at the end of these processing flows, it can be of enormous value for the more abstract features of cognition and behavior.

In this sense, several studies have been carried out that show that when the hidden meaning of certain ambiguous images is learned, the neural patterns within the DMN change, whereas less reorganization is observed in the unimodal cortex [142]. Other studies show that during goal-oriented external thinking processes, the DMN represents characteristics of the context of the task, rather than the specific details of the steps necessary to achieve a goal [143]. Other studies show that the activity in the DMN regions is related to relatively abstract characteristics of cognition, such as the "level of specificity" of the stimuli [144].

All these studies show that peripheral brain systems are involved in specific characteristics of cognition, whereas DMN may reflect more abstract characteristics of cognition. These abstract characteristics do not directly create the basis of experiences, but rather convey higher-order information about several of their abstract characteristics [145].

c. *The isolated structure of the DMN (whose nodes are separated at the maximum distance from the sensorimotor periphery) explains that it is not directly involved with the sensory information of the environment (perceptual decoupling).*

It is currently known, based on several studies, that DMN is involved in various types of cognition, such as emotion [146], spontaneous cognition [147], mental time travel [148] and situations in which decisions related to the task are enriched with information other than that provided by the sensory inputs [149].

In these cases, cognition and behavior move away from immediate sensory inputs, and instead focus on internal representations. This pattern of information processing is called *perceptual decoupling* [150], and supports the mechanisms of imagination and creativity, allowing us to transcend the here and now, and imagine different places and times [151].

Consistent with this cognitive mechanism, memory recall is accompanied by reduced activity in the visual cortex during *delayed match activity* [152]. Similarly, memory deficits associated with epilepsy are related to the inability to reduce activity in a similar set of regions [153]. It is possible that the topographic location of the DMN, allows it to be freed from the limitations of the sensorimotor regions [154], and allows for the creation of the appropriate conditions for the emergence of types of uncoupled cognition (such as memory).

4.2.7. Relationship of the topographic structure of the DMN with human creative capacity

The topographic structure of the DMN has a direct relationship with the creative capacity of the human brain, since it allows it to manipulate heterogeneous high-level information, abstract and not related to external stimuli.

The topographic model described for the DMN [155] shows that it is a group of brain regions that are functionally and anatomically more distant from peripheral sensorimotor nodes and provides further explanation of some of its previously known functions. The location of the DMN at the top of the information process provides an explanation for its abstract functionality, and of wide range. The physical and functional distance of DMN with peripheral sensorimotor systems provides an explanation for its functionality in cognition and behavior that are often unrelated to external events.

The topographic structure of the DMN is therefore able to explain the reason why it is involved with highly abstract cognitive processes of cognition and that are often only loosely related to the events that happen at a given moment.

As a consequence, two basic characteristics of the DMN, related to creative processes, have now been agreed upon from a topographic perspective:

a. *Progressive integration hypothesis.*

The topographic structure of the DMN also corresponds to the organization of the brain in *cortical hierarchies,* based on physical distance and *progressive integration* [156].

The *progressive integration hypothesis* defines the ability of the DMN to describe abstract characteristics of the ongoing mental content, involving different regions of the cortex. The different regions of the DMN may represent generic information that is shared by lower levels of the hierarchy, although the information in these levels may vary from each other in its specific details. This hypothesis provides an explanation why the DMN is involved in many completely different representational states, which share certain more abstract general characteristics (such as their dependence on memory), although they have different specific informational content [157].

Cortical hierarchies also serve to modulate the temporal dynamics of complex systems. Based on this, the DMN collaborates so that the signals distributed in the different peripheral cortical regions occur closer in time [158], something that is currently believed to occur during the memory retrieval process [159].

Cortical hierarchies are also the general basis that supports what is known as *predictive cognition* [160], who propose that cortical systems are optimized to reduce the mismatch between expected and observed patterns of neuronal activity, a parameter known as *prediction error*.

The set of evidence suggests that complex representations of information can be created through the self-organization of brain activity based on a cortical hierarchy [161]. In relation to it, the DMN is involved in the monitoring process and the correction of prediction errors of the brain. The neural patterns of the DMN can provide information about the degree to which specific brain contexts are predictable, which can be useful for switching between exploratory and exploitative modes in the foraging process [162].

Additionally, it can be said that reinforcement learning studies, which can be easily characterized by prediction error models, show activity in the medial prefrontal regions of the DMN [163].

In summary, the current view of the activity of the DMN shows how *cortical hierarchies* shape brain activity based on various cognitive mechanisms, such as, for example, abstract representation, stable dynamics or prediction error.

b. *Relative deactivation pattern of the DMN.*

The topographic perspective also explains the *relative deactivation pattern* of the DMN.

From a topographic perspective, the conditions that allow the activation of “positive task” networks, such as the ECN, are the same that prohibit the use of long-term knowledge to guide the subsequent behavior. In this sense, several investigations have been carried out using stimuli that do not allow semantic associations and procedures, which makes the behavioral and neural responses unpredictable (such as the randomization of the trial and the temporal fluctuation of the presentation of the stimulus). The reduced activity in DMN is because these conditions prohibit the brain from depending on memory information.

This phenomenon is amplified due to the location of the DMN regions, since as they are separated the maximum distance from the sensorimotor nuclei, their activity is less influenced by the incoming sensory information of the environment.

On the other hand, the DMN is activated in different situations than when the ECN does. In particular, during *delayed match* (Fig. 4.9), the DMN regions increase their activity when cognition combines the input sensory information with the information from the previous trial to make a decision. In contrast, the DMN has a much lower activity when the same decision is made based solely on input sensory information [164]. Therefore, DMN is activated when complex behavior is based on previously stored knowledge in memory.

When examining the topography structure of the DMN it is observed that some regions are closer to certain unimodal networks than others (for example, the middle frontal gyrus is closer to the motor cortex, while the angular gyrus is the closest to the visual cortex). This suggests that the cortex can be divided into a set of mutually exclusive local cortical "fields" centered around the regions of the DMN (Fig. 4.10,g). These cortical fields span different regions of the unimodal cortex and therefore offer a new point of view to understand the differential cognitive contribution of each of the specific nodes of the DMN.

It is possible that the contribution of specific DMN regions in higher order cognition is partially limited by the functions associated with the specific unimodal systems that are closest to them. For example, it has been observed that the angular gyrus integrates auditory and visual information [165], and this could possibly be thanks to the location of the angular gyrus in the center of a cortical field between the auditory cortex and the visual cortex. (Fig. 4.10,c,g). However, an exception to this rule is the auditory cortex which, unlike the visual or somatosensory cortex, is notably closer to some nodes of the DMN (for example, the inferior frontal gyrus, the angular gyrus and middle temporal cortex) than other primary systems [166]. However, this rule exception may have an important justification, as these regions of the DMN have been shown to be important for language processing [167]. Therefore, it is possible that proximity to the auditory system allows these regions of the DMN to control language processes to organize cognitive function, perhaps through the inner speech [168].

In summary, and because of its topographic structure, the DMN integrates information across the cortex, which is very important in its creative activity, since it needs the coordination of several different regions. In addition, the DMN manipulates generic and abstract information, since being at the greatest possible distance from the sensory unimodal networks. The information is progressively stripped of the maximum of concrete details, of the here and now, and is transformed with the maximum level of abstraction possible. This mechanism of perceptual decoupling supports the basic mechanisms of creativity, which allows us to transcend the here and now, and allows us to imagine non-existent things. Complementarily, the different nodes of the DMN involve different cognitive processing, depending on the unimodal systems to which they are related. Finally, and as a consequence of its topographic structure, the DMN is activated in activities that are based on previously stored knowledge in memory (rules), as is the case of creative activity.

4.3. Localization of the DMN at the end of the main gradient in the cortex and its relationship with creativity

In addition to the topographic study of the DMN, and with the aim of knowing the general functionality of the DMN, in recent years several studies have been carried out on the spatial processing gradients of the brain. These processing gradients allow increasingly abstract levels of representation of information, and the DMN has been observed to be located at the end of the main gradient of the cortex. This circumstance gives the DMN a fundamental role in creativity.

4.3.1. The principal connectivity gradient provides a general model of the structure of the cortical organization

The topographic structure of the cerebral cortex provides an organizing principle that limits cognitive processes. In a complementary way, in recent years the functional structure of the brain has been explained based on the existence of multiple large-scale networks [169], each with a different functionality [170]. Some of these networks have basic primary functions, such as the control of movement or the perception of images and sounds. Other networks have higher cognitive functions, such as attention, or cognitive control [171]. And some networks have a functionality that is still less known, as is the case of the DMN [172]. The topography of these distributed networks has been identified in considerable detail using multiple methods [173], but the reasons for their particular spatial relationship, and how this defines their function, is not clearly known.

With the latest mapping local processing stream technologies, spatial processing gradients have been identified that allow increasingly abstract levels of representation of information. These gradients usually extend along the adjacent cortical regions in a staggered manner [174]. Some examples are the following:

- There is a ventral *occipitotemporal processing gradient* (in the visual domain) that transforms the information that describes the simple visual characteristics of objects, (encoded by neurons in the primary visual cortex), into more complex visual descriptions of these objects (in the regions anteroinferior temporal cortices). Finally, it collaborates in the realization of multimodal semantic representations (in the middle temporal cortex and the anterior temporal cortex), providing the meaning of what we do, hear and see at all times [175].
- In the prefrontal cortex, there is a *rostral-caudal processing gradient*, whereby goals become increasingly abstract in anterior areas further away from the motor cortex [176].

These processing gradients provide a systematic mapping between spatial position and a functional spectrum of increasingly abstract representations [177].

Processing gradients help to understand the relationship between specific regions and functions in separate domains [178], and it has been proposed that the more abstract functions of the cortex can follow a similar trajectory, hypothesizing that the abstract categories emerge from the convergence of information through modalities (Fig. 4.11).

This hypothesis has been improved [179], and it has been argued that the association cortex gains its functional attributes through its increasing spatial distance from the constraints that determine the functional specialization of the primary cortex.

As a result, it can be deduced that there may be macroscale gradients that integrate information across multiple domains into progressively more abstract representations, in which local gradients can be located within specific cortical systems.

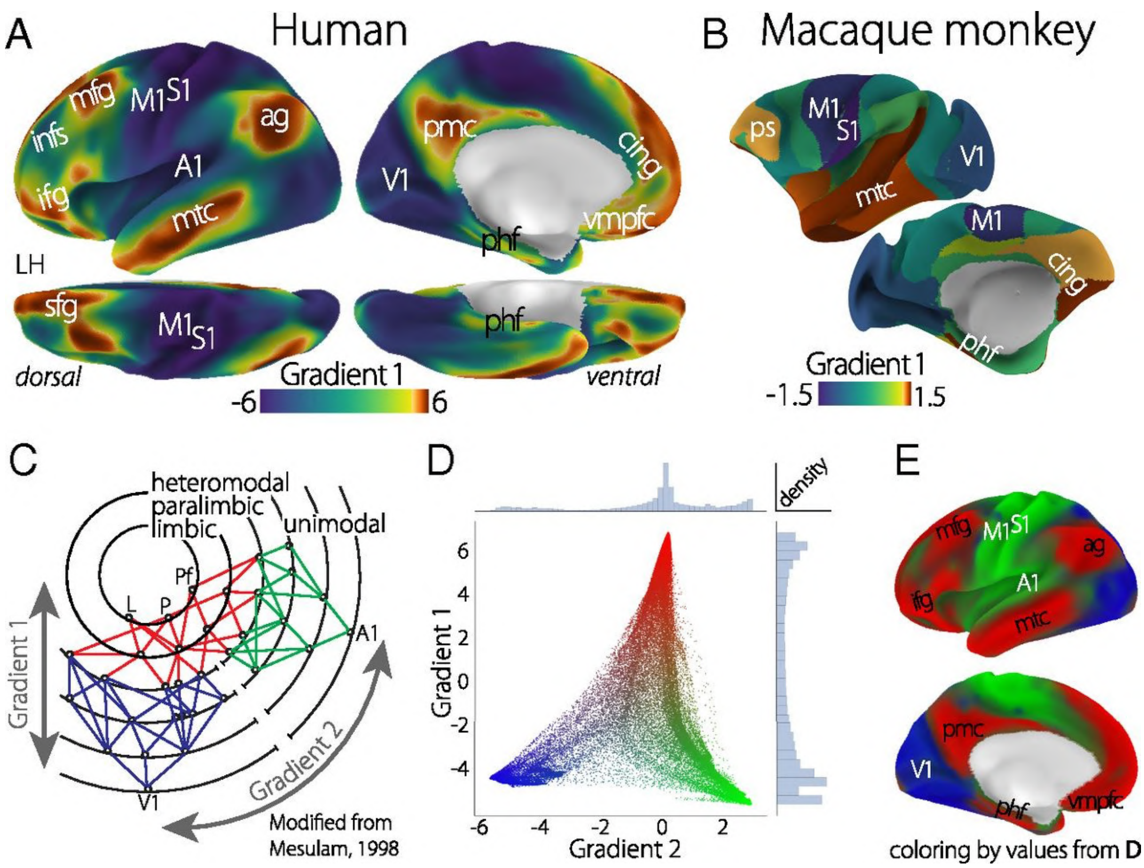

Figure 4.11. A. and B. The principal gradient of connectivity (in human and macaque monkey) shows a spectrum between unimodal regions (dark blue) and transmodal regions (sienna), which in the human cortex, peaks in regions corresponding to the DMN.
C. The image of connectivity organization (suggested by Mesulam) proposes a hierarchy of processing from distinct unimodal áreas, to integrative transmodal areas.
D. Scatter plot of the first two connectivity embedding gradients. Gradient 1 extends between primary sensorimotor and transmodal regions (red). Gradient 2 separates somatomotor and auditory cortex (green) from visual cortex (blue).
E. Colors from the scatter plot are presented on the cortical surface for anatomical orientation
(Source: Margulies, D. S., et al. (2016). Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proceedings of the National Academy of Sciences USA*, 113, 12574-12579)

4.3.2. DMN as a hub that integrates representative information across de brain

One of the large-scale neural networks is the DMN, and its function is not yet fully understood. As seen in previous sections, it was observed that the DMN was deactivated during external orientation tasks [180]. However, it has subsequently been shown that the DMN is activated in tasks that depend on the information retrieved from memory, such as remembering past events, or thinking about the future, or considering the mental states of other people [181]. It has also been observed that the DMN is involved in states that are less related to events in the environment at each moment, such as daydreaming, or wandering the mind [182], and engages in lapses in external processing [183].

However, the general cognitive function of the DMN is not yet known as it is also involved in a large number of cognitive domains. The DMN is activated in the recovery of autobiographical memory, social cognition and future thinking, and it has also recently been shown that it works (collaborating with the regions directly involved) in cognitive control during complex tasks of working memory [184].

Based on the information currently available on the DMN, it seems that it is not linked to a specific form of informative content, and it has been suggested that it acts as a hub that integrates representative information across the cortex [185].

4.3.3. DMN is located at one end of the main processing gradient

To understand the topographic organization of the cerebral cortex on a large scale [186], an in-depth recent study has been carried out [187] to observe how the main variance in cortical connectivity is related to the topography of the structure and function.

In this study four basic questions have been addressed:

- Is there a *connectivity gradient* in the human brain that reflects the systematic integration across modalities in a hierarchical way?
- Is the *connectivity gradient* related to the geometric structure of the cortex?
- Is the *connectivity gradient* able to explain the spatial distribution of large-scale networks and their associated functions?
- Does this *connectivity gradient* help to know the functionality of the DMN?

The study was carried out by characterizing the components that describe the maximum variance in the functional connectivity patterns (the extent to which the nodes agree in the spatial distribution of the correlations) throughout the human cerebral cortex (Fig. 4.11). The functional connectivity matrix consisted of 91,282 cortical and subcortical "grayordinates" with a resolution of 2 mm from the pre-processed release of the S900 dense connectome from the *Human Connectome Project* (HCP) [188]. These data were obtained from one hour of *resting-state* fMRI data acquired from 820 healthy adult individuals.

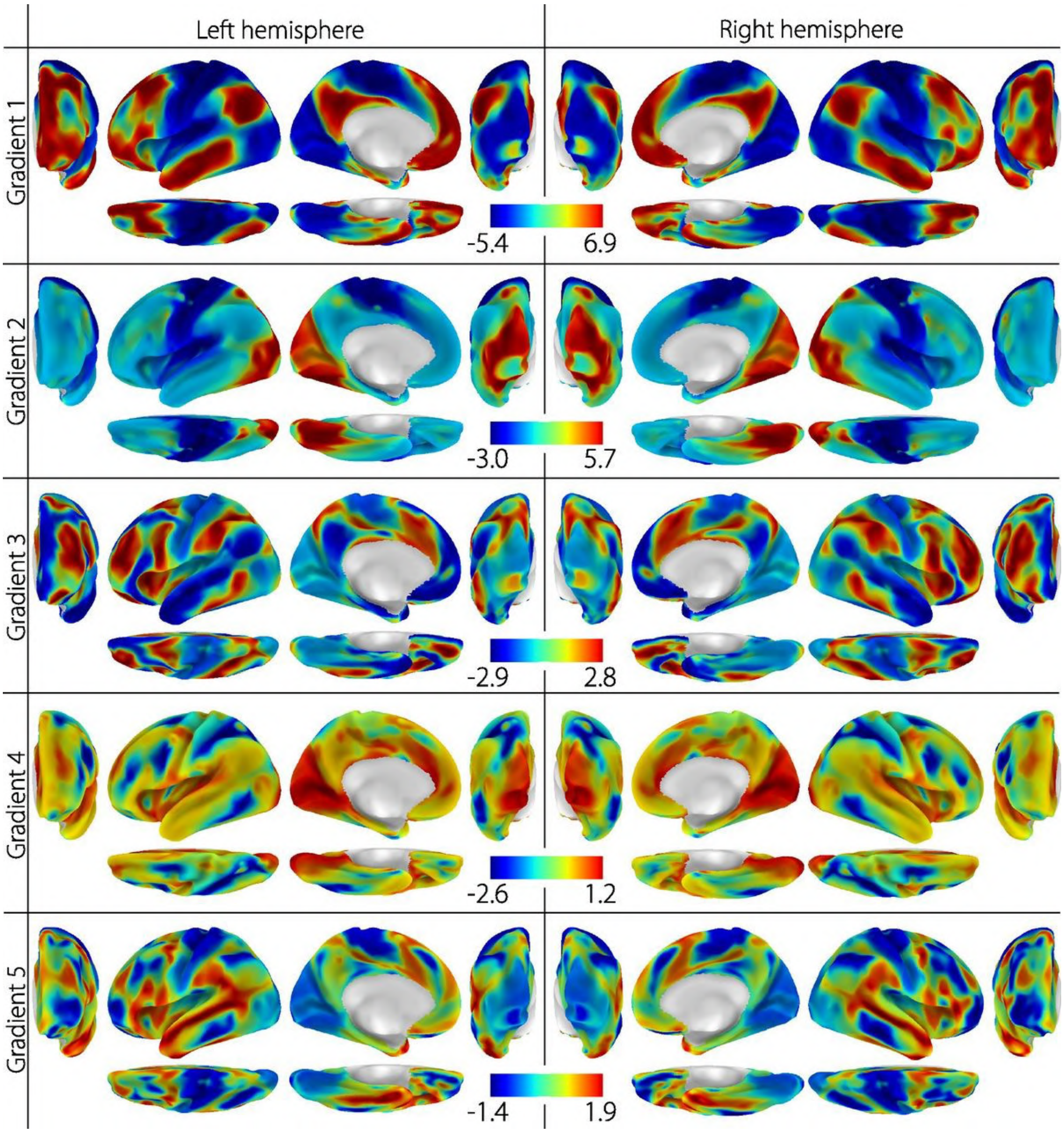

Figure 4.12. The principal gradient of connectivity in both the (A) human and (B) macaque monkey cortices shows a spectrum between unimodal regions (dark blue color), and transmodal regions (sand color), which peaks in regions corresponding to the DMN.
(Source: Margulies, D. S., et al. (2016). Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proceedings of the National Academy of Sciences USA*, 113, 12574-12579)

To carry out the study, a method was used that captures gradients in connectivity patterns over space, usually called *connectctopies* [189]. This method is called *diffusion embedding* [190] and allows both local and long-distance connections to be projected into a common space more effectively than methods that use linear dimensionality reduction, such as *principal component analysis*. The resulting graphs, called *gradients*, identify the position of the nodes along the respective embedding axis that encodes the dominant differences in the connectivity patterns of the nodes.

When conducting the study, it was possible to answer the four questions previously indicated.

4.3.3.1. Connectivity in the brain is constituted by means of a *main gradient*

Connectivity in the human brain is constituted by means of a *main connectivity gradient* (Fig. 4.12), which is anchored at one end by the primary and unimodal visual, somatosensory/motor and auditory regions, and at the other end by the regions that are part of the DMN. The regions between the two extremes of the *main gradient* include the inferior frontal sulcus, the intraparietal sulcus, and the inferior temporal sulcus, which constitute the heteromodal integration and higher-order cognitive regions [191].

4.3.3.2. The DMN peaks of the *main gradient* are equidistant from the primary areas

The *main connectivity gradient* provides a general model of the general structure of the cortical organization. In this structure, the nodes corresponding to one end of the *main gradient*, the central regions of the DMN, are at a maximum geodesic distance from the primary sensory/motor regions (Fig. 4.13) [192].

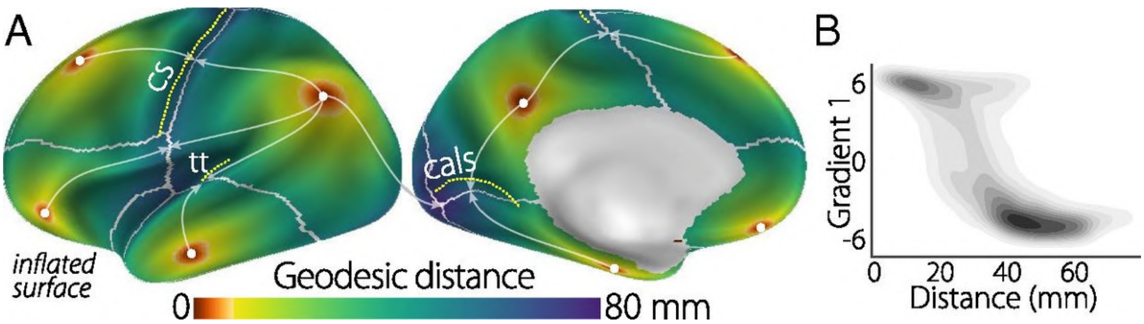

Figure 4.13. Cortical-topography organization of the main gradient
A. The minimum geodetic distance to seven seed nodes across the DMN. The morphological landmarks of the primary areas indicated by white dotted lines (the central sulcus (cs) (somatosensory / motor), the calcarine sulcus (cals) (visual), and the transverse temporal gyrus (tt) (auditory)), are equidistant from the surrounding DMN peaks.
B. Negative relationship between the geodesic distance of seven positive peak locations and the main gradient
(Source: Margulies, D. S., et al. (2016). Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proceedings of the National Academy of Sciences USA*, 113, 12574-12579)

4.3.3.3. The *main gradient* captures the spatial design of large-scale networks

Although large-scale neural networks have been delimited in detail [193], a spatial scheme had not been delimited to explain the transition from one network to another. To delimit it, a recent study has been carried out [194] in which the commonly used parceling consisting of seven networks has been examined [195] with respect to the position of each lattice along the *main gradient* (Fig. 4.14).

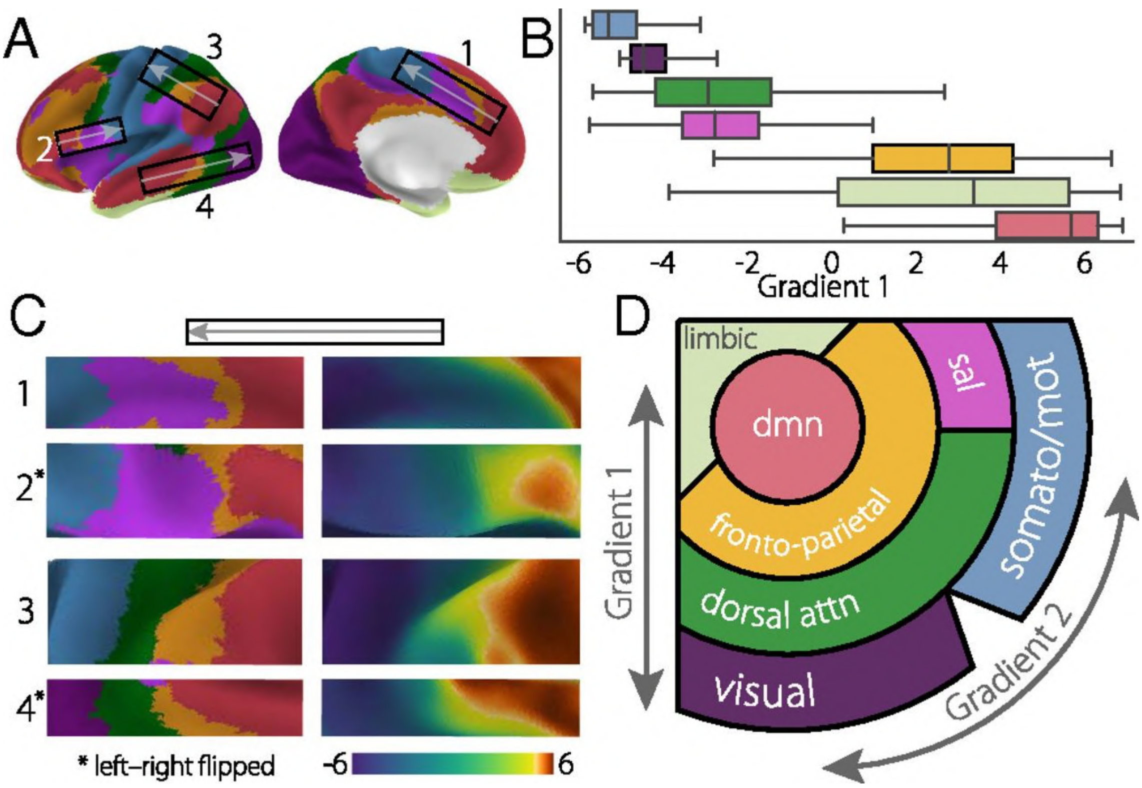

Figure 4.14. Representation of the principal gradient
A. Principal gradient values for each of the seven networks.
B. Box plots ordered by the mean value.
C. Illustrative snippets taken from A to show the repeating patterns of lattice spatial adjacency captured by the main gradient.
D. A schematic of the spatial relationships of canonical networks in a state of rest. (Source: Margulies, D. S., et al. (2016). Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proceedings of the National Academy of Sciences USA*, 113, 12574-12579)

In this study it was shown (Fig. 4.14) that neural networks are not randomly distributed, since the cortical nodes of the same network tend to cluster in similar topographic positions. The DMN occupies an extreme position along the *main gradient* and has a maximum separation with the visual and motor networks, which are at the other extreme. The limbic network is an exception since it includes a wide range of values.

Therefore, it could be verified that the *main connectivity gradient* provides a framework for the spatial organization of neural networks, and captures similar transitions between them, which occur through the cortical lobes (Fig. 4.14).

4.3.3.4. Distribution of functions along the *main gradient*

To carry out the study of functional correspondence of the main gradient, an analysis was made using the *NeuroSynth* database [196], and the BrainMap database [197]. In this study, the association between a list of functionalities with the regions of interest created from bins of five percentiles of the main gradient was examined.

As a result (Fig. 4.15), at one end of the gradient the functionality of the unimodal nodes is characterized by simple terms that describe action and perception, such as "motor processing", "visual perception processing", "multisensory processing" and "auditory processing". In contrast, at the other end of the gradient, the functionality of the DMN uses more complex terms such as “social cognition”, “verbal semantics” and “autobiographical memory”, which are tasks based on complex representations abstracted from specific sensory and motor processes. Between these extremes, generic functions such as "cued attention", "inhibition" and "working memory" appear in the regions corresponding to the anterior *Dorsal attention network* (DAN) and *Salience network* (SN).

4.3.4. The location of the DMN in the *main gradient* explains its functionality

The location of the DMN at one end of the main gradient assumes an anatomical organizational structure, which may provide clues about its role in cognition.

1. In the first place, this anatomical organizational structure explains the fact that DMN has been commonly associated with activity unrelated to external stimuli, such as daydreaming or mind wandering [198]. The DMN is located at a maximum distance from the systems involved in perception and action, both anatomically and in their functional connectivity. And this indicates that neuronal activity in these regions is likely to be similarly remote with direct input information [199].

2. Second, the DMN is located equidistant from all sensory/motor systems and is involved in a wide range of functions that require integration between multiple sensory systems, such as social cognition [200], semantic [201], and episodic [202], goal-directed

working memory tasks [203], and reward-guided decision making [204]. The two main features of the DMN related to abstraction (the independence of the stimuli, and the heterogeneity of the content) could be explained due to its position at the end of a topographic hierarchy (and therefore equidistant from the unimodal networks). As a consequence, the DMN would act as an information integration center for the different sensors [205] (Fig. 4.14).

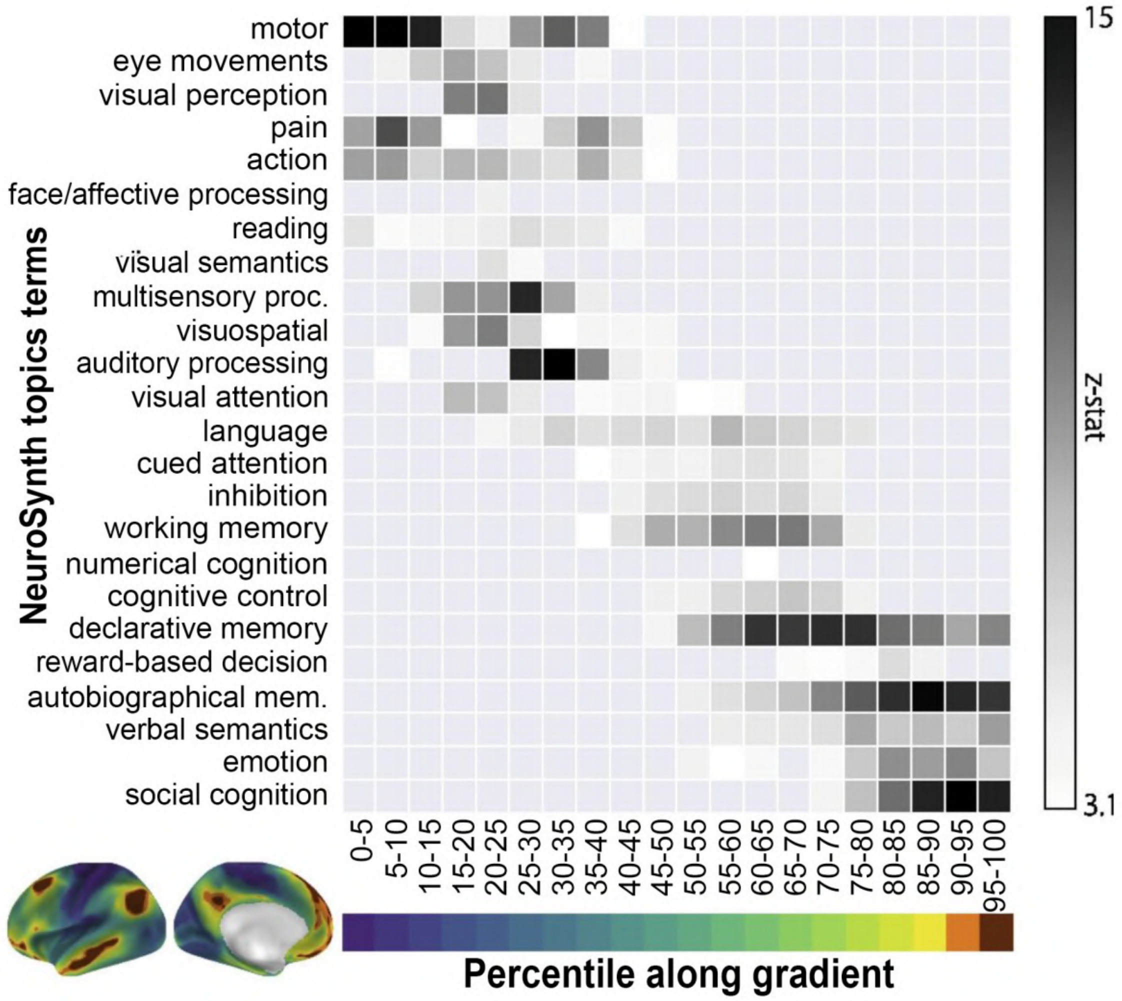

Figure 4.15. *NeuroSynth* analysis of the regions of interest along the main gradient using 24 functional terms. The terms are ordered by the weighted average of their location along the gradient. The terms at the top are related to sensory processing, the middle terms refer to general cognitive functions, and the terms at the bottom refer to abstract cognitive processes and related to higher-order memory.
(Source: Margulies, D. S., et al. (2016). Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proceedings of the National Academy of Sciences USA*, 113, 12574-12579)

The *main gradient* shows a much broader topographic organization of connectivity on a large scale [206] which explains the spatial structure of local processing flows over the entire surface of the cortex. The *main gradient,* in addition to showing local processing flows within a global framework, suitably identifies the large-scale networks along a continuous spectrum. Thus, current *multimodal cortical parceling techniques* [207] provide an effective complementary means of identifying crust parcellation.

The DMN has a great importance in human cognition, and in particular in creativity, since it allows a cognitive processing independent of the here and now. This cognitive processing is adaptive and very flexible, since the most abstract representations of the stimuli allow the generation of alternative behaviors, allowing original and creative thoughts to emerge [208].

For this reason, the DMN plays a fundamental role in creative and planning processes. [209], although for similar reasons DMN is also involved in various psychiatric disorders [210]. Therefore, the brain's ability to process information beyond the here and now has its advantages and also certain risks.

4.3.5. Relationship of the location of the DMN in the main gradient with human creative capacity

The *main gradient* shows an organization of connectivity on a large scale which explains the spatial structure of local processing flows over the entire surface of the cortex. The DMN is located at one end of the *main gradient* which explains its functionality unrelated to external stimuli, such as daydreaming or mind wandering, and it allows for cognitive processing independent of the here and now. This cognitive processing of the most abstract representations of the stimuli allows for the generation of alternative behaviors, permitting original and creative thoughts to emerge.

4.4. Relationship of the neurocognitive processes of the DMN with human creative capacity

As seen in the previous chapter, coordinated activity between three large-scale networks (DMN-ECN-SN) plays a fundamental role in human creativity.

In addition, and based on recent discoveries about its complex functionality, it has been seen that DMN, by itself, has an important role in human creativity. This section compiles the most recent studies on DMN and its relationship with human creativity.

4.4.1. Brain regions involved in creativity

There are several studies on divergent thinking (considered a central component of human creative capacity) that have resulted in a relatively consensual set of results [211].

These works indicate that there are several brain regions involved in creative processes:

- The inferior prefrontal cortex (IPFC) (region of the ECN). Involved with controlled memory retrieval [212] and with central executive processes [213].
- The DMN. Involved with internally directed attention and spontaneous cognition [214].

The inferior prefrontal cortex (IPFC) belongs to the ECN, which has an apparently opposite functionality to the DMN [215], and it is not known how both networks cooperate in creative activity. Both networks could collaborate in isolation, or alternatively they could be part of a functionally interconnected network.

To answer this question, recent research was carried out using resting-state fMRI to examine whether the ability to generate creative ideas corresponds to differences in the intrinsic organization of functional networks in the brain. [216].

The study revealed two important characteristics:

- DMN showed greater connectivity with the inferior left frontal gyrus (left IFG) in the high creativity group.
- The right IFG also showed greater functional connectivity with the bilateral inferior parietal cortex (IPL), and the left dorsolateral prefrontal cortex (dlPFC) the high creativity group.

Based on this study, it can be deduced that a neurocognitive factor of human creative capacity is based on greater functional connectivity between the inferior prefrontal cortex (IPFC) (involved in cognitive control) and the DMN (involved in low-level imaginative processes)

4.4.2. Neurocognitive processes involved in creativity

In general, studies on human creativity have revealed two different, and apparently contrary, types of neurocognitive processes:

- *Controlled cognitive processes*. In these processes, the ECN -and specifically the inferior prefrontal cortex (IPFC)- is activated, which performs a top-down control over attention and cognition.
- *Spontaneous cognitive processes*. In these processes, the DMN is activated, which performs functions of *blind-variation, selective-retention processes and internally directed attention*.

4.4.2.1. Controlled cognitive processes

Several studies show that divergent thinking involves top-down control of attention and cognition. Many of these studies show that certain higher order cognitive abilities, such as fluid intelligence [217], working memory capacity [218], and verbal fluency [219], support the creative process by providing the executive control necessary to guide recovery memory and inhibit prominent but not original ideas [220].

However, the role of cognitive control in the cognitive creative process remains unclear, as there has been research supporting an explanation of creativity as a poorly controlled process [221].

Cognitive control plays a key role in thinking, as shown by many research works using electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). Several investigations have shown that performing divergent thinking tasks activates brain regions associated with cognitive control, such as the inferior frontal gyrus (iFG) and the inferior parietal cortex (IPL) [222].

An fMRI study has also been carried out to analyze the differences between performing tasks of low creative demand with respect to performing tasks with high creative demand [223]. In this study it was observed that when performing tasks more creative demand produced a greater activation of the left angular gyrus (AG) (region of DMN), and a decrease in the activation of the right inferior parietal cortex (IPL) (region of DMN). Regardless of the level of demand of the task, a greater activation of the left IFG, el anterior cingulate cortex (ACC) (region of ECN and SL) and the precentral gyrus. This suggests that controlled memory retrieval and internal attention are important in divergent thinking.

The inferior prefrontal cortex (IPFC) (region of ECN) is also routinely triggered in various neuroimaging studies of *divergent thinking* [224].

In a very ambitious study (which included 34 functional magnetic resonance imaging studies made when performing a wide variety of creativity tasks) it was evidenced that the left IFG was one of the regions most frequently activated when creative ideas are generated [225].

Similarly, another important study [226] showed that the left IFG increased its activity as the creative quality of the responses in the divergent thinking test increased, which reinforces the role of the inferior prefrontal cortex (IPFC) during the performance of creative tasks.

These and several similar studies provide great evidence that the inferior prefrontal cortex, a region associated with controlled semantic retrieval [227] and inhibition of prepotent response, is of great importance in performing creative tasks [228].

4.4.2.2. Spontaneous cognitive processes

The same *divergent thinking* studies that detect activation in brain regions associated with controlled cognitive processes also detect activation of regions associated with spontaneous processes, that is, of the DMN [229].

Some recent studies reinforce the relationship of DMN with divergent thinking based on its functional connectivity [230]. These studies have used the resting-stage fMRI technique, a technique that measures spontaneous temporal correlations between brain signals dependent on blood oxygen level. One of these studies [231] showed that the connectivity between the mPFC and the PCC increased according to the scores obtained in the *divergent thinking* tests. Another study [232] showed an association between divergent thinking and some regions of the DMN, reporting greater functional connectivity between the medial prefrontal cortex (mPFC) and the middle temporal gyrus (MTG) (region of DMN).

Furthermore, an ambitious recent study found divergent thought-related activation in regions of the DMN, including the posterior cingulate cortex (PCC) and the inferior parietal cortex (IPL) [233].

As a conclusion of the previous studies, it can be concluded that *divergent thinking* (a valid indicator of human creative capacity) is related to the functional activation of the DMN (network associated with spontaneous cognition) and the inferior PFC (ECN region, associated with cognitive control).

Based on these previous studies, a recent study has been carried out in order to determine in detail the cognitive processes involved in divergent thinking. This study analyzed the resting state functional connectivity in subjects with low and high capacity for *divergent thinking* [234].

The results showed that individuals with high *divergent thinking* ability had greater connectivity between the inferior prefrontal cortex (bilateral IFG) and the DMN (mPFC, PCC and bilateral IPL). Specifically, in the most creative individuals, a greater functional connectivity was detected between the left IFG and the most important regions of the DMN (mPFC, PCC and bilateral IPL), and a greater connectivity between the right IFG and the bilateral IPL (but not the mPFC and PCC) (Figs. 4.16 and 4.17).

Therefore, this study demonstrated that brain regions that are linked to divergent thinking are more functionally connected in highly creative individuals.

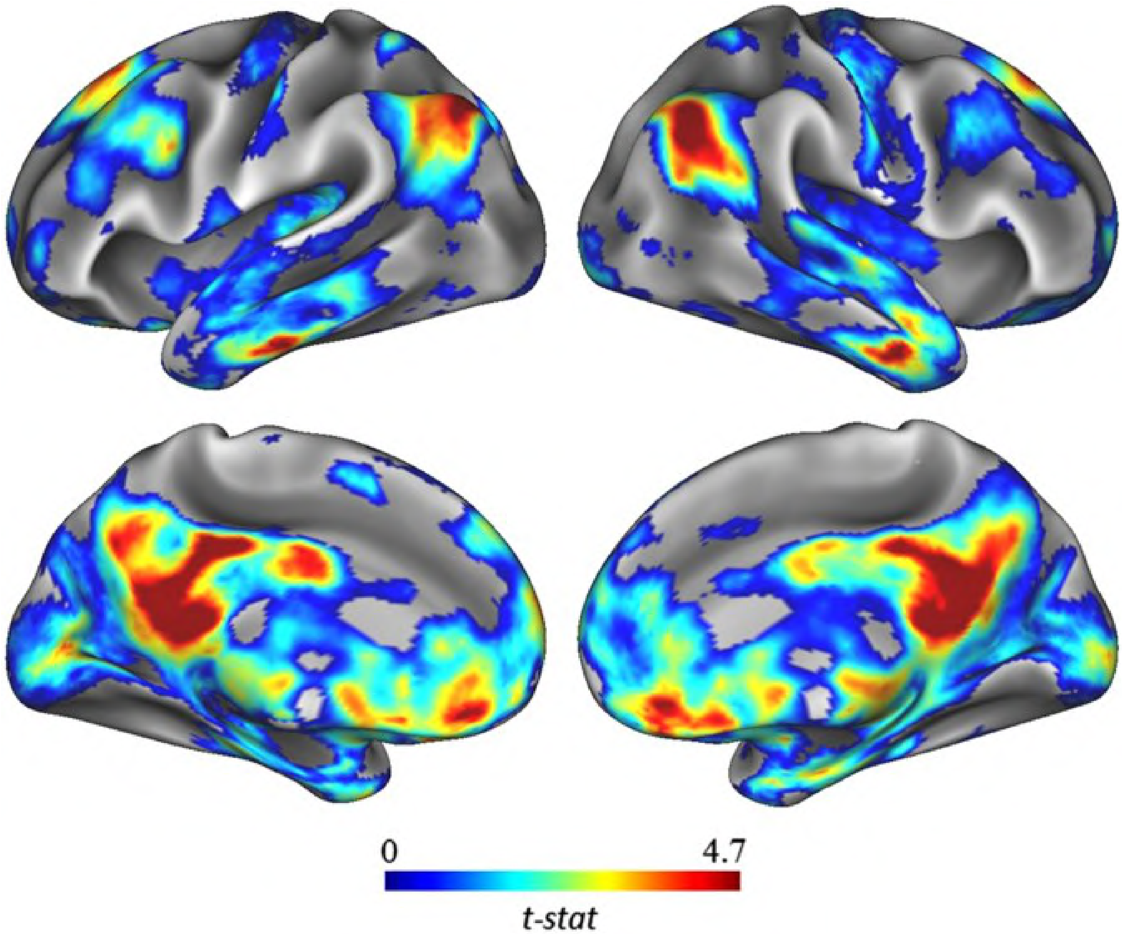

Figure 4.16. Seed-to-voxel connectivity maps to see potential group differences in functional connectivity between the left IFG and other voxels. The maps show increased functional connectivity associated with greater divergent thinking ability. ROI-to-ROI analysis.
(Source: Beaty, R. E., Benedek, M., Wilkins, R. W., Jauk, E., Fink, A., Silvia, P. J., Hodges, D. A., Koschutnig, K., & Neubauer, A. C. (2014). Creativity and the default network: A functional connectivity analysis of the creative brain at rest. *Neuropsychologia*, 64, 92-8).

4.4.3. Types of collaboration between brain regions associated with controlled cognitive processes and spontaneous cognitive processes to support divengent thinking ability

There is currently a consensus that the *divergent thinking* ability (as an indicator of human creative ability) is based on close cooperation between brain regions associated with controlled cognitive processes and spontaneous cognitive processes. However, it is still not clear how these seemingly opposing regions can collaborate, although various theories and explanations have been proposed.

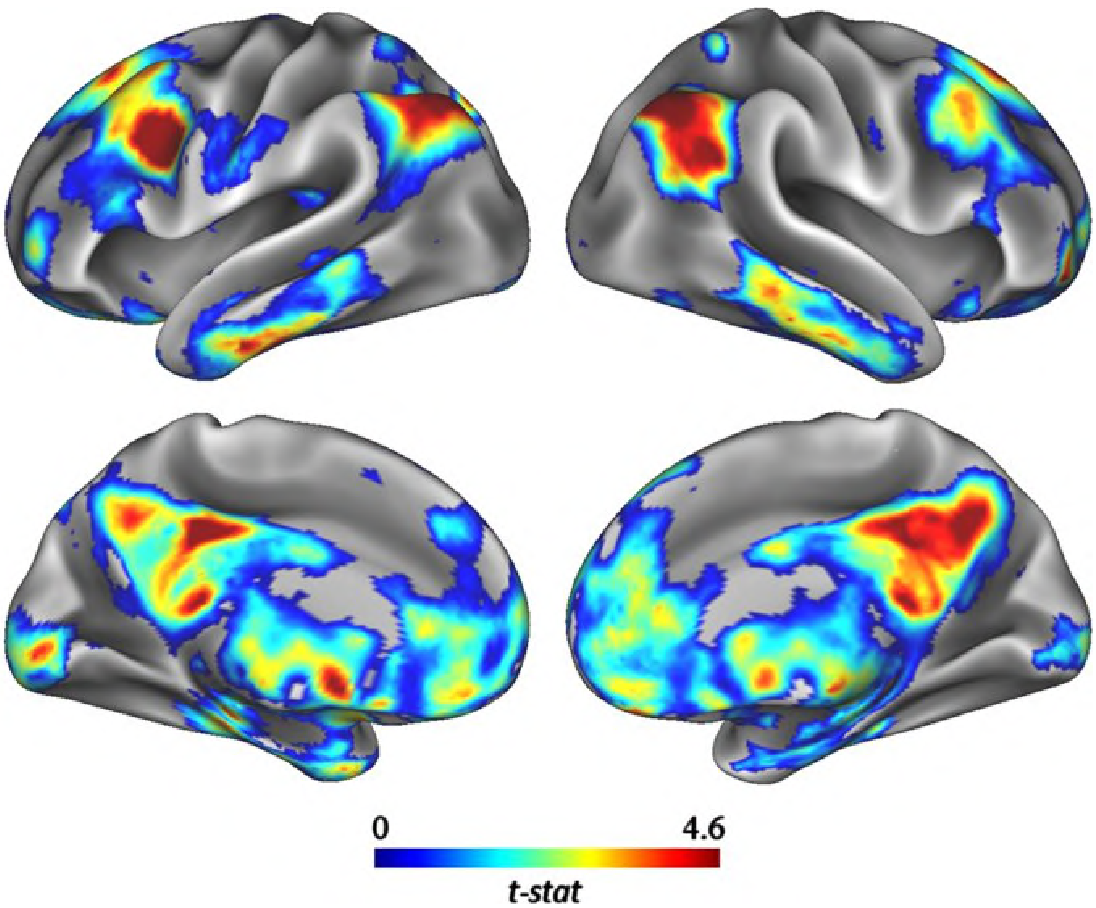

Figure 4.17. Final analysis. Functional connectivity between the high and low creative groups in the IFG and the rest of the brain. The maps show increased functional connectivity associated with greater divergent thinking ability.
(Source: Beaty, R. E., Benedek, M., Wilkins, R. W., Jauk, E., Fink, A., Silvia, P. J., Hodges, D. A., Koschutnig, K., & Neubauer, A. C. (2014). Creativity and the default network: A functional connectivity analysis of the creative brain at rest. *Neuropsychologia*, 64, 92-8).

4.4.3.1. *Blind variation* and *selective retention* processes

The most convincing explanations (from an information processing point of view) of collaboration between two apparently opposing networks suggest that the joint activation of the DMN and the ECN correspond, respectively, to *blind variation*, and *selective retention* processes [235].

The blind variation and selective retention theory (BVSR) is a conceptual evolutionary model of the creative process proposed by Campbell [236] and expanded by Simonton [237] suggested that DMN could generate an uncontrolled process of *blind variation* based on random conceptual combinations. In a complementary way, Jung also suggested that the

ECN could perform a controlled process of *selective retention*, which involves the evaluation of the activity of *blind variation*.

Therefore, the BVSR conceptual model could be valid for the neurocognitive functioning of the brain, since the increase in functional connectivity between the DMN and the bilateral IFG may reflect *blind variation* and *selective retention* processes that work more closely, and more effectively, in the most creative people.

4.4.3.2. *Failing to deactivate* theory

An alternative theory suggests high creative capacity may be based on a “failure to deactivate” regions of the DMN during tasks that require focused external attention [238]. This theory is based on several works in which it was shown that highly creative people were not able to suppress activity in the precuneus (region of DMN) while performing a working memory task (in which the ECN is involved). This suggests that creative ability can benefit from the coactivation of regions of the ECN and the DMN.

4.4.3.3. Differential contributions of DMN and ECN

A recent study on creative drawing evidenced differential contributions of ECN and DMN during the different stages of the design process [239]. In this study, the DMN was activated more strongly during the idea generation stage, and instead the regions of the ECN were activated more strongly during the idea evaluation stage.

4.4.3.4. Flexible cognitive control

Another functional connectivity study showed a greater coupling of the ECN network and the DMN network throughout the creative process, reinforcing the idea that the creative process requires flexible cognitive control [240].

Taking these studies into account, new research was carried out and a consensual account has been created that creativity is a process of *controlled attention* [241].

As is known, DMN is involved with a wide range of imaginative processes, such as mind wandering [242], mental simulation [243], and episodic future thinking [244], which have great relevance for creative thinking. Consequently, the functional connectivity (related to divergent thinking) between the inferior prefrontal cortex (IPFC) (region of ECN) and the DMN may reflect a top-down control of bottom-up processes. In other words, the cognitive control mechanisms of the lower prefrontal cortex may be responsible for directing and monitoring the spontaneous activity of the DMN.

Divergent thinking could use this process of controlled attention to prevent outstanding and unoriginal ideas from getting in the way of the creative process. It has been observed that when carrying out the famous “tasks of alternative uses”, the first responses that are generated correspond to concepts strongly associated semantically with the objects to be used (for example, when it is requested to generate alternative uses for bricks, the first answers are usually: "build a brick house", which is uncreative) [245]. In this sense, cognitive control can collaborate in divergent thinking by inhibiting non-original ideas and shifting attention to other different semantic categories [246]. Therefore, the ECN, and specifically the lower prefrontal cortex, appears to perform certain necessary functions of supervising the generation of ideas. In fact, recent studies have shown that ECN interacts with DMN during mental simulation processes [247].

Therefore, the existence of greater connectivity between the right IFG and the inferior parietal cortex could reflect the ability of highly creative people to exert top-down control over the imaginative process that arises from the DMN. The left IFG can provide oversight by guiding search processes and evaluating potential candidate responses. In fact, the left IFG has been implicated in several divergent thinking functional magnetic resonance imaging studies [248], and controlled memory retrieval [249].

In summary, and based on the set of studies shown, the increase in functional connectivity between the inferior prefrontal cortex (ECN) and the DMN may correspond to a greater capacity of creative individuals to control their imagination, executing complex search processes, inhibiting information irrelevant to the task and selecting ideas from a large set of alternatives.

4.5. Proposal to change the name of the DMN: *Deep cognitive network* (DCN)

DMN owes its name to the fact that it was initially detected because it was activated in the absence of external stimuli.

However, based on a large number of studies today it is known that DMN is involved in several high-level cognitive functions related to autobiographical, episodic and semantic memory, mental simulations, mind wandering, future thinking, empathic attitude, affective processing, moral judgment, aesthetic judgment, creativity, narrative comprehension, space navigation, decision-making based on rewards, etc. Furthermore, the DMN has an important role in the integration of the cholinergic and dopaminergic systems dedicated to memory and emotion.

These activities are very varied in nature, and it may appear that they all have something in common. However, all of them are high-level cognitive activities, related to abstract forms of human experience.

The activity of the DMN has a high level of abstraction and is unrelated to external stimuli, and this is because the main nodes of the DMN are located at a maximum distance from the systems involved in perception and action, both anatomically and in their functional connectivity. Additionally, the DMN nodes are located equidistant from all sensory/motor systems and is involved in a wide range of functions that require integration between multiple sensory systems (social cognition, semantic, and episodic, goal-directed working memory tasks, reward-guided decision making, etc.). Therefore, the DMN would act as an information integration center for the different sensors.

Due to the fact that this network is involved with various types of high-level cognitive functions, related to the essential and highest values that are usually attributed to human nature, I propose that it be renamed as *Deep cognitive network* (DCN).

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CHAPTER 5

Identification and analysis of the neurocognitive bases of human creativity

Chapter 5. Identification and analysis of the neurocognitive bases of human creativity

One of the objectives is to carry out a compilation of the current knowledge regarding the neural bases of human creativity. These studies usually measure human activity based on the performance of subjects in *Divergent Thinking tests*, *Torrance tests of Creative Thinking*, and many others. *Divergent Thinking tests* are the most commonly used to measure creativity and, although their validity and practical value have been criticized [1], they are currently the best way to measure human creativity. Divergent thinking does not guarantee real creative achievement, but *Divergent Thinking tests* are reliable and reasonably valid predictors of a creative potential. They do not provide all-or-nothing validity, but they are an important indicator [2]. In addition, some researchers [3] have compared the result of certain tests (*Torrance tests*) with the creative level demonstrated in performing certain tasks (writing a text), and have shown that the higher the test scores, the higher the creative level demonstrated in real life.

The following sections aim to structure and group these neural bases, and therefore identify the fundamental neural factors that enable the human brain to solve problems creatively.

A second objective of this work is to analyze the basic structure of these neural bases to identify a series of patterns in the information processing of highly creative people. Based on these patterns, the conceptual structure of a computer system -based on artificial intelligence- that emulates the creative activity of the human brain can be designed.

5.1. Need to separately identify and synthesize the neurocognitive bases of creativity

In general, research on the human brain is being carried out in a bottom-up way, that is, very specific investigations of certain brain processes and structures are being carried out, and little by little links are being established between them, with the aim of to create, sooner or later, a general paradigm about the structure and functioning of the brain. In the same way, in this chapter the different factors of human creativity are grouped, analyzed and synthesized (based on an enormous amount of research). All these factors have a different nature, although by intertwining them in a coherent way, a general paradigm can be identified on the neurocognitive structure of the creativity of the human brain.

5.2. Neurocognitive substrate of human creativity

Creativity is one of the most attractive and, at the same time, most ambiguous concepts that exists. It is thus not surprising that we can find a huge number of definitions, and a vast number of articles, that try to delimit what creativity is and what it is not, as well as different ways to enhance it [5]. Here we will refer to creativity as the dynamically self-reconfiguring process under which solutions to a problem are achieved, in a new and unexpected way [6]. In this context, an enormous number of studies analyzing brain activity (in creative and non-creative individuals) have been carried out while subjects perform clearly creative activities. Based on this research, the different neural bases that justify the enormous creative capacity of the human brain have been compiled, synthesized and analyzed.

As a result, 17 main characteristics of the human brain have been differentiated (although there may be more) that underlie this high creative power. These 17 factors are described below, and parallels are suggested to create an artificial intelligence system that emulates the creative activity of the human brain.

5.2.1. Structure of the human cognitive system based on large-scale neural networks

From what is currently known, the human cognitive structure is based on different areas of the brain that cooperate to form neural networks, which in turn cooperate with each other in different ways (Fig. 5.1).

The main large-scale neural network studies began in 1990 [7], and more recently the new techniques of *Diffusion tensor imaging* (DTI) and *Resting state functional magnetic resonance imaging* (fMRI) have made it possible to characterize new structural and functional networks, both when the brain is in a resting state [8], or when it is active [9]. It should be noted that the main neural networks of the brain (and the subnets that compose it) show a close correspondence in an independent analysis of activity patterns at rest or performing a task [10]. This suggests that functional networks are coupled at rest and they engage systematically during cognitive activity.

Of all the networks identified, three of them have a fundamental role in human creativity: the *Executive control network* (ECN), the *Default mode network* (DMN), and the *Salience network* (SN) [11].

The fact that the human cognitive system is based on neural networks is the first element found that supports human creativity. Each neural network is not a completely defined set with a fixed neural structure. Instead, it is a diffuse and flexible neural set, with a structure that continues to register subtle changes [12]. Therefore, every time a specific neural network is activated, even if the stimuli are the same, its structure is slightly different. The same happens with specialized areas that are grouped into networks. In addition to not having specific limits, each one can belong to several networks. It can therefore be said that humans never have the same processing system. In other words, the same problem is solved in a slightly different way each time, to the point that a small change in the external stimuli can generate significant variations in some networks.

To understand the human cognitive structure based on flexible neural networks and how they work, a valid example could be construction worker crews. There are specialized crews that do formwork, or crews of painters, carpenters, masons, ironworkers, etc. Each crew performs a certain task, never with the same workers, but using those that are needed for each job. Each crew has a fixed number of specialized workers, but it also has a variable number of additional workers who can change continuously. Therefore, a certain worker could be called to be part of a crew, one day for excavation, another to put up a wall, the next to work on a structure, and the following to paint. If the number of crews was fixed, and each crew always had the same workers, the resulting building or structure would always be the same. On the other hand, if the number of crews were different, with a variable number of workers who also change, the buildings would always be different (that is, more creative).

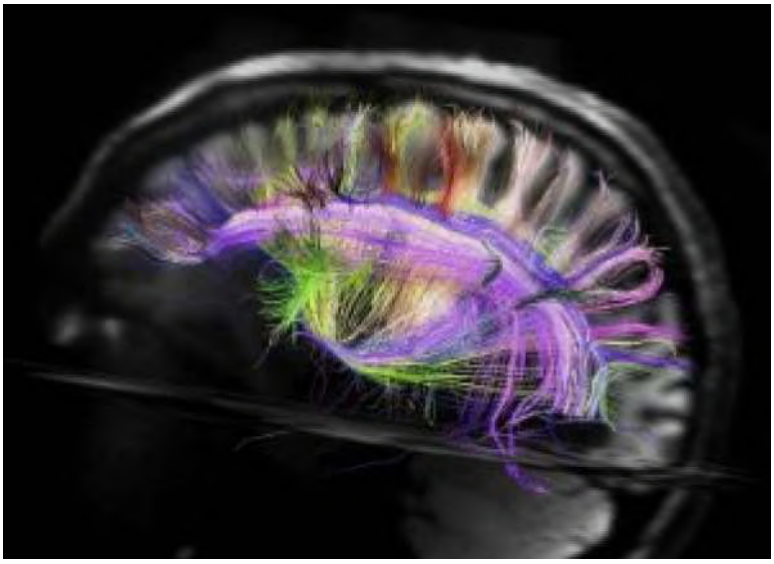

Figure 5.1. *Connectome* simulation of neural networks in brain

(Source: Bardin, J. (2012). Neuroscience: Making connections. Nature, 483, 394-396)

Another important characteristic of large-scale networks is that they remain active even when no activity is taking place [13]. Some networks that are activated by performing tasks, such as the ECN for example, continue with certain unconscious activity performing minimal testing and monitoring tasks. On the other hand, other networks increase their activity when no task is being carried out, such as the DMN. Its activity is unconscious, and therefore it gives the feeling that no activity is being carried out, however the brain is enhancing a very intense activity.

This explains the fact that, after an incessant conscious effort trying to find a creative solution to a problem, in periods in which no activity is being carried out, very creative ideas arise, and it seems to us that they arise out of nowhere, since we are not aware of the incessant work that the brain is doing.

5.2.2. Multimodal organization of the brain

Today it is commonly accepted that interdigitated networks occur as a whole in the brain and this generates human cognition. Therefore, the subdivisions of sensory, multimodal and cognitive processing should be studied from the point of view of interdigitated systems and network interactions, and not as segregated parts [14].

In this *multimodal organization* of the brain the information flows through the cortex in a hierarchical way [15], and sensory information flows into the upper multimodal, heteromodal, and transmodal convergence zones [16]. It can therefore be said that a *multimodal integration network* (MIN) integrates the primary sensorimotor cortices with the parallel systems at the top of the functional hierarchy of the brain.

For example, when analyzing the primary visual cortex, direct connections, decreasing connectivity gradients, and convergence pathways were identified, until reaching, after the last steps, the distributed cortical regions, now known as *the cortical hubs* of the human functional brain [17]. The same was done when analyzing the primary somatosensory cortex, and the primary auditory cortex.

In general, the *multimodal structure* of the human brain allows the progressive integration of neural signals from unimodal regions to transmodal networks. This progressive integration allows the codification of the general and invariant characteristics of the different objects, entities and processes; which in turn allows a higher-order cognition, as is the case of processes related to creativity.

5.2.3. Topographic distribution of large-scale networks, and their nodes

It is currently known that the topographic structure of the brain is not accidental, and the different large-scale networks have their main nodes distributed along the cortex in a perfectly convenient way to perform their functions. The functionality of each large-scale network is determined by its precise topographic location, and with a certain separation from the sensorimotor unimodal networks. In this sense, the main nodes of the DMN are located at a maximum topographic distance from the primary sensorimotor unimodal networks, which enables a fundamental role in human cognition. In a complementary way, the DMN is located at one end of the main gradient, with the greatest possible distance from the sensorimotor unimodal networks [18].

The topographic structure of the component nodes of the different large-scale networks of the cortex may have developed as a consequence of cortical expansion throughout human evolution (*Tethering hypothesis*) [19] (Fig. 5.2).

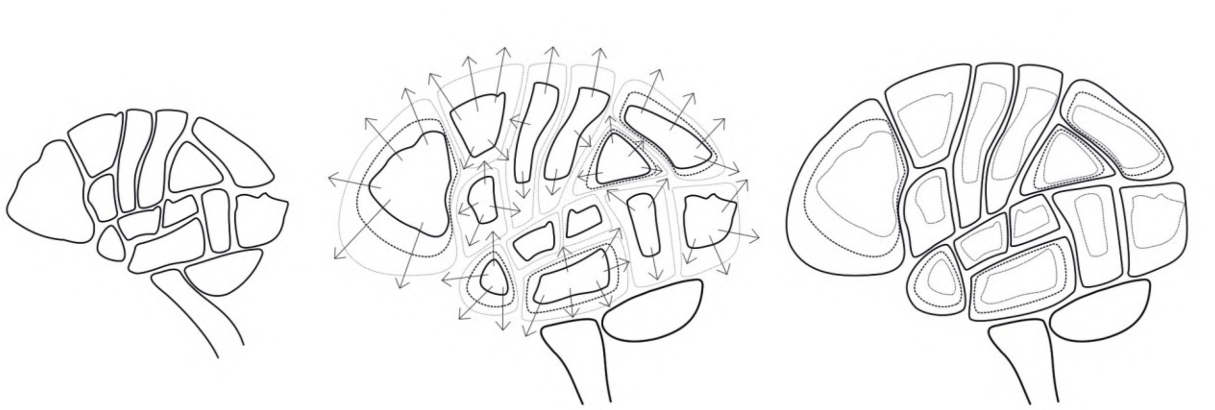

Figure 5.2. Illustrative Scheme of the *Tethering Hypothesis* (Drawing Luis De Garrido)

This evolutionary hypothesis of cortical expansion suggests that by expanding the cortex in the regions of the association cortex, these regions were freed from the limitations of sensory hierarchies. This allowed diverse functional associations to be created between these regions, especially in humans. The different large-scale networks evolved, consolidating their respective functionalities, and strategically locating their main nodes, at the appropriate distance from the sensorimotor unimodal nodes. Each node of each network was positioned at the appropriate distance with respect to said unimodal nodes in order to ensure their specific functionality and the functionality of the networks to which they belong. According to this hypothesis, the regions of the DMN are the ones that have changed their functionality the most throughout evolution [20]. Furthermore, the anterior-posterior functional axis of the DMN (which is evidenced, for example, in the strong temporal correlation between the activity of the MPFC and the PMC) may have been created in a recent evolutionary development [21].

This topographic structure allows neural networks to exist far from the sensorimotor nodes, so that the information has the opportunity to gradually abstract along its path. In this way, neural activity can move away from the primary processes of the here and now, and can have a high cognitive level. The high level of abstraction allows the semantic manipulation of information, and the generation of creative thoughts.

On the other hand, the hierarchical topographic distribution allows different networks, involving different levels of abstraction, to be established strategically positioned in the cortex. In this way, the collaboration of these networks allows a balance between processes of different levels of abstraction.

In a complementary way, the different large-scale networks are strategically positioned to guarantee their functionality and effectiveness. For example, the different nodes of the SN networks are strategically located between the nodes of the DMN and those of the ECN, and this allows efficient dynamic switching (which is a basic mechanism that enables human creative capacity).

5.2.4. Collaboration between the ***Executive control network*** (ECN), ***Salience network*** (SN) and ***Default mode network*** (DMN)

In the current research, three networks directly related to human creativity have been identified: the *Executive control network* (ECN), the *Default mode network* (DMN) and the *Salience network* (SN). Activation of the ECN and especially of the DMN has been observed during creative tasks, although the most important factors the collaboration and competition between them [22].

The ECN network is activated in the presence of external stimuli that require our attention. Certain abilities related to creativity are attributed to the ECN network, such as working memory [23], fluid intelligence [24], verbal fluency [25], and inhibition of the prepotent response [26]. These executive network functions are believed to support creative thinking by providing the control of attention necessary to manage complex search processes, and to inhibit irrelevant and external knowledge.

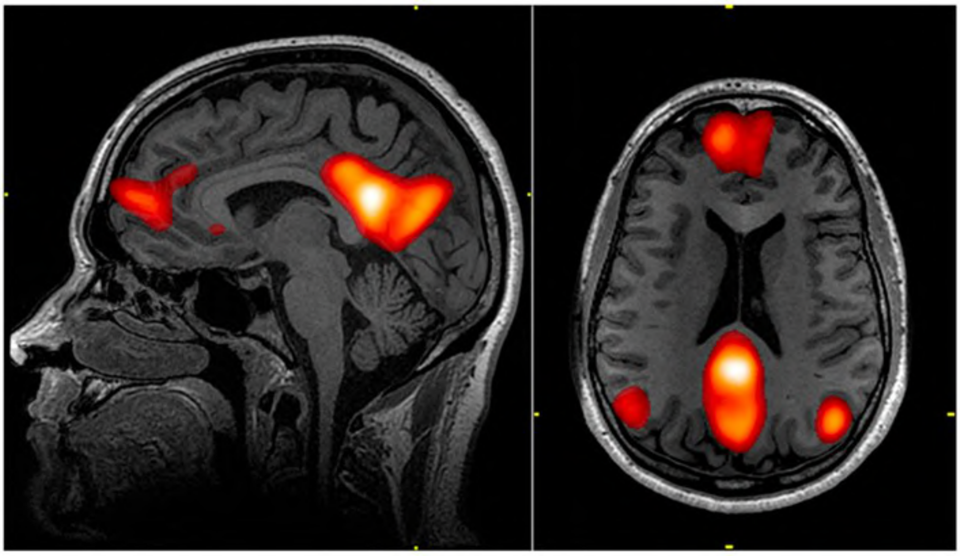

Figure 5.3. *Default Mode Network* (DMN)
(Source: Menon, V. (2011). Large-scale brain networks and psychopathology: a unifying triple network model. *Trends in Cognitive Sciences*, 15(10), 483-506)

In contrast, the DMN network (Fig. 5.3) is activated internally, in self-generated thoughts, and in the absence of external stimuli [27]. The DMN is also associated with cognitive processes that require internally-directed or self-generated thinking, such as that which occurs when the mind is wandering [28], in future thinking [29], perspective thinking [30], and mental simulation [31]. The apparent overlap between these processes and those related to the imagination has fueled speculation that the DMN is important for creativity [32]. In fact, many studies have been carried out showing the activation of the DMN in creative processes [33]. In any case, the DMN anticorrelates at all times with the *Dorsal attention network* (DAN).

Therefore, the ECN and the DMN are apparently opposite networks. They usually act in such a way that when one is active, the other is deactivated [34]. However, it has been observed, firstly, that there is an overlap of these networks (Fig. 5.4), and, secondly, that sometimes both networks cooperate when it is necessary to carry out tasks that require goal-directed cognition and extended evaluation of internal information [35].

The goal-oriented control of cognition is carried out by the ECN, which is at the top of a cortical hierarchy to organize behavior in a goal-oriented environment [36]. The ECN network routinely acts in opposition to the DMN, as it improves their responses in situations where tasks become more difficult [37].

However, sometimes ECN and DMN can work together. For example, even when neuronal activity is reduced in the DMN due to increased demand for external tasks, some regions of the DMN, such as the posteromedial cortex (PMC), show increased connectivity with regions of the ECN [38], and support task-relevant cognition [39].

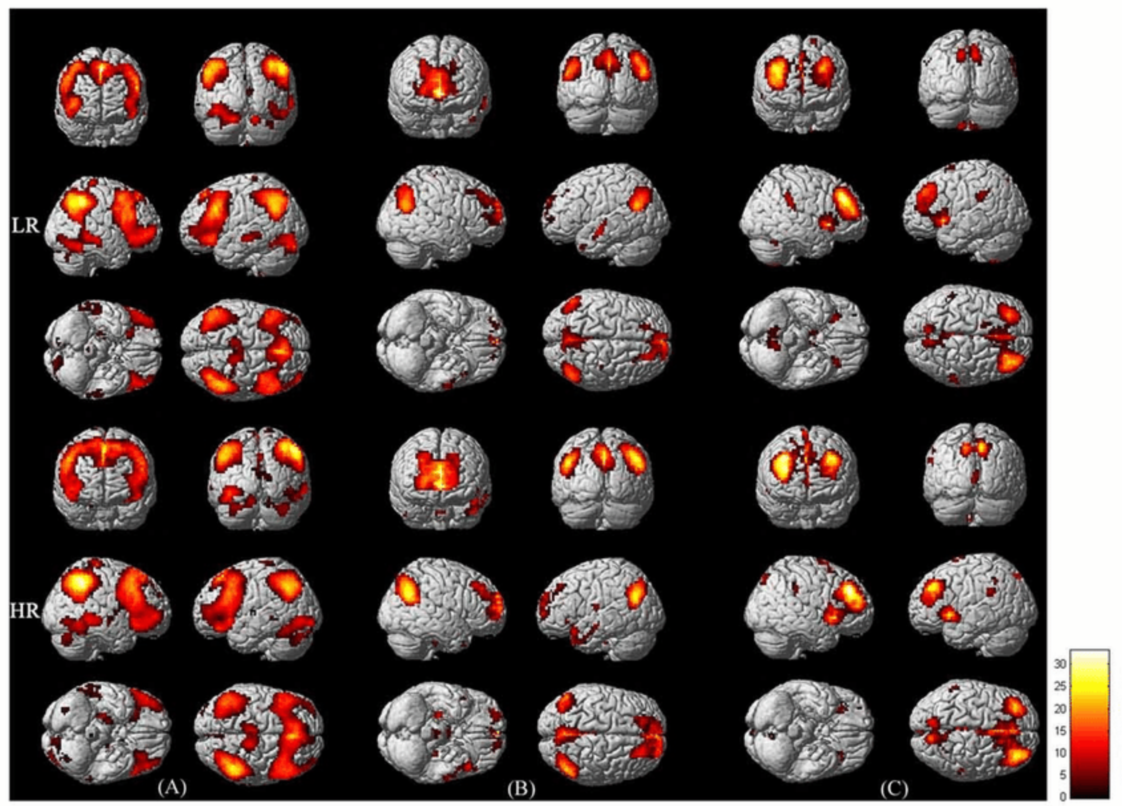

Figure 5.4. Functional connectivity maps of the *Executive control network* (ECN), *Default mode network* (DMN) and *Salience network* (SN)
(Source: Wu, X., Li, Q., Yu, X., Chen, K., Fleisher, A., Zhang, J., Reiman, E., Yao, L., & Li, R. (2016). A Triple Network Connectivity Study of Large-Scale Brain Systems in Cognitively Normal APOE4 Carriers. *Frontiers in Aging Neuroscience*, 8. 10.3389 / fnagi.2016.00231)

This collaboration also occurs during autobiographical planning [40], and in situations where decisions combine both prior knowledge with task objectives [41]. It is possible that these interactions are possible because the ECN is spatially fractionated into specialized regions to interact with the DMN, and those linked to other ECN regions more closely involved in external tasks [42]. These interactions are guided by the DLPFC, which is involved in the hierarchical organization of behavior [43], partly through interactions with the basal ganglia [44]. According to this view, the regulation of off-task spontaneous thinking with respect to the current level of external demands depends on the interactions between the dorsolateral prefrontal cortex (DLPFC), the dorsomedial DMN regions and the *Dorsal attention network* (DAN) [45].

Many higher order cognitive functions depend on top-down regulatory processes to ensure that goals are achieved. In this sense, the personal and social actions in which the DMN is involved also need a control process, performed by the ECN.

As has been said in the previous chapters, when faced with a certain creative task, the ECN is initially activated, in order to analyze the problem, and begin with the search for solutions through a goal-directed process. The more previous experience you have, the more frequently the DMN will be activated [46], which makes use of internal rules, previously created, at the same time that it is modifying them with the new problem that is being solved. The DMN performs more intense cognitive activity, since it has been observed that the brain consumes more energy when it is apparently at rest (without external stimuli) than when it is apparently active (as a consequence of external stimuli) [47]. This collaboration-competition between both networks is maintained until the problem is resolved.

However, if the problem is very complex, there is little previous experience, or it is poorly defined, the process continues incessantly in a conscious way, and also in an unconscious way. Even in periods of rest, in which apparently no task is being carried out, the DMN continues with its unconscious work, managing the self-generated thoughts, and the proposals of the MTL. Occasionally, and also unconsciously, the ECN is activated. It may be the case that the unconscious evaluation of the ECN detects a valid creative idea, in which case a set of redundant signals is generated in the cortex, generating a momentary burst of consciousness (“stream of consciousness”), in which we are aware that an apparently valid idea has been generated. An idea that requires creative conscious control, in this case carried out by the ECN. Consciously, and also unconsciously, the process continues until the idea is definitively refined.

The *Salience network* (Fig. 5.5) is the one that decides which of the two antagonistic networks is active at each given moment.

The SN is involved in the reallocation of attentional resources to prominent events in the environment [48], and is therefore believed to play a dynamic switching role between other brain networks, especially the DMN and the ECN [49].

In this context, functional connectivity between the DMN, SN and ECN may reflect dynamic switching between large-scale networks during divergent thinking (Fig. 5.6). That is, the *Salience network* is the one used to determine which of the two networks should be activated, and when they must act in an antagonistic manner or when they must cooperate. In the presence of external stimuli and tasks, it activates the ECN network, and in its absence, the DMN network.

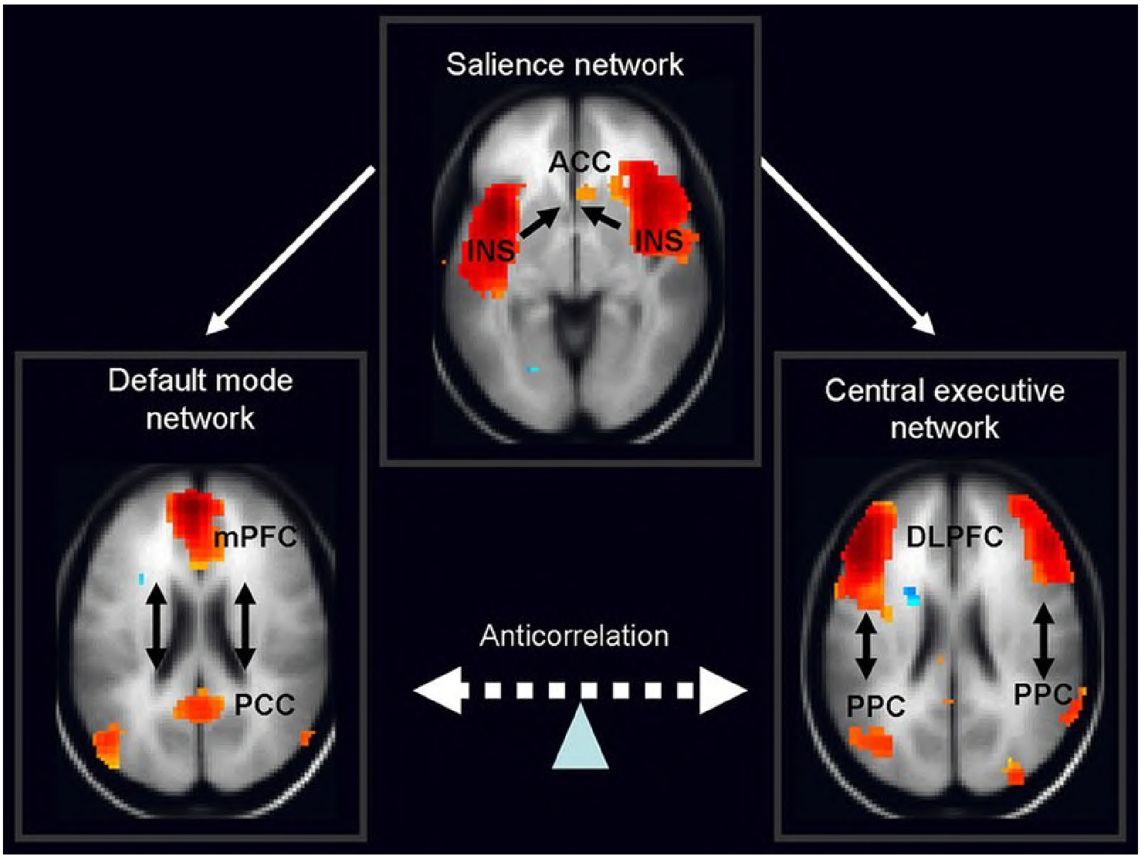

Figure 5.5. The *Salience Network* (SN) is theorized to mediate switching between the *Default mode network* (DMN) and *Executive control network* (ECN).
(Source: Menon, V. (2011). Large-scale brain networks and psychopathology: a unifying triple network model. *Trends in Cognitive Sciences*, 15(10), 483-506)

Within the *triple network model*, the ECN has an important role in human creativity since it is essential for maintaining and processing information in working memory, and for making decisions through goal-directed strategies [50]. In addition to one of the main regions of the ECN, the DLPFC plays a key role in human creative capacity.

As discussed in Chapter 3, the DLPFC is in charge of prioritizing cognition that matches the demands of a particular context. DLPFC helps prioritize off-task thinking by reducing processing of task-relevant signals [51]. This is further supported by the fact that DLPFC lesions prevent patients from ignoring external sensory input [52]. Therefore, the DLPFC may contribute to the decoupling of attention from external sensory stimuli, which is necessary for efficient processing of self-generated information [53], and is a fundamental mechanism that enables the enormous potential of the human creativity.

On the contrary, it may be the case that there is a problem in the operation of the left DLPFC, and that the generation of self-generated thoughts cannot be controlled. In this case, there will be problems at work, at school, when driving, etc. since distractions occur as a result of not being able to suppress the appearance of self-generated thoughts. On the other hand, this failure in the operation of the left DLPFC enables a mixture of information (between sensory information, and self-generated thoughts), and this greatly enables the generation of creative ideas [54].

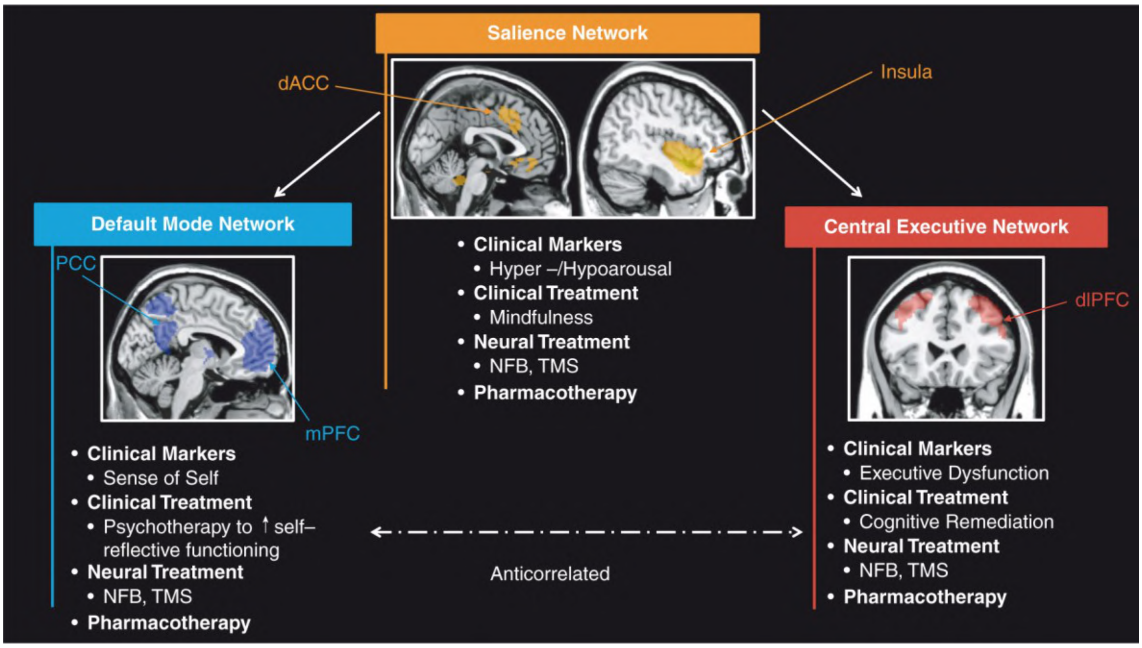

Figure 5.6. Functional connectivity maps of the *Executive control network* (ECN), *Default mode network* (DMN) and *Salience network* (SN)
(Source: Menon, V. (2011). Large-scale brain networks and psychopathology: a unifying triple network model. *Trends in Cognitive Sciences*, 15(10), 483-506)

The DLPFC is also directly involved in creative mechanisms, performing a greater integration capabilities in sensorimotor areas. Using a computational network control technique (NCT) to structural brain imaging data acquired through diffusion tensor imaging, both intelligence and creative ability were quantified [55]. This technique allows characterizing the potential role of each region in regulating whole-brain network function based on its anatomical footprint and a simplified node dynamics model. As a result, it was observed that intelligence is related to the ability to guide the brain system to neural states that are easy to reach by the right IPL and lower integration capabilities in the left RSC. Creativity was also found to be related to the ability of the right DLPFC to guide the brain system to elusive states and greater integration capabilities in sensorimotor areas. Therefore, the DLPFC, which plays an important role in performing a context-dependent prioritization of off-task thoughts, is also important, in general, in the control of creative processes. Furthermore, it was observed that the different facets of creativity (fluency, flexibility and originality) are related to generally similar but not identical network control processes.

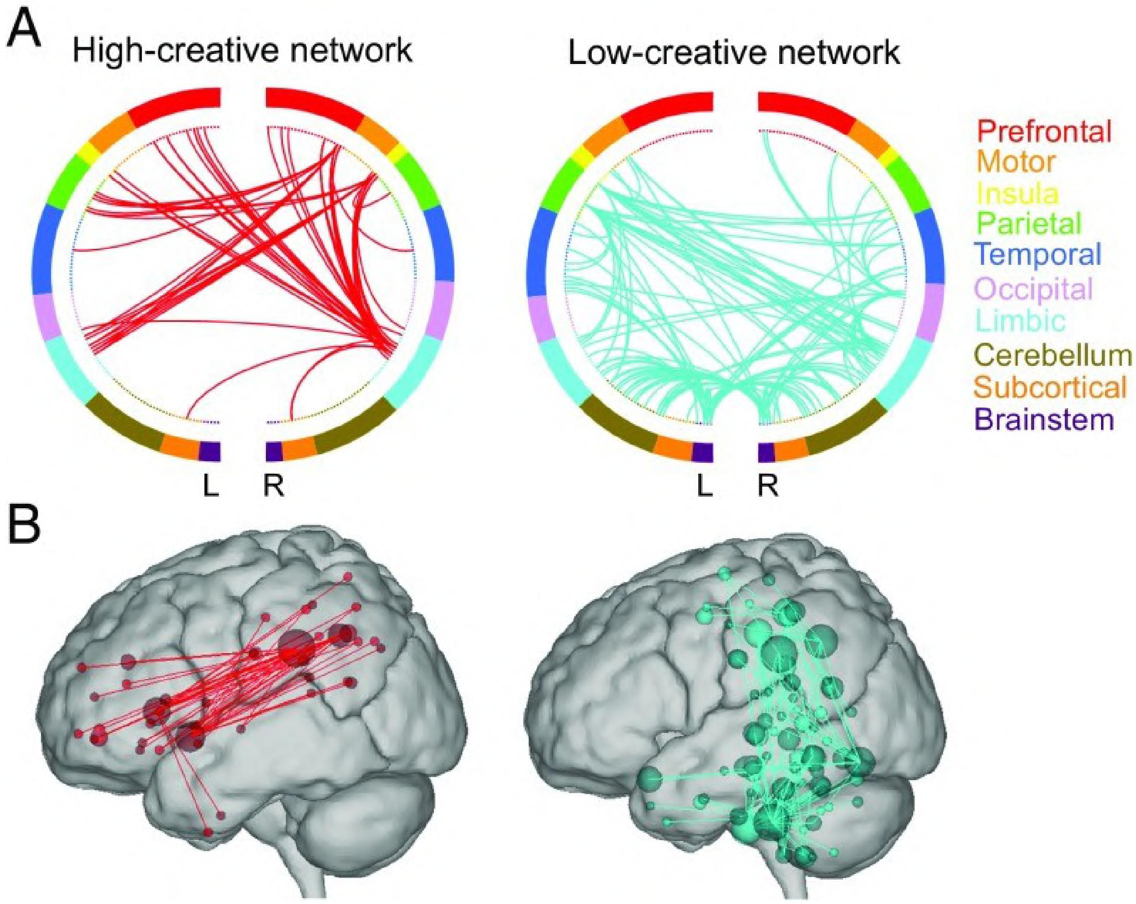

Figure 5.7. Representations of the networks of high and low creativity
(Source: Beaty, R. E., Kenett, Y. N., Christensen, A. P., Rosenberg, M. D., Benedek, M., Chen, Q., Finke, A., Qiu, J., Kwapil, T. R., Kane, M. J., & Silvia, P. J. (2018). Robust prediction of individual creative ability from brain functional connectivity. *Proceedings of the National Academy of Sciences USA*, 115(5), 1087-1092)

The collaboration between the ECN, the SN and the DMN in the creative processes is so close that it has recently been discovered that some of the main regions of these networks constitute a large-scale network directly involved in creativity (Fig. 5.7). Using a recently developed technique in fMRI data analysis, connectome-based predictive modeling, creative ability has recently been identified and modeled as a function of variation in whole-brain functional connectivity [56]. Thus, a brain network associated with creative ability has been identified, composed of regions within the DMN (posterior cingulate cortex), SN (left anterior insula), and ECN (right dorsolateral prefrontal cortex), large-scale networks that often function in opposition. This suggests that creative ability depends on the ability to coactivate brain systems that tend to work in opposition at rest and during demanding tasks. As a consequence, this study showed that a person's ability to generate original ideas can be reliably predicted from the strength of functional connectivity within this network, indicating that creative thinking ability is characterized by a profile of distinct brain connectivity.

5.2.5. The role of the *Default mode network* (DMN)

In the previous section we have already seen the enormous importance of the existence of a network such as the DMN (Fig. 5.3) since it is involved in various processes related to human creativity. However, among all the factors, five stand out above the rest.

- Self-generated thoughts are related to the activation of the DMN, such as, for example, thinking about oneself or thinking about other people, as well as episodic representations of events that are not related to external sensory events [57]. Therefore, the DMN constitutes a source of self-generated information, not related to the sensory information, and this allows a high-level cognitive activity, which in turn enables creative processes. Self-generated thoughts can be directly or indirectly related to the task, or they can even be chaotic or random, which encourages the creative capacity of the brain.

- It was commonly known that the DMN deactivated during tasks [58], however, now we know that DMN increases its activity by performing tasks in which cognition and behavior must utilize the memory of related previous experiences, for example: when the decisions to be made depend on the information that has been generated in a previous trial [59], when task-relevant stimuli should make use of long-term memory [60], when the context of a certain task is retrieved from memory [61], when a certain action rule has already been coded that can be used in subsequent actions [62], etc. That is, the DMN is activated during externally focused tasks, when they are easy to perform, when they are boring, or when they have been previously very practiced. This means that to solve a problem, the DMN collaborates with ECN with relevant information, related to the problem, and previously stored in memory, in the form of cognitive rules.

- The nodes in the DMN are separated topographically at the maximum distance from the sensorimotor regions, and this explains that it is not directly involved with the sensory information of the environment. It is possible that the topographic location of the DMN, allows it to be freed from the limitations of the sensorimotor regions [63], and also allows creating the appropriate conditions for the emergence of different types of high-level uncoupled cognition. This pattern of information processing is called *perceptual decoupling* [64], and supports the mechanisms of imagination and creativity, allowing us to transcend the here and now, and imagine different places and times [65]. The different nodes of the DMN are conveniently distributed along the cortex, and associated with certain different sensorimotor regions (although the maximum possible physical distance from them). This explains why DMN is involved in a wide variety of apparently unrelated cognitive processes, although all of them are abstract in nature.

- The DMN is located at the end of the *main connectivity gradient* (the sensorimotor unimodal networks are located at the other end), and this allows it engaging in high-level cognitive processes, separate from the here and now. This enables the DMN to represent rough, general and abstract information about patterns of brain activity, that could be common for different potential configurations at lower levels of the hierarchy.

To understand this, an example could be given, comparing the information represented in the place cells of the Hippocampus, and in the grid cells of the entorinal cortex. The place cells represent specific characteristics of a certain scene or space (such as the color of some columns) [66]. On the other hand, the grid cells represent characteristics of the relationships between the place cells (for example, if the columns are of the same color or different colors). Therefore the grid cells provide the same information, general and invariant, to represent all the possible situations of a given spatial context, although these possible situations may be different from each other, and differ in some details.

This explains that the DMN is involved in different states of representation, that you share general features, but differ in their specific information.

5.2.6. The role of the *Medial temporal lobe* (MTL)

The *medial temporal lobe* (MTL), includes the hippocampus, amygdala and parahippocampal regions (Fig. 5.8), thus it has a direct relationship with the *medial temporal subsystem* of DMN (which includes the hippocampus, parahippocampal cortex, RSC, inferior PPL, and vmPFC) [67]. In fact, recent studies show that the parahippocampal cortex is functionally coupled to DMN [68].

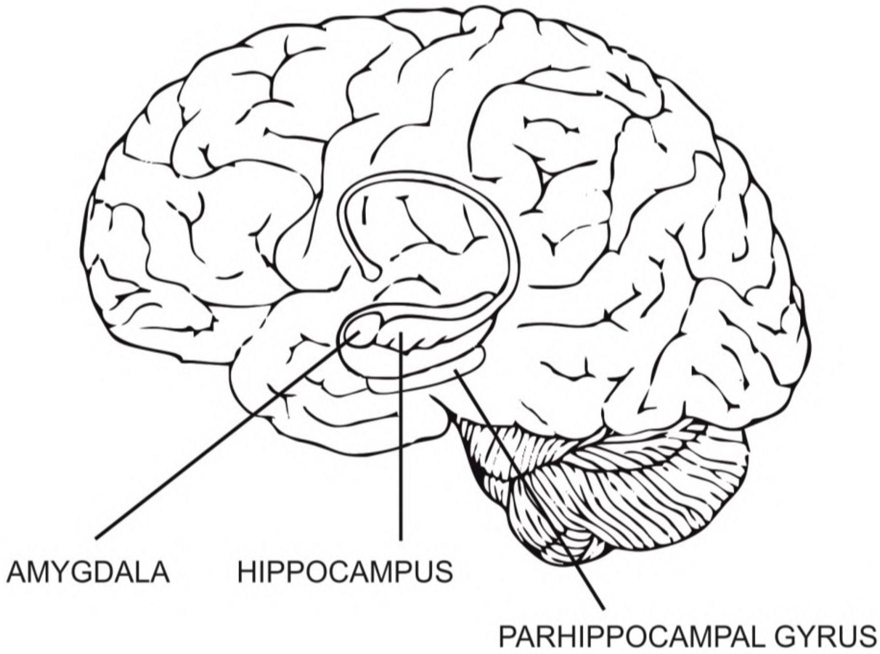

Figure 5.8. MTL location (Drawing Luis De Garrido)

The MTL plays a fundamental role in the creative process for several complementary reasons:

First, the MTL memory network is involved with associative processing [69] and with the memory retrieval process [70]. The MTL activates in the creation of semantic and episodic associations, and also in recovering these associations [71]. It is also involved when mental simulations of past events and possible future events are carried out, which require the recombination of stored information [72]. In fact, the hippocampus is involved in memory and imagination [73], the parahippocampal cortex is involved in spatial and scene recognition [74], and both involved in the creative process. The hippocampus increases its activity during visual art design [75] and also in divergent thinking [76]. On the other hand, the parahippocampus is capable of creating new associations (or accessing old associations) that the hippocampus soon afterwards mixes with other information to build episodic simulations [77]. The associative capacity of the MTL suggests that it is especially important for creative thinking, since it allows generating new ideas by making associations of previous ideas. Therefore, the MTL, together with self-generated thoughts, are the true engine of generation of basic ideas of the human brain.

Secondly, recent studies also show that the MTL is important for the creation of hierarchically organized representations and also to map complex multidimensional spaces [78]. Initially, it was believed that the cognitive maps produced by the MTL served only to represent the physical space, but now it is known that they map multiple sources of information in a rough and low-dimensional way [79]. The hippocampus is important for establishing broad cortical contexts based on patterns acquired through experience, and in this sense its connections with the DMN may be very important [80]. According to this view, the ability of the hippocampus to map task spaces depends on recurring connections with regions of the DMN, such as the MPFC [81]. Furthermore, recent studies sow also that microstructural features within the MTL have independent links with the large-scale connectivity gradients involving the DMN [82]. Therefore, the relationship between MTL and DMN helps to understand the way in which the brain represents complex task spaces and the hierarchical control of behavior. In fact, there is a clear parallel between the hierarchical cognitive organization of information and the spatial representation, and it is logical that both (and other parallel cognitive activities) are carried out by the same region. In any case, both functionalities are essential for the creative process.

Thirdly, it should be mentioned that the MTL is essential for the creation process with a graphic or special component (such as architectural design, painting, sculpture, etc.). The place cells of the hippocampus describe specific characteristics of spatial representations (such as the color of wall surfaces, the location of windows, the shape of objects in a scene, etc.) creating a complete cognitive map with the information of a certain scene, based on information provided by the senses, or based on self-generated and imagined information [83]. This information from the place cells will be combined with the information stored in the grid cells of the entorhinal cortex, which describes relationships between the information stored in the place cells [84]. The information included in the grid cells is more abstract and general, and can be common to multiple scenes. That is, the grid cells provide the same information for different scenes that share general characteristics, although they differ in certain details [85]. The MTL is therefore essential to create non-existent scenarios, and therefore to facilitate the creative process.

5.2.7. Relationship between *Working Memory* (WM) and *Task Induced Deactivation* (TID)

The *working memory* (WM) is a limited capacity storage system that is involved in the maintenance and manipulation of information over short periods of time [86]. Several psychological studies have related *working memory capacity* (WMC) with human creativity [87].

They show that the DMN is deactivated when tasks involving WM are performed. As mentioned above, the DMN network is activated when we are at rest, and deactivated in tasks that require attention, being externally directed [88].

The specific process of deactivation of the DMN is called TID (Task Induced Deactivation). Subjects with low WMC have been observed to have low TID capacity. Conversely, subjects with high WMC have a high TID capacity [89].

The low TID level observed in the precuneus of creative individuals may thus indicate that they are not capable of inhibiting or suppressing cognitive activity that is irrelevant to the task (task unrelated thought) [90], during a complex task involving WM. Creative individuals are characterized by cognitive disinhibition, that is, by their inability to inhibit or suppress certain cognitive activity [91], and reduce negative priming.

It could be speculated that creative people are incapable of suppressing unnecessary cognitive activity in the DMN, and this inability can help them associate two ideas represented in different networks [92]. The inability to suppress an irrelevant network when one is recruited can lead to the intrusion of irrelevant network thoughts and can allow two isolated ideas to combine [93]. Studies have been carried out in which a large WMC has been associated with positive attitudes towards the discipline of certain scientific studies, while a low WMC is associated with more negative opinions regarding those studies [94]. Therefore, a high WMC is associated with disciplined student processes (more disciplined and formal, and therefore less creative), while a low WMC is associated with dissatisfaction with them (and therefore possibly a desire to explore more chaotic and more creative alternative paths).

This idea of creativity has been widely established in the past, and it has been suggested that increased creativity can be accomplished using brain networks in which knowledge of one domain helps organize a different one that may share some of its attributes [95].

On the other hand, and in a complementary way to the above, it should be taken into account that when performing undemanding tasks, people with higher working memory create few self-generated thoughts unrelated to the current task [96]. On the other hand, when more demanding tasks are performed, people with greater cognitive control generate more self-generated thoughts not related to the task [97].

5.2.8. The role of the insula (and, in general, the *Salience network*)

The insula (Fig. 5.9 and 5.10) is believed to be involved in consciousness and play a role in diverse functions usually linked to emotion or the regulation of the body's homeostasis. These functions included compassion and empathy, taste, perception, motor control, self-awareness, cognitive functioning, and interpersonal experience.

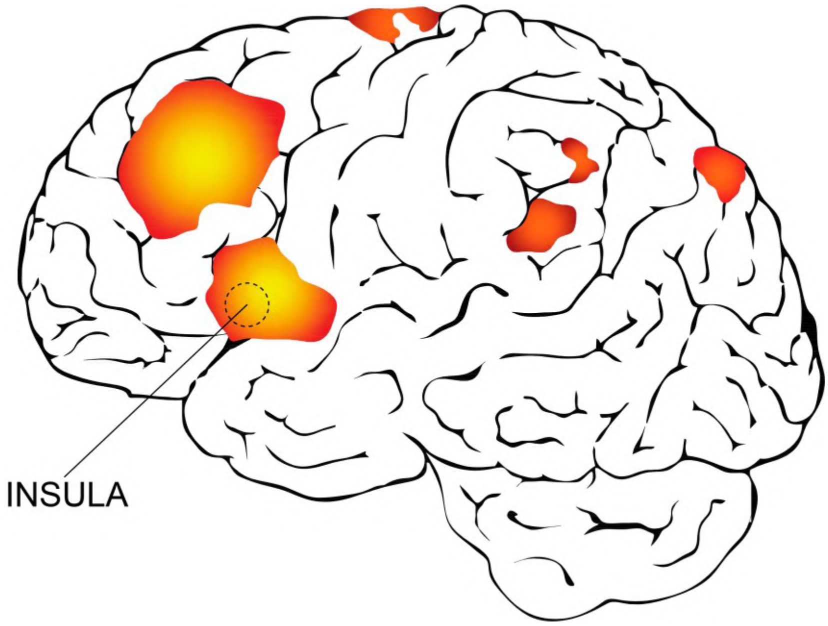

Figure 5.9. Insula and *Salience network*, drawing by Luis De Garrido

The insula is an integral node used to mediate dynamic interactions between other large-scale networks involved in external events and self-related cognition [98]. The insula is sensitive to external/salient events, and its main functions are to mark such events for further processing and initiate appropriate control signals.

The insula and the anterior cingulate cortex (ACC) make up the *Salience network* that is in charge of segregating the most relevant internal and external stimuli used to direct behavior [99].

The basic functions of the insula are:

1. Bottom-up detection of outgoing events.
2. Switching between other large-scale networks to facilitate access to attention resources and working memory when an external event occurs.

3. Interaction between the anterior and posterior insula to modulate autonomic activity to salient stimuli.

4. Functional coupling with the ACC that facilitates quick access to motor system.

The *Salience network* (SN), with the insula as its integral center, assists the corresponding brain regions in generating appropriate behavioral responses to salient stimuli.

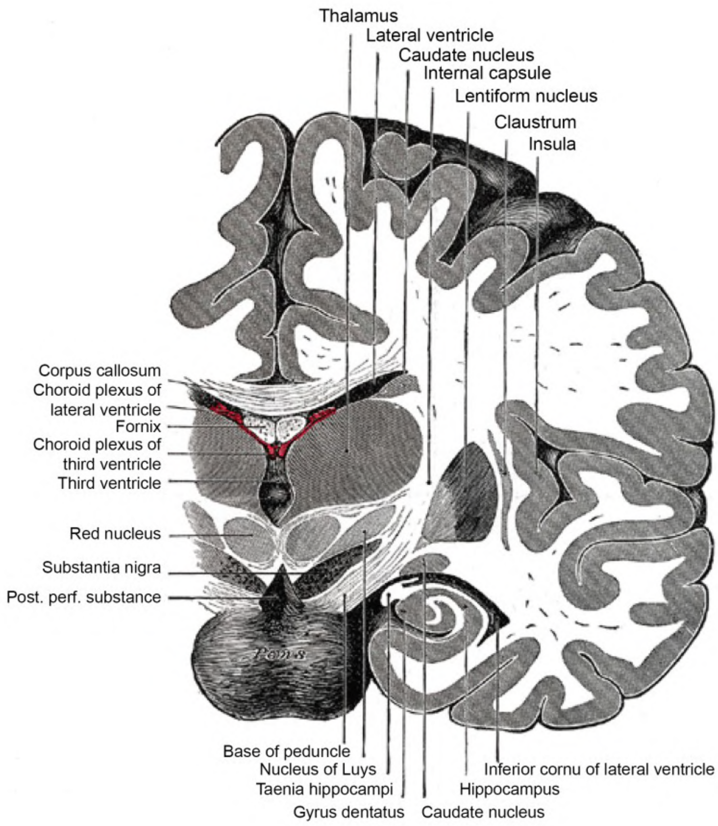

Figure 5.10. Coronal section of brain showing insula, gyrus and thalamus

Previous studies suggested that the ACC inferior frontal gyrus is involved in a variety of supervisory, decision-making, and cognitive processes [100]. It is assumed that the main function of the *Salience network* (and specifically the insula) is to identify external stimuli transmitted through the senses. Once these stimuli have been detected, the insula facilitates the processing of task-related information by initiating appropriate transient control signals. These signals involve the areas of the brain that mediate high-level cognitive, attentional and working memory processes while decoupling the DMN.

These switching mechanisms help direct attention to external stimuli, which, as a result, become more important and relevant.

5.2.9. The role of the angular gyrus (left AG and IFG)

Angular gyrus (Fig. 5.11) is involved in multimodal integration and vividness; and left angular gyrus (left AG) is activated through a wide range of semantic processes, and is a component of the DMN that is deactivated when performing goal-oriented tasks [101].

The angular gyrus (AG) plays a strategic role in the human cognitive system, since it is involved in countless processes such as: semantic processing, reading and comprehension, number processing, attention and spatial cognition, memory retrieval, conflict resolution, theory of mind, social cognition, visuospatial processing, production of sentences with meaning, reading and coding of symbols and, especially, the processing of the sequences of actions that must be carried out in a task [102]. In fact, it constitutes an important *cross-modal integrative hub* of the cognitive system [103].

The AG is the head node of the *predictive coding framework* [104] that models the brain as a hierarchical inference engine that attempts to optimize probabilistic representations of what caused its sensory input. In this framework, the AG acts as an interface between bottom-up converging multisensory inputs and top-down predictions (Fig. 5.12). The top-down predictions are transmitted through backward connections and compared with the representations that are generated in the AG. Comparing both values creates a prediction error, whose value is sent to higher cognitive levels to adjust and optimize future predictions. The recurring exchange of bottom-up prediction errors and top-down predictions continues until the prediction error is minimized at all levels of the system. Therefore, the intermodal integration carried out in the AG can be seen conceptually as the sum of this recurring exchange.

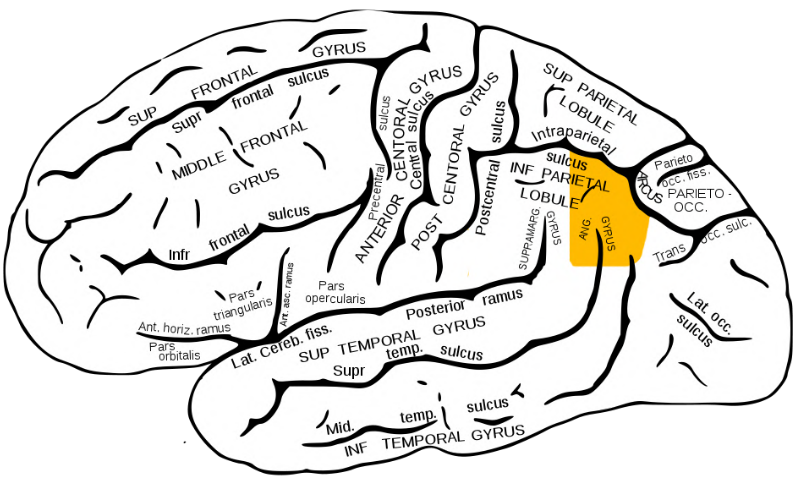

Figure 5.11. Angular gyrus

This framework can explain the multiple functions of the AG. For example, semantic access is a key neurocognitive process in language comprehension and sentence reading. Likewise, the memory retrieval consists of the retrieval of learned rules and facts that are important in the processing of numbers and in the conversion of letters to sounds during reading. Categorizing events and shifting attention to relevant information are important in social cognition, memory, and spatial cognition.

Most of the functions in which the AG is involved are related to some necessary aspects in the creative process, for which, in general, it constitutes a key factor in human creativity. However, certain areas of the AG are especially important.

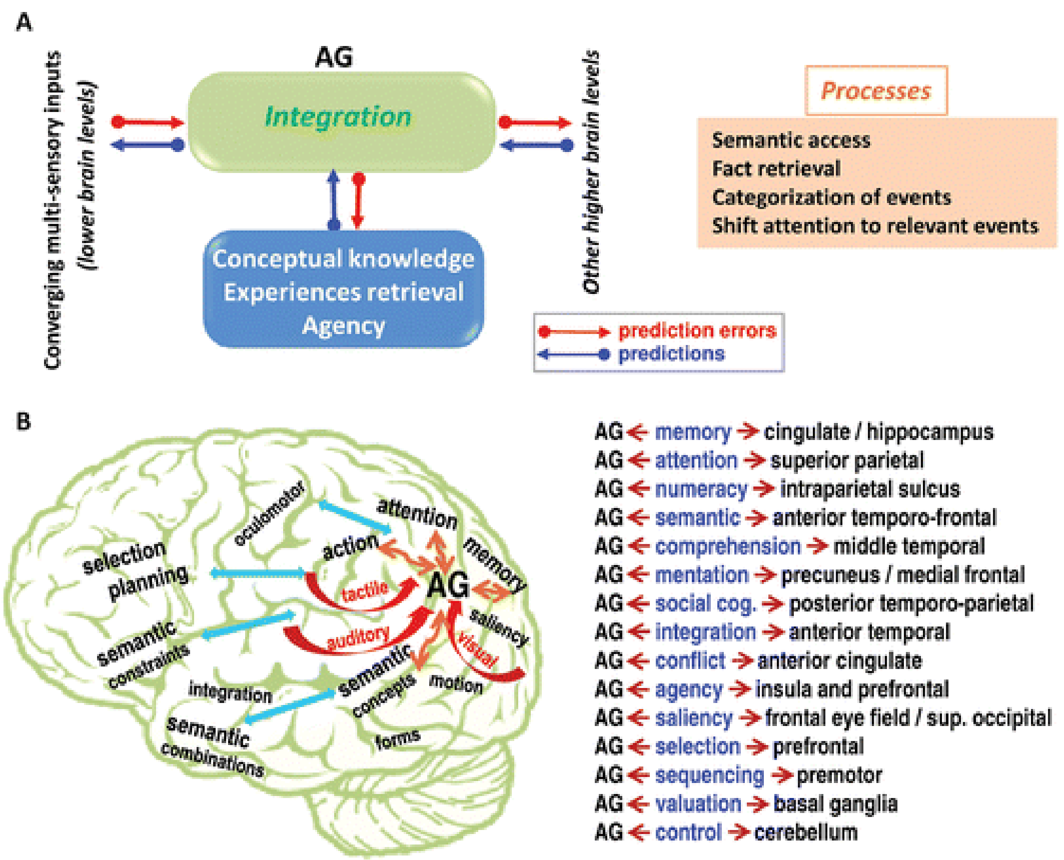

Figure 5.12.
A. Framework of the multiple functions of the angular gyrus (AG).
B. Interplay between the AG and other distributed subsystems.
(Source: Seghier, M. L. (2013). The angular gyrus: multiple functions and multiple subdivisions. *Neuroscientist*, 19(1), 43-61)

The left AG also plays an important role in human creativity because it is part of two networks related to human creativity: the Semantic network and the DMN network. It has been proposed [105], that thoughts not related to tasks (during states of passive consciousness) are essentially semantic because they involve the activation and manipulation of acquired knowledge about the world. This semantic process is interrupted during effortful tasks that require concentration to solve external problems. This interruption reduces the competition between attentive resources and exogenous and endogenous executives.

Several studies have also shown that groups of people with high divergent thinking skills had high connectivity between the inferior frontal gyrus (IFG) and the DMN. The IFG is involved in various executive processes [106], such as memory retrieval [107], and prepotent response inhibition [108]. Connectivity between the IFG and the DMN is interpreted as a highly creative ability of individuals to exercise top-down control over imaginative processes derived from the DMN.

5.2.10. Dynamic and fuzzy memory system for storing and retrieving information

Memory is distributed throughout our brain and, in general, there are three phases (Fig. 5.13) in the information storage and retrieval process [109]:

1. Coding: reception, processing, and combination of the received information.
2. Storage: creation of a permanent record of the encoded information. This entails the excitation of synapses in short-term memory, and new protein synthesis in long-term memory.
3. Retrieval: remembering the information stored in response to a signal for use in a certain process or activity.

When information is stored in the human brain, it is not done statically and directly, but in a dynamic and fuzzy way, as it is processed and filtered. Therefore, only part of it is stored, conveniently encoded, depending on its importance and the need to retrieve it. In the same way, when such information is retrieved it is not done statically or directly either, but must also be processed and is continuously mixed dynamically with other information.

Several recent experimental studies have shown that when a new perception is acquired, or a new concept is learned, a group of new *engram cells* and their associated circuits is formed in the brain [110]. It has therefore been postulated that creative thinking is a form of neuro-physiological processing in which a new group of *engram cells* arises that encodes a novel design, concept, or idea, through the formation of new connections and/or modulation associations between groups of *existing engram cells*, which represent pre-existing perceptions, memories or concepts [111]. In this sense, the information retrieved from memory is always somewhat different from the initial information, having been transformed according to the vital interests of a certain person. Therefore, the basic mechanisms of human memory enable creativity on their own. Even if you wanted to retrieve an exact copy of a certain event, it would be impossible since changes will always be made [112].

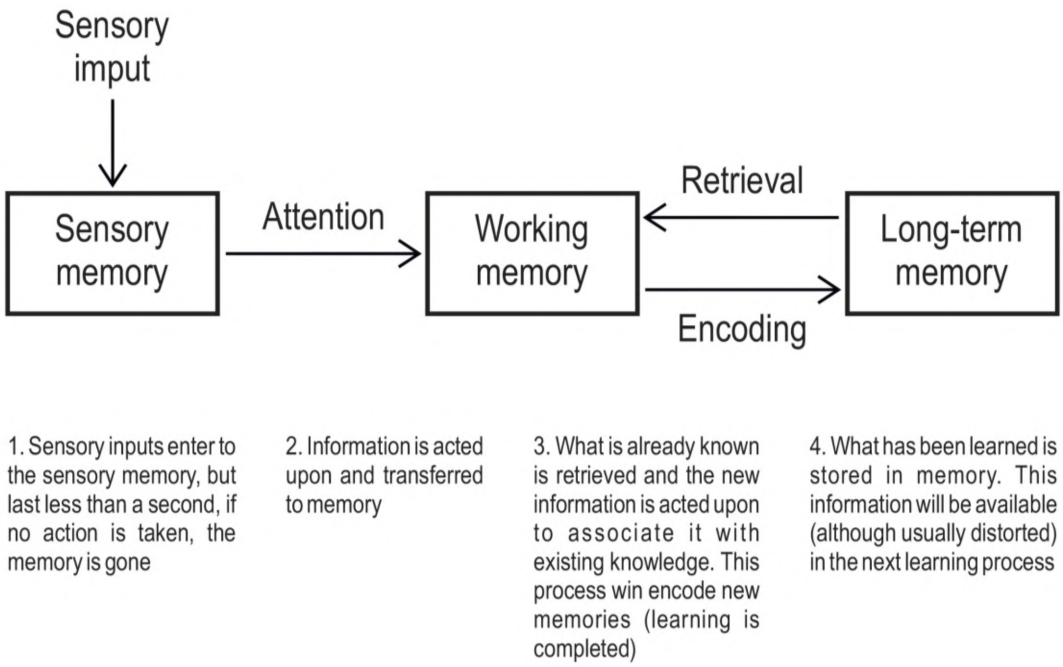

Figure 5.13. Phases in the storage and retrieval process in memory (Drawing Luis De Garrido)

5.2.11. Importance of the episodic memory

Different studies relate episodic memory to human creativity, showing that the greater a subject's episodic memory, the greater their creative capacity [113]. Episodic memory (Fig. 5.14) is responsible for storing specific personal experiences, so the evocation of these memories can be understood as a way of mentally reliving past events. Episodic memory is generally considered to be the system that supports semantic memory [114].

The basic objective of the creativity process is to find creative ideas to solve a certain problem, and the usual way to do it is looking for information in our memory that can help solve the problem. The key is to find "new memories" related to the problem we are trying to solve. Some studies have demonstrated the role of the left AG in episodic recovery, and in the coding that contributes to aspects of the subjective mnemonic experience [115], which reinforces both what is stated in this section.

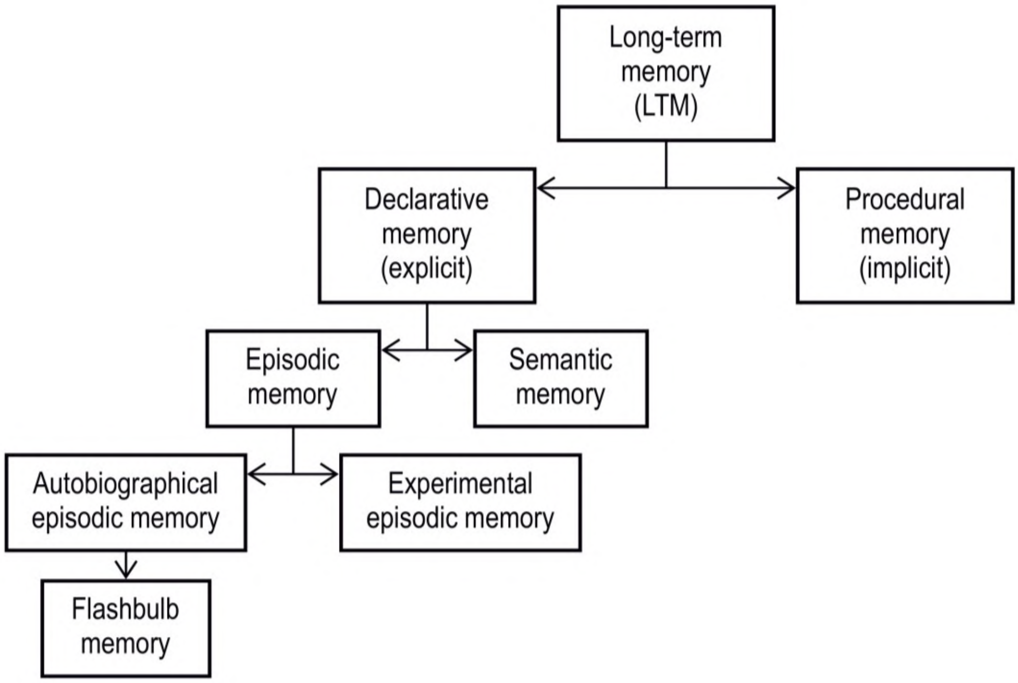

Figure 5.14. Types of memory (Drawing Luis de Garrido)

Several researchers [116] have explored the influence of a memory technique called "episodic-specific induction". This technique is based on processing a set of episodic information prior to the retrieval of data from memory. By following *episodic specific induction*, participants were able to find more alternative uses for the objects than by following the control task.

These studies allow us to infer that creative activity requires that new paths be found to access memory to find information relevant to the problem. Existing knowledge is required that can be manipulated in alternative ways to perform new creative tasks.

5.2.12. Importance of the semantic memory

It was traditionally accepted that semantic memory (conceptualization) are encoded in the brain as representations distributed through various regions. This means that each generated concept is associated with a certain verbal or sensorimotor experience [117].

However, what is currently thought of semantic memory is similar, but under a much expanded concept. Today it is assumed that additionally there are cortical regions that are fundamental to integrate and refine the "raw information" generated by the sensorimotor and verbal regions, and transform it into coherent, complete and refined transmodal semantic representations [118]. Until now, two of these regions had been identified, which act as interfaces: the middle temporal gyrus (MTG), and the anterior temporal lobe (ATL).

- *Middle temporal gyrus, MTG*

The MTG is a nucleus for integration of auditory and visual information [119].

- *Anterior temporal lobe, ATL*

Together with the modaly-specific regions (those that encode the information of the same type of sensory stimulus), the regions of the ATL also contribute fundamentally in the creation of semantic memory [120], and are involved in verbal and non-verbal semantic processing [121]. Therefore the ATL (Fig. 5.15) constitutes a *cross-modal center* of representation in which several specific sources of information are integrated [122].

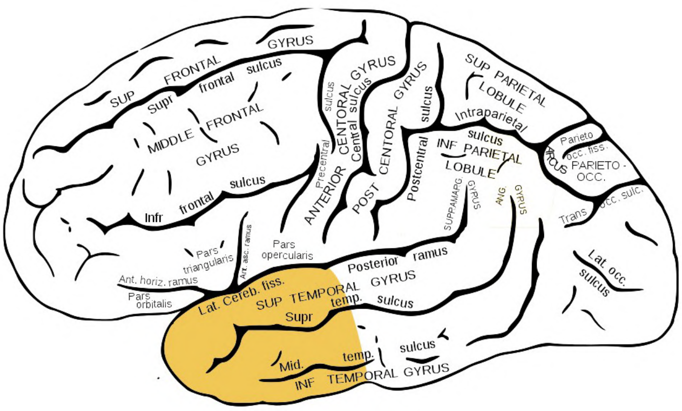

Figure 5.15. ATL location

Within this semantic model, conceptual knowledge is created through a combination of transmodal and modality-specific representations [123]. Logically, the modality-specific information is a basic source for the construction of concepts, but it is insufficient, since the different “attributes” (characteristics of objects) are combined in complex and non-linear ways when forming a concept [124].

In this context, the cross-modal center can provide two important "semantic functions”:

- It allows creating correct mappings between the modality-specific "attributes" and a certain relevant concept.

- It allows creating cross-modal representations that provide the basis for making semantic generalizations taking into account conceptual similarities, rather than superficial similarities (which constitute the central function of semantics) [125].

This semantic model is confirmed by several clinical evidences, for example by the fact that when this cross-modal center of representation is damaged (for example, due to *semantic dementia*), errors of excessive generalization are made (strange components are accepted in a group, for example, a wolf is accepted as a type of dog) and sub-generalizations (the atypical components of a group are rejected, for example, a Chihuahua is rejected as if it were not a dog) to a certain concept [126].

Semantic memory is essential for the creative process since the new concepts that must be created must be based on the modification of existing concepts, or on the fusion of several of them. Therefore, knowing the mechanism by which the meanings and characteristics of the concepts are established (both those already existing and those to be created) is essential to know the mechanisms of human creativity.

Using new computational techniques, the semantic network has been studied, through the analysis of free associations. As a result, it has been shown that the most creative people have a richer and more flexible associative network than the less creative people [127]. The semantic memory networks of individuals with low creative ability and individuals with high ability were compared and the resulting networks were different. The semantic memory network of more creative people seems more dispersed and made up of more subparts.

On the other hand, it has been seen that since the creative process in general is composed of a combined set of top-down and bottom-up cognitive processes, the structure of the mental lexicon plays a key component. This mental lexicón is directly related to creative capacity (especially a bottom-up process) or to cognitive control processes (top-down). In fact, recent studies show that fluid intelligence is more related to the structure of the lexical network, while creative processes are more related to its flexibility [128]. These findings therefore provide valuable information on the structural and functional properties of semantic networks

Finally, a recent network percolation study (for the removal of weak links from a network) has been used to computationally examine the robustness of semantic memory networks of individuals with low and high creativity [129].

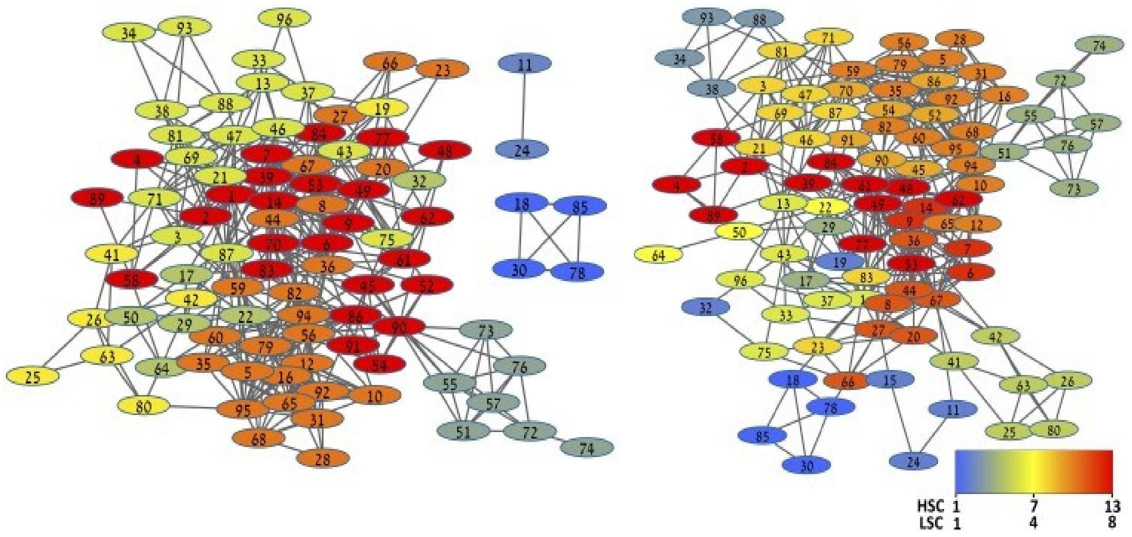

Fig. 5.16. LowSC and HighSC networks. The nodes are numbered according to their labels and colored from blue to red according to their percolation order
(Source: Kenett, Y. N., Levy, O., Kenett, D. Y., Stanley, H. E., Faust, M., & Havlin, S. (2018). Flexibility of thought in high creative individuals represented by percolation analysis. *Proceedings of the National Academy of Sciences USA*, 115(5), 867-872)

The results show that the semantic network of highly creative individuals is more robust than the semantic network of less creative individuals (fig. 5.16). Greater robustness is related to stronger links connecting between different components of similar semantic words in the network, and this can help facilitate the propagation of activation in your network. Therefore, this study supports the associative theory of creativity, in which high creative ability is related to a flexible structure of semantic memory.

The new computational technologies open a new path for the investigation of semantic memory, since the role of semantic memory in creativity has been mostly deduced theoretically, but it is far from being understood from a neurocognitive point of view. However, in recent years, computational tools and the use of networks have been applied to carry out research. These studies yield important and unique quantitative insights into the role of semantic memory structure in creativity, quantifying its structure, connectivity, and distance [130].

5.2.13. Influence of emotional information

It is widely known that memories related to events with a high emotional content have much higher levels of detail and persistence than normal ones [131]. These memories have been associated with high activation of the amygdale [132].

An event with high emotional content is an event directly related to the well-being and survival of an individual, and therefore it should be stored in greater detail. This is usually done by doing less filtering, and by associating it with other information previously stored that is significant for a certain individual. In this way, more information is stored, and the coding created is much richer and more complex. When retrieved, more highly detailed information is thus available, although it may also be distorted.

This means that emotional information encourages greater creativity (Fig. 5.17), since (regardless of the parallel activation of certain stimulating processes) it is information that is associated at a certain moment with that being manipulated [133]. Therefore, as the amount of information is greater (with unexpected relationships) there are a greater number of unexpected exploration paths and the possible solution would seem surprising a priori and, therefore, more creative [134].

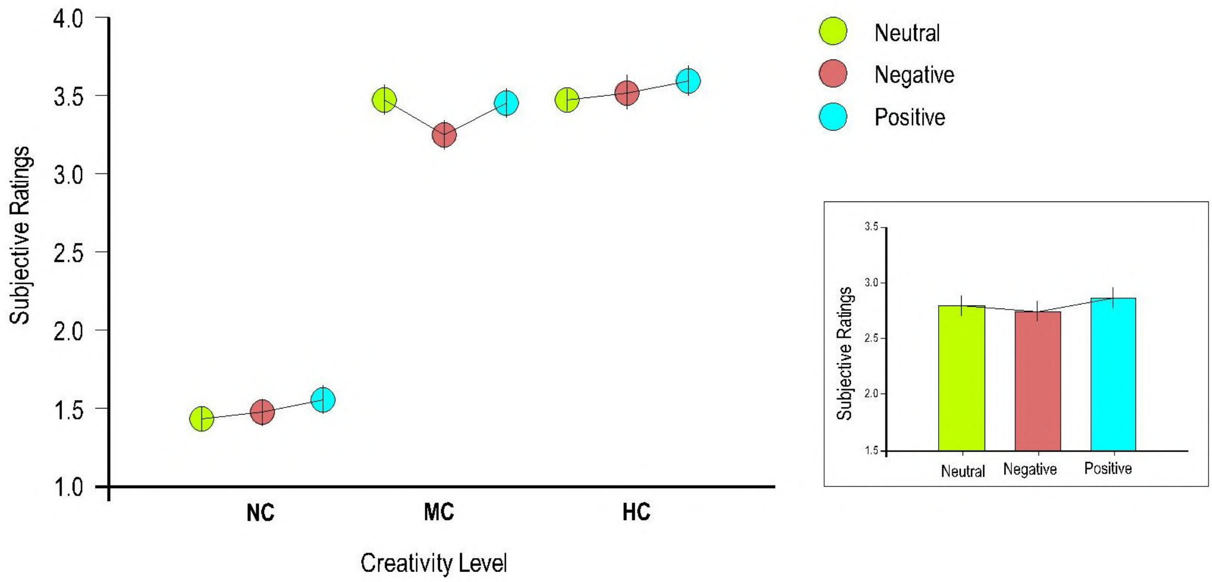

Figure 5.17. Creativity level and emotional content
(Source: Mastria, S., Agnoli, S., & Corazza, G. E. (2019). How does emotion influence the creativity evaluation of exogenous alternative ideas?. *PloS one*, 14(7), e0219298)

5.2.14. Increased efficiency of neural networks due to motivation

Motivation has a direct influence on the creative process, and it is known for example that the reward processing activates regions involved with creativity [135]:

- Dorsomedial PFC
- Ventral/dorsal striatum

The dorsomedial PFC belongs to the DMN, so emotion stimulates this network directly involved in creativity. On the other hand, the striatum coordinates multiple aspects of cognition, including both action and motor planning, motivation, decision-making, reinforcement, and reward perception [136].

Furthermore, in recent years it has been discovered that motivation even affect the functional structure of neural networks (Fig. 5.18).

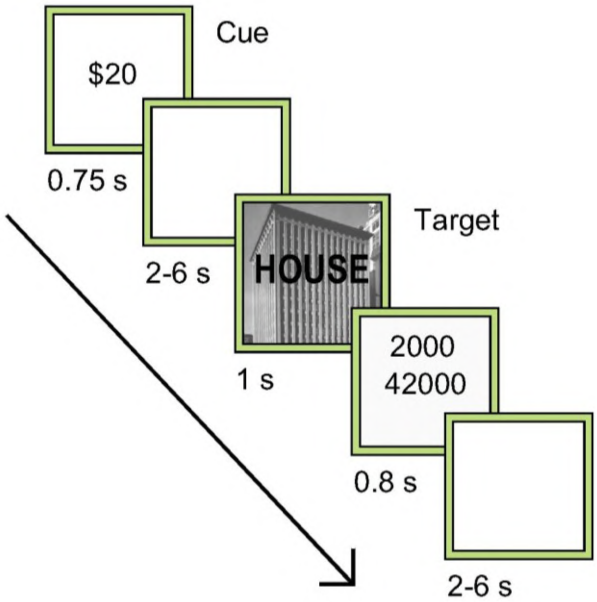

Figure 5.18. Experimental paradigms to study the influence of motivation on neural networks. (Source: Kinnison, J., Padmala, S., Choi, J. M., & Pessoa, L. (2012). Network analysis reveals increased integration during emotional and motivational processing. *Journal of Neurosciences*, 32(24), 8361-72)

Through graph-theoretic network analysis, it has been shown that motivation increase the global efficiency of neural networks and decrease their decomposability [137]. This is because motivation generally improves signal communication between areas of the brain. Specifically, functional connectivity increases in the cortex but is not substantially altered within the subcortical areas (Fig. 5.19, Table 5.1).

Reward > no-reward				
Location	x	y	z	Label
Parietal				
Intraparietal sulcus				
R	24	−54	40	IPS_R
L	−27	−52	41	IPS_L
Inferior parietal lobe				
L	−28	−42	41	IPL_L
Frontal				
Rostral anterior cingulate cortex				
R	13	39	8	rACC_R
Medial prefrontal cortex				
R	6	8	39	MPFC_R
L	−8	7	39	MPFC_L
Supplementary motor area/pre-SMA				
R/L	0	−6	57	SMA_R
Frontal eye field				
R	34	−11	48	FEF_R
L	−31	−12	50	FEF_L
Precentral gyrus				
L	−48	−4	37	PCG_L
Middle frontal gyrus				
R	26	46	25	MFG_R
L	−28	35	29	MFG_L
Anterior insula				
R	31	17	11	aIns_R
L	−35	26	5	aIns_L
Subcortical				
Midbrain				
R	7	−15	−8	MB_R
L	−10	−18	−8	MB_L
Putamen				
R	17	9	−2	Put_R
L	−19	9	2	Put_L
Caudate				
R	10	9	2	Caud_R
L	−10	9	2	Caud_L
Nucleus accumbens				
R	13	6	−7	NAcc_R
L	−13	6	−7	NAcc_L

Table 5.1. ROI peak locations of regions involved in motivation (L: Left, R: right. Talairach coordinates) (Source: Kinnison, J., Padmala, S., Choi, J. M., & Pessoa, L. (2012). Network analysis reveals increased integration during emotional and motivational processing. *Journal of Neurosciences*, 32(24), 8361-72)

The reward effect during perception and cognition depends on the interactions between the valuation regions and the frontoparietal regions important for attention and executive control [138]. These interactions involve increased control and behavioral improvement during challenging task conditions (and a greater likelihood of reward).

In this sense, recent studies show higher functional connectivity between caudate, frontal ocular field and the intraparietal sulcus, when a reward is promised [139]. For example, the left/right caudate and the right nucleus accumbens exhibited increases in functional connectivity to all regions but one.

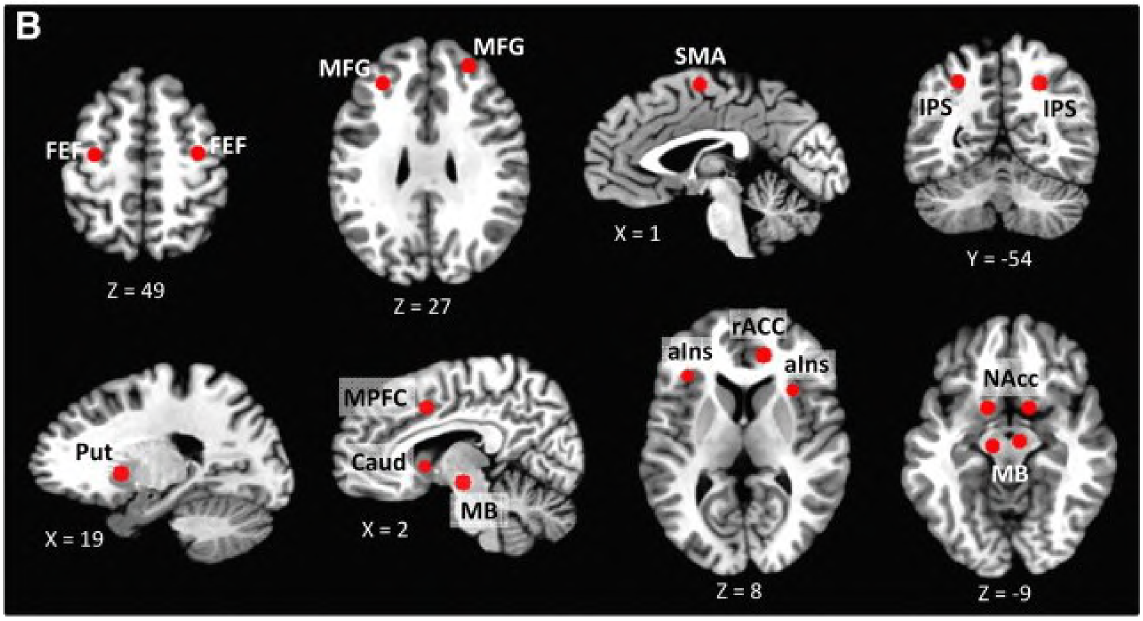

Figure 5.19. Anatomical images showing ROI used in the network analysis of motivation. (Source: Kinnison, J., Padmala, S., Choi, J. M., & Pessoa, L. (2012). Network analysis reveals increased integration during emotional and motivational processing. *Journal of Neurosciences*, 32(24), 8361-72)

Therefore, the general increase in the connectivity of large-scale networks increases the effectiveness of the networks involved in creativity.

5.2.15. Less general filtering of information. D2 dopamine receptors in thalamus

Several investigations show how dopaminergic neurotransmission plays an important role in creative thinking and behavior [140] (Fig. 5.20), and specifically, the relationship between creative ability and the number of dopamine D2 receptors (D2 Binding Potential) in the thalamus and striatum [141] (Fig. 5.21). These investigations suggest that when the density of D2 receptors decreases in the thalamus its clearance thresholds decrease and the flow of thalamo-cortical information increases, as does activity in divergent thinking tests [142].

Figure 5.20. Dopamine D2 receptors

As a result, the hypothesis has been established that the highest yields and scores in divergent thinking correspond to a low density of D2BP in the thalamus, and a high density of D2BP in the striatum (Table 5.2).

Measure	Age	BIS	ZF	AM	TN	Raven	Thalamus	Striatum	FC
M	59	296	103	98	95	39	2.60	2.63	0.40
Minimum	41	269	83	72	80	29	1.86	2.27	0.21
Maximum	65	350	119	117	114	52	3.28	2.99	0.65
SD	8	23	13	15	10	6	0.50	0.18	0.15

Age = Participant age
BIS = Berliner Intelligenz Struktur Test scores
ZF = BIS subtest figural fluency
AM = BIS subtest verbal fluency
TN = BIS subtest numerical fluency
Raven = Raven's Standard Progressive Matrices Plus scores
Thalamus = Dopamine D2 receptor biding potential (D2BP) in the thalamus
Striatum = D2BP in the striatum
FC = D2BP in the frontal cortex

Table 5.2. D2BP in the Thalamus and Striatum (Moises, H. W., Frieboes, R. M., Spelzhaus, P., Yang, L., Köhnke, M., Herden-Kirchhoff, O., Vetter, P., Neppert, J., & Gottesman, II. (2001). No association between dopamine D2 receptor gene (DRD2) and human intelligence. *Journal of Neural Transmission*, 108, 115-121)

The thalamus, among other things, is responsible for conveniently filtering the information it collects before forwarding it to the cerebral cortex [143]. In this way, the information that is considered trivial or insignificant is eliminated, leaving that which is considered relevant.

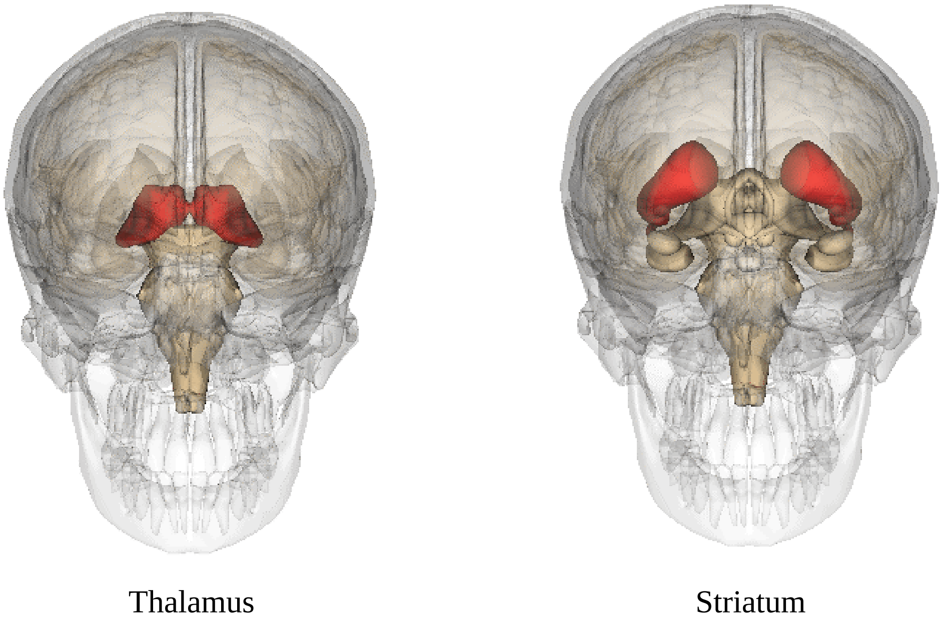

Figure 5.21. Thalamus and Striatum

A lower density of D2 receptors in the thalamus implies a lower inhibitory effect, with the thalamus filtering less, and a greater flow of information that reaches the cerebral cortex (which oversees reasoning and cognition). This excess of information in creative people promotes unexpected relationships. Conversely, in people with psychotic symptoms (especially schizophrenics), it seems to cause disorganization of information. Therefore, it could be assumed that creativity is associated with less information filtering in the thalamus, so that cortical areas register an increase in available information.

The striatum, among other things, mediates reward cognition, motivation, certain inhibitory control functions, skill learning, and stimulus-response learning [144]. Another role proposed for the striatum is chunking action sequences into units [145]. By chunking series of information pieces into a single unit, execution becomes more reliable and rapid. On the other hand, chunking leads to more stereotyped and less flexible behavior. A higher density of D2 receptors in the striatum implies a higher inhibitory effect, and therefore less chunking is generated. This means that many pieces of information remain unpackaged and can be arranged in a more flexible and unpredictable way, creating new combinations of information, and therefore generating greater creative activity.

5.2.16. Cooperation, overlapping and reconfiguration of large-scale neural networks

The network structuring of the functions of the human brain significantly increases the wealth of our cognitive system [146]. These networks incorporate more or less specialized areas for information processing. The different areas do not specialize in a single action, but in a general group of actions that are roughly related to a certain specialization. In this way, some areas belong to several networks, while others only belong to a few.

When a certain network is activated, either by means of an external or internal stimulus, several specialized areas are activated, and many of these are included in other networks. It may be the case that one network activates another and that there is an overlap of networks (fig. 5.22) at a certain time, which could lead to reconfiguration [147]. This allows a direct data transfer that would not be possible otherwise or that would only take place indirectly [148].

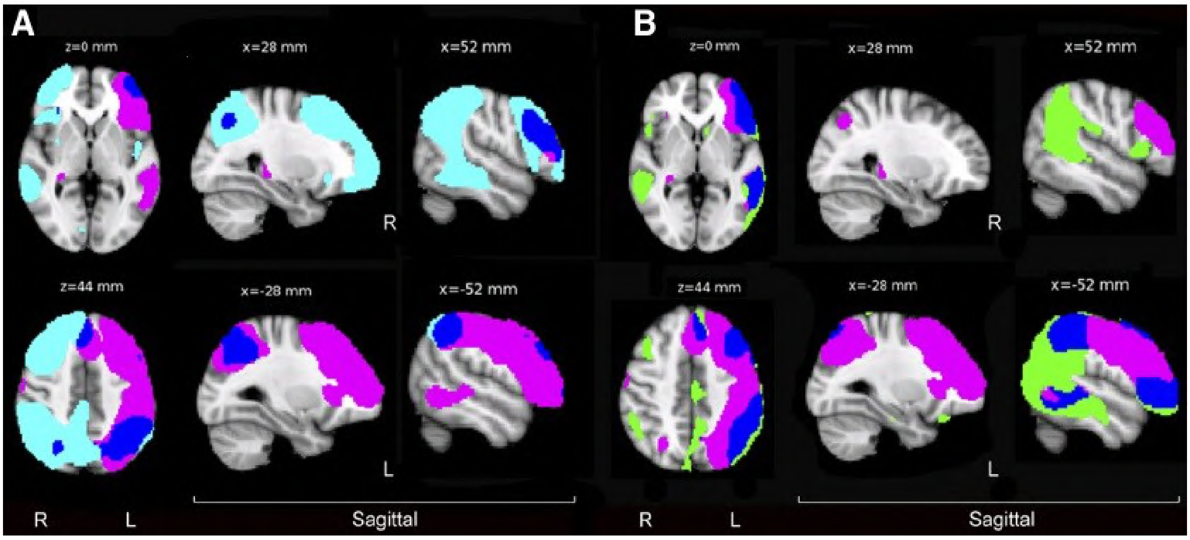

Figure 5.22. Overlapping of neural networks (dark blue) in the left frontal and parietal lobes supporting separate functions.
A. Speech-specific left FTP network (magenta) overlaps with a mirror right FTP network (turquoise) that corresponds to the count and decision trials.
B. Left FTP speech network (magenta) overlaps with a less spatially extensive left-lateralized FTP network that is deactivated in all three conditions, with the most deactivation in speech (green)
(Source: Leech, R., & Sharp, D. J. (2014). The role of the posterior cingulate cortex in cognition and disease. *Brain*, 137(1), 12-32)

An example may help to understand the process. If a middle-aged or elderly subject is asked to smell the pages of a schoolbook, a certain network will be activated. When asked to describe what memories come to mind, they will surely tell us of a scene that occurred many years ago in school when they were a child. They would have activated a second network due to the activation of the first one, and there would be an overlap between the two. If the subject is asked for specific details about certain memories, they may be able to give us some details, such as the shape of the tables in their classroom, the shape of some child's shoes, or even indirectly, some anecdote related to another event in the same school. In fact, the subject could provide detailed information that they could not have given us, or would be more distorted, if it had been requested without smelling the book.

The overlapping of networks acts as a direct bridge for the processing of information, because each specialized area belongs to several networks at the same time (Fig. 5.23).

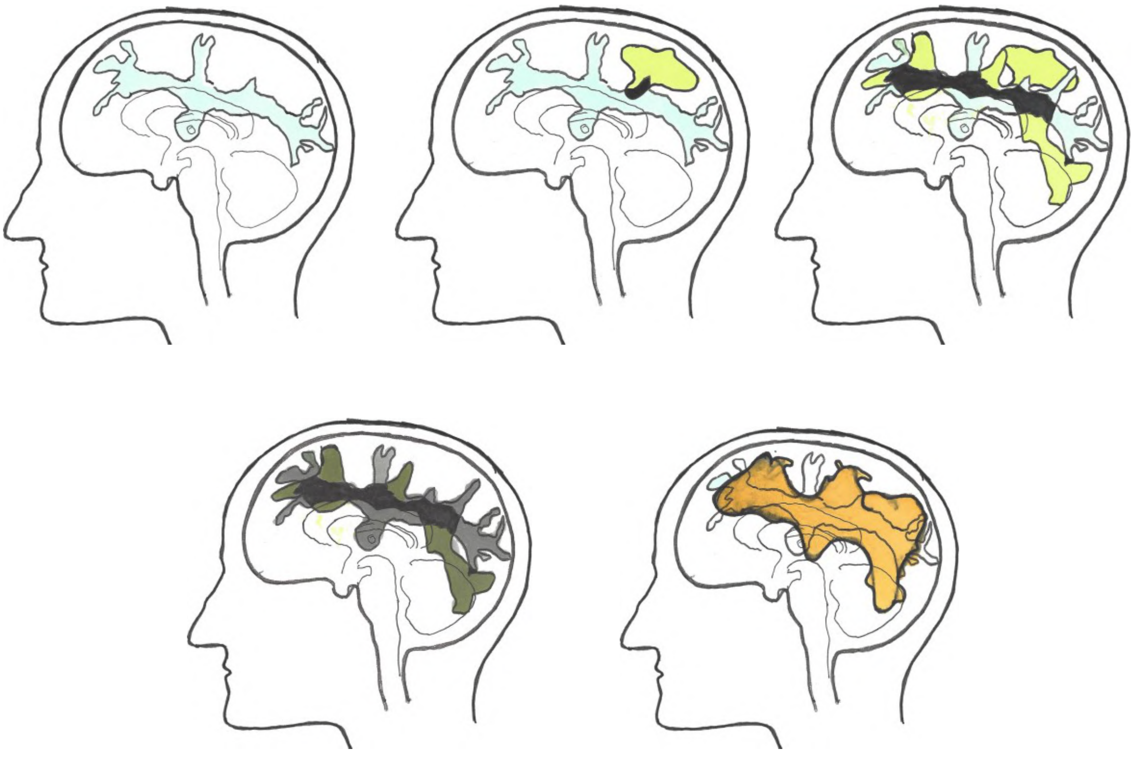

Figure 5.23. Overlapping of large-scale neural networks (Drawing Luis De Garrido)

5.2.17. Hierarchical structure of the brain. Functionally complementary top-down and bottom-up functioning of neural networks

Many higher order cognitive functions depend on top-down regulatory processes to ensure that goals are achieved. This control is performed by the ECN. The ECN also plays an important role in the executive control of attention [149].

The central core of the ECN (DLPFC, IPL and precuneus) form another control subnetwork that initiates and adjusts the top-down control [150], together with a cingulo-opercular network that maintains the objectives of the task and consists mainly of the dACC and the frontal operculum [151].

The ECN performs a top-down control even in the activity of the DMN in personal and social cognitive aspects. The DMN activates when no task is being performed, and is involved in the self-generation of internal thoughts. But it is also activated when certain tasks that require access to memory are performed, and it interacts dynamically with other neural networks (Fig. 5.6). Specifically, the ECN collaborates with the DMN in order to facilitate a goal-directed cognition. This collaboration is manifested in the strong functional connectivity existing between the inferior prefrontal cortex (IPFC) (region of ECN) and the DMN, and allows a top-down control of their bottom-up processes. In other words, the cognitive control mechanisms of the inferior prefrontal cortex may be responsible for directing and monitoring the spontaneous activity of the DMN [152].

The brain also works in a complementary top-down mode [153] (Fig. 5.24). For example, from a control point of view, it filters high-level information and continuously generates predictions [154]. The brain does this constantly and contrasts the expectations with reality. If they do not match, it analyzes the basic high-level details. If these all match, then it analyzes lower-level details, and so on. Visual control, for example, works this way [155].

From the point of view of the creative process, in general the ECN is frequently related to top-down cognitive control functions [156]. Therefore, the fact that the process of evaluating ideas activates the ECN implies the need to perform a top-down control in creative evaluation, which suggests that a commitment to a high level of cognitive control that can facilitate an analytical processing.

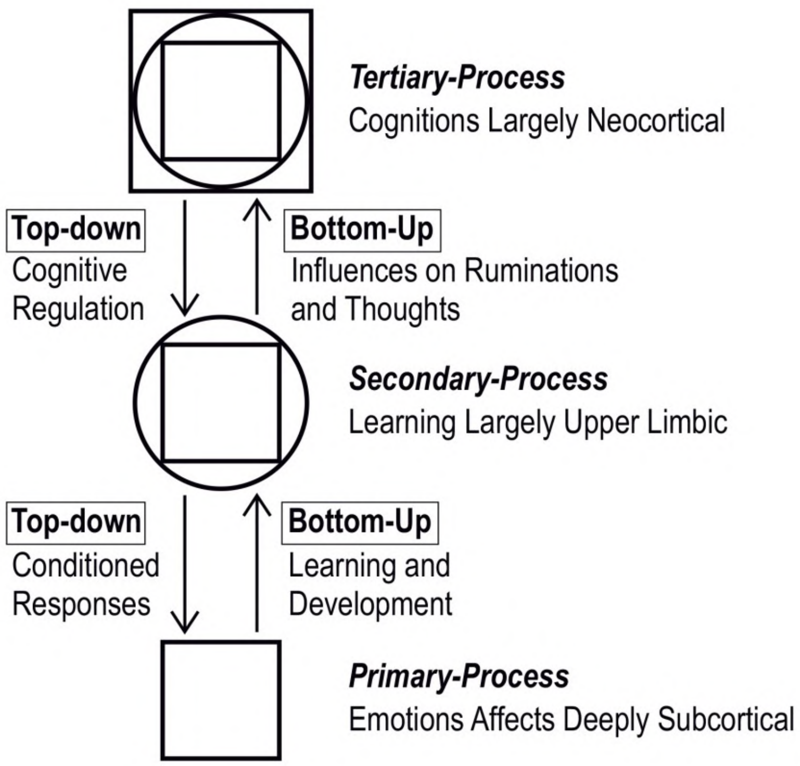

Figure 5.24. A summary of the hierarchical bottom-up and top-down (circular) causation that is proposed to operate in every primal emotional system of the brain. The schematic summarizes the hypothesis that in order for higher MindBrain functions to mature and function (via bottom-up control), they have to be integrated with the lower BrainMind functions, with primary-processes being depicted as squares (red), secondary-process learning as circles (green), and tertiary processes, by rectangles (blue). The color-coding aims to convey the manner in which nested-hierarchies are integrating lower brain functions into higher brain functions to eventually exert top-down regulatory control.
(Source: Panksepp, J. (2011). The basic emotional circuits of mammalian brains: do animals have affective lives? *Neuroscience Biobehavioral Review*, 35(9), 1791-804)

Alternatively, in the human brain there is also a general set of bottom-up processes. For example, the information flows through the cortex in a hierarchical way [157], and sensory information flows bottom-up into the upper multimodal, heteromodal, and transmodal convergence zones [158]. The human cognitive system works from the bottom-up in regard to low-level information filtering and concept generation [159]. It collects small pieces of information and creates larger pieces of information by creating conceptual structures. For the creation of the concept “family”, for example, it gradually collects information about the many types of existing families, and based on this experience, it generates the concept “family”. The more information that is collected related to the family, the more links can be generated between isolated pieces of information, which will allow a greater number of classifications and conceptual groupings, thus the concept of “family” will be richer and better defined.

The *Salience network* (SN) also uses a functional bottom-up structure, through which it continuously detects possible salient events. As part of de SN, the AI and the ACC collaborate in the integration of bottom-up attention switching with top-down control, as well as in the polarization of sensory inputs. The AI receives a wealth of multimodal sensory information, but the ACC, and the associated dorsomedial prefrontal cortex (DMPFC) receive very little sensory information [160]. On the other hand, the ACC and the DMPFC have great connectivity with the motor system, the AI has very little. Complementarily, the ACC and the DMPFC have direct connections with the spinal cord, and with the subcortical oculomotor areas [161], so they have direct control over the action. This anatomical connectivity, together with the *von Economo* neurons (which allows a rapid connection between the AI and the ACC), allows the *Salience network* to involved in both attention and motor responses to salient sensory stimuli.

As has been said, the DMN also performs a bottom-up process of integration of information that flows through the cortex. The *core subsystem* of the DMN is made up of the PCC and the amPFC [162]. The ventral PCC and the ventral dorsal PCC are anatomically strongly connected to each other and also to the precuneus, located adjacently [163]. Therefore, the PCC is an integration zone that supports the bottom-up attention of the relevant information for behavior coming from both memory and perception [164].

Notes 5

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CHAPTER 6

Neurocognitive-based human creativity paradigm

Chapter 6. Neurocognitive-based human creativity paradigm

The origin of human creativity has always been a mystery, and has been analyzed based on its results. Throughout history, innumerable speculations have been made about the processes that sustain creativity, since there were no means to be able to detect brain activity in detail.

For this reason, and until recently, creativity has been studied as a consequence of brain activity, considered a black box, since only the results generated have been analyzed, but not its internal processes. Based on this, and through trial and error techniques, innumerable strategies and methodologies have been designed capable of stimulating and amplifying creativity. In the same way, analyzing human creative behavior, creative processes have been conceptualized, and based on this, computer systems have been designed, with a certain degree of creativity.

However, if the neurocognitive mechanisms that support creative processes were known, human creativity could be substantially improved, since more effective creative methodologies could be designed, and the creative computational systems implemented would undoubtedly be enriched. In the same way, pharmacological means could be used, as well as bionic and robotic mechanisms that, acting in symbiosis with the human brain, could amplify its creative capacity.

To this end, this chapter analyzes the different neurocognitive factors, identified in the previous chapter, in order to create a neurocognitive paradigm of human creativity. Based on the analysis of each factor, certain concrete suggestions have been generated to amplify its effectiveness. By grouping the suggestions of all the factors, one has some idea of the relative importance of each of them, and as a whole, a set of indications will be generated to improve human creativity. This set will be called the *neurocognitive-based human creativity paradigm*.

This neurocognitive paradigm of human creativity allows defining guidelines for action to amplify it, especially on the basis of adequate education and the adoption of new lifestyles. However, the use of bionic devices, pharmacological substances and computer systems will gain more and more importance.

6.1. Analysis of the different methods that amplify creativity, based on the knowledge of the human neurocognitive structure

Most of the methods discussed in chapter 2 follow a mechanistic methodology, so knowledge of the neurocognitive basis of human creativity does not provide any information to improve on. However, other methods depend directly on human neurocognitive activity, so knowing their bases would allow them to be improved. Suggestions to improve these methods and new ones are proposed below.

1. *Establish analogies with known problems*

The human brain has an enormous capacity to make analogies at a high semantic level, which is why methods based on making analogies can be considerably improved.

In a first stage, the number of attributes of a certain concept or object must be identified, making an effort to determine them from different points of view, different contexts and different levels of abstraction. For example, if you want to define the concept "chair", some of its identifying attributes are easy to identify, such as "height", or "number of legs". And if the concept is defined with this type of attributes, the semantic analogies that can be established are very limited. On the other hand, if more complex attributes are established (such as "softness", "perception", "warmth", etc.) the number of semantic analogies (relationships based on similar attributes) that can be established are very high, and many of them of a high semantic level (that is, with a very indirect relationship to its habitual perception).

In a second stage, relationships must be established with other different concepts based on the desired attributes.

This improved method can be performed individually, as well as in groups. Of course, based on this general ideal, many different methods can be established.

2. *Problem solving (vertical thinking)*

The *problem-solving* strategy may seem uncreative, since it is based on the analysis of a well-defined problem, and on the concatenation of logical decisions until a valid solution is reached that resolves it. Initially, it might be thought that if two similar problems are posed, using the *problem-solving* strategy would generate very similar results. And in general, it is so.

However, certain chaotic components can be incorporated to break free from the determinism of the method. The characteristics of the problem to be solved can be subtly modified and replaced by similar conditions. Initially the change may seem small, however the results can be surprising in some cases. Based on the neurocognitive bases of human creativity, conventional *problem-solving* methods can be improved. The strategy to generate consists of the establishment of certain meta-strategies of a general nature, which can be refined to solve a particular problem. For this, it is convenient to have a little specialized multidisciplinary preparation, and to have very specialized information from a few areas of knowledge. By having certain knowledge of different areas of knowledge, it is easier to transfer from one to another, and a greater number of high-level semantic analogies can be made. The more one knows about certain areas of knowledge, the more easily the necessary decisions will be concatenated sequentially.

3. *Brainstorming*

Brainstorming methods are the ones that can be improved the most based on the knowledge acquired about the neurocognitive factors of human creativity.

In order to generate a greater number of creative ideas, it is advisable that in a *Brainstorming* session unusual paths be explored, and at the same time related in some way to the problem to be solved. Based on this, many alternative methods can be proposed, such as the following:

- *Brainstorming with children*

It is about incorporating 50% of children, in such a way that there are about 8 expert adults and about 8 children between 7 and 10 years of age. Adults begin by proposing ideas and this encourages the participation of children, who obviously have no knowledge of the problem to be solved. The children listen to proposals and let their imagination run wild. The ideas generated by children can be interpreted by adults, who in turn generate more armed ideas. This method takes advantage of the enormous associative capacity of children.

- *Brainstorming tenth man*

The method consists of incorporating a person in all the sessions who proposes an idea that he considers to be as opposed as possible to all the ideas that are being proposed. The ideas of this person will stimulate unsuspected paths to be taken in the creative cognition of the rest of the group's components.

- *Brainstorming with punishment*

It is used as a method of motivation not the reward, but the punishment. If a certain number of ideas is not generated, and if a minimum of them do not pass the evaluation processes, the components are punished. The punishment should not be very high, but it should be forceful, for example, the salary of the members of the losing group can be reduced by 20% and awarded to the winning team.

- *Brainstorming by stages*

Two sessions are held. In the first session ideas associated with a problem related to the problem to be solved are generated, and in the second session ideas are already developed to directly solve a certain problem.

- *Inductive brainstorming*

It is a double process. In a first stage, various solutions are shown to a problem that has nothing to do with the problem to be solved. In a second stage, a conventional *Brainstorming* is developed.

- *Brainstorming with non-experts*

It is a *Brainstorming* in which the components have no connection with the problem to be solved.

4. *Lateral thinking*

The diverse methodologies that are usually carried out under the concept of *lateral thinking* are all valid. All of them fulfill the objective of forcing new cognitive paths to be explored to those that are usually different. However, some techniques are more effective than others. In my own experience, the most effective are those in which information is mixed or the existing one is altered. And that is consistent with the neurocognitive bases identified so far. The brain has redundant mechanisms for filtering information, modifying information, and mixing information. At the moment the criteria for performing the three tasks are not known, although some aspects are determined by the biological nature of the brain itself. However, the manipulation of information is determined by the initial structure with which it was created, and by the personal experience of the individual. On certain occasions the current information is randomly mixed with self-generated information, or randomly modified information.

For this reason, associative methods with a high semantic level should be encouraged above all (ie associations with different levels of abstraction based on the choice of specific attributes of the information). Also interesting are incremental methods, in which specific information about a certain event that occurred in certain circumstances is added to the information related to the problem. Finally, the substitute methods in which part of the problem information is replaced by another chaotic or random one.

One of the most effective methods of *lateral thinking* is to solve the problem in installments. One day the problem begins to be solved. It is abandoned, and several days or months later it is solved again from the beginning. Several days or months later it is resolved again. Evidently this method is only useful for solving less urgent problems.

6.2. Suggestions to identify a human creativity paradigm based on the analysis of its neurocognitive bases

This section provides different suggestions to stimulate human creativity, based on the analysis of each of the neurocognitive factors identified in the previous chapter. The integration of the different factors with the different suggestions makes it possible to create a human paradigm of creativity.

6.2.1. Suggestions based on the structure of the human cognitive system based on large-scale networks

The cognitive structure based on large-scale networks, grouping regions with different functionality [1] implies enormous flexibility in cognition, and inherently provides a high creative potential since it implies the generation of subtly different thoughts, even when they are generated in identical circumstances. The neural connections that are established when generating cognitive processes always differ in small details. In this way, two identical experiences generate slightly different neuronal activity. Large-scale networks enable neurocognitive processes in parallel, and this transversality is another important aspect of human creativity.

What this factor suggests is that it is extremely important to increase as many structural neuronal interconnections as possible, both within the different regions and in the structural connecting tracts that group them.

Therefore, from an educational point of view, it is essential that in the first years of our life we carry out as many transversal activities as possible, avoiding specialization in any of them. The important thing is that as many different activities are carried out. From a pharmacological point of view, substances could be used that reduce the process of destruction of neuronal connections. From a bionic point of view, mechanical systems could be incorporated to amplify the process of establishing neuronal connections in childhood, and to maintain them throughout our lives, increasing neuronal activity in a wide variety of regions.

6.2.2. Suggestions based on the multimodal organization of the brain

The multimodal structure of brain [2] suggests two things. On the one hand, the brain favors serial cognitive processes. On the other hand, the gradual transformation of information and cognitive processes is favored, from more concrete to more abstract. The brain therefore favors abstraction. This suggests that in the education of children different strategies should be established that amplify this process of abstraction, and thus stimulate and maintain related neural connections. The usual children's exercises should be extended in order to stimulate the generation of abstract concepts. For example, if a child makes a figure of an elephant out of clay, it could be suggested that he create another figure that reminds him of what he has just modeled, be it animal, vegetable, or mineral. Following the work, he could model an object in the classroom that reminds him of what he has just modeled. Finally, he could be asked to relate his figure to certain concepts that he is experiencing at that time. For example, it could be proposed that he associate his clay figures with certain abstract concepts in his environment: friendship, fights, love, study, respect, work, laughter, crying, pain, etc ... and must create a story that integrates the objects with the concepts. This type of exercise should continue to be done at any age, gradually increasing its complexity, and adapting appropriately to the different environments of each individual.

6.2.3. Suggestions based on the topographic distribution of large-scale networks, and their nodes

The strategic topographical location of the different brain regions suggests that they are right where they should be [3]. This means that the proximity and distance of some areas from others is important to establish their functionality, at least in their most important aspects, such as the level of abstraction, and collaboration in the cognition of different complex problems in different areas associated with certain sensorimotor regions. Specific sensory information activates immediate direct processes, but almost immediately it integrates with each other, and gradually abstracts until the maximum level of abstraction allowed by the brain structure is achieved. Therefore, the topographic structure facilitates the integration of parallel processes with serial processes, creating an enormous wealth of information processing.

Again, the establishment and maintenance of the neural links that make this topographic structure possible must be stimulated to the maximum, carrying out all kinds of activities that involve different experiences in an integrated way, and that must be continuously abstracted. For example, 4- to 6-year-old children could be asked to make up a story based on sensory experiences they have had in a previous experience. This story should incorporate the feelings they have with the people in the classroom and with their family. Obviously, sensory experiences should be as extensive as possible. In advanced age, analogous exercises should be performed with different levels of abstraction. For example, if you travel to a new city, let's say Florence, as we walk, we must mentally generate fantastic stories that run in the physical space that we are traveling, but with fictitious personalities, brought from various times and places, creating a mental story, in which we are a protagonist. The story must be mixed with specific sensations of the momento: heat, thirst, fatigue, noise, a beer, etc.

6.2.4. Suggestions based on the collaboration between ECN, SN and DMN

The creative process involving the collaboration between the DMN and the ECN on the basis of the switching process carried out in a complementary manner by the SN and the DLPFC, is the main engine of the creative process [4]. This neurocognitive process is not completely defined, but its essence is more than enough to give an explanation to some of the most surprising phenomena of the creative process. Based on this, neurocognitive exercises can be established, both in early childhood and throughout our lives, to maintain and reinforce the process.

In the first years of a child's life, the establishment of a wide range of interrelated cognitive processes, not very specialized, and at various semantic levels, should be stimulated above all. In other words, superficial and interrelated knowledge of a wide variety of activities should be promoted. However, in-depth knowledge and specialization in those fields in which the child exceptionally excels should be gradually encouraged.

Once this is done, problems should be raised with an incremental level of complexity and difficulty. Initially, you should start with a compilation of information, and an analysis of the problem to be solved. A *problem-solving* process then begins in which the ECN is in control, and the DLPFC keeps self-generated thoughts in check. Using several different logical strategies (action-reaction, divide and rule, logical analysis, etc.) may solve the problem. It is the moment to pose a more complex problem, or less defined, and at the same time the evaluation criteria (its quantity and its requirement) must be gradually increased. Consequently, it is possible that a *problem-solving* process cannot solve the problem. In this case, you must continue working hard, and uninterruptedly (through partially conscious and partially unconscious processes), trying to make a chain of decisions that can solve the problem posed. It is possible that, after this hard and uninterrupted work, the problem will not be solved, and with this it is possible that motivation is reduced, and tiredness appears. It is time to take a break and “disconnect” from the problem. By doing so, the SN can activate the DMN, the DLPFC gives free rein to self-generated thoughts, and the MTL begins to manipulate the information creating all kinds of associations and creating a conceptual-spatial map of the idea that is being formed, within of a certain environment. An unconscious process is generated, involving semantic associations of various levels, the association of ideas is strengthened, previously established rules are activated, etc. In short, the brain "starts to play" with the information based on complementary fuzzy processes. As if that were not enough, in some cases the DLPFC does not work correctly, and self-generated information is mixed with current information. All this happens unconsciously, while we have a routine conversation, we drive, we walk, we watch a movie, we clean the floor, etc.

After the break we go back to work. The SN detects an internal salient stimuli, and activates the ECN, while the DLPFC cuts off self-generated thoughts and the MTL calms down. A new *problem-solving* process begins, trying to pick up the situation where it left off. However, something has changed, as we come across new ideas, and decisions seem to take a new direction. This is because previously the information related to the problem has been mixed with new information, and now it has been slightly transformed. The *problem-solving* process continues (through a partially conscious and partially unconscious process), and it may be that at the end of the process we will end up solving it. However, it could also happen that we cannot solve it. In this case the process is repeated. We take a break and a conglomerate of unconscious processes is released, while we perform a boring, inconsequential, repetitive task, etc. And during this period something surprising can happen: it gives us the feeling that we have solved the problem. It is as if we have a flash of consciousness, and the solution appears out of nowhere. In this case, we stop what we are doing, we become aware of the situation, we write down something, and we do certain conscious processes of *problem solving*, both of materializing ideas and evaluating them. And we realize that we believe we have solved the problem.

This process always happens. At least as long as the process is repeated:

- Gather all possible and specialized information and assimilate it
- Consciously do extensive work to try to solve the problem
- After repeated attempts to solve the problem, working hard, we take a break
- Throughout the rest period the solution appears out of nowhere

What actually happens is that the DMN has been activated, sometimes also the ECN, the self-generated thoughts pile up, the MTL begins to make associations, the DMN begins to play with the transformed information, applying rules that it had previously recorded in memory

All these actions and some more are carried out incessantly unconsciously. Although we have decided to take a break, the brain continues to work, even more intensely, but we are not aware of it. At a given moment, the infinity of processes that occur can reach a point where the conditions previously established to solve the problem are met. The ECN has performed a pre-evaluation, and the SN detects a salient internal stimuli. In this case, complete control is ceded to the ECN, and a flash of consciousness is generated, so that the cognitive resources are focused on the ECN. In this case, the problem, in its essential statement, has been solved. We feel a sense of joy and satisfaction, and of euphoria in many cases.

What is left to do is debug different aspects. In this process of debugging the idea, pauses should also be taken, and let the solution "mature", or "refine". The process of debugging the initial idea is not as intense, but it follows a similar pattern to the one discussed above.

This process can be trained, performing increasingly complex and less defined problems. In this way the rules generated by the DMN will be more and more varied, the self-generated thoughts more and more diverse, and the process will be more and more efficient.

6.2.5. Suggestions based on the role of the DMN

The DMN is involved in the management of abstract information, as it is located at the end of the main processing gradient [5]. We feel this information as "very personal and deep" since it is especially self-referential and related to imagined processes and especially about our future. Based on previous experiences, the DMN generates action rules, which it uses as more experience is acquired [6]. These rules are applied each time it is activated, although each time it uses different information, and in any case it is rough information with a high level of abstraction.

All of this suggests several things. In the first place, and coinciding with previous suggestions, the abstraction of all the experiences that we have should be encouraged, instead of paying attention to their concrete details. Second, we must "internalize" the manipulated information, adding certain emotional and personal biases, in order to turn it into an intimate experience. This is what is usually called the internalization or assimilation process. Finally, it is important to stimulate the generation of rules, which are guidelines for action. These rules should be as generic as possible, so that they can be applied to a multitude of problems and circumstances.

One of the exercises that must be carried out both in childhood, as in any moment of our life, consists in abstracting the problem that we have in progress, reducing it to its conceptual essence. In this way, a multitude of internal rules previously stored and related to previous personal experiences can be applied. These rules, applied to current information, will generate surprising, novel and valuable ideas. Any daily act we must try to see it at various levels of abstraction.

6.2.6. Suggestions based on the role of the MTL

Without a doubt, MTL is one of the regions that most develop with training. The posterior hippocampus of many taxi drivers is bigger than normal [7], and this is because they are forced to create a mental map of all the streets of the city, in which they also locate places, events and personal experiences. This allows them to establish routes with incredible ease, meeting the varied demands of their customers. This allowed them to create very complete conceptual-spatial frameworks in which to develop their activity. In fact, the conversation of taxi drivers was more creative, entertaining and witty before the existence of GPS.

The MTL creates associative maps, in which it integrates concepts and experiences with spatial structures (such as experiences in the different spaces of the university, on the streets of a city, on the daily commute to work, etc.).

The main suggestion is that activities that require the development of spatial vision should be encouraged. For example, draw the back of the object in front of us, imagine an object and draw it, imagine an alternative route to go to the beach, draw a previously seen object from memory, etc. The development of spatial vision must be consistent with the development of a conceptual story, and the exercises suggested in the first section are useful for this.

The integration of information to create non-existent objects also depends on their conceptual structure. The creation of as many attributes as possible should be encouraged at all times.

6.2.7. Suggestions based on the relationship between *Working memory* (WM) and *Task induced deactivation* (TID) with creativity

This point redounds on the importance of the information mix as a stimulus for creativity [8]. A very complex or poorly defined problem is difficult to solve, so information must necessarily be added to define it more completely, and based on it solve it, establishing the appropriate concatenation of decisions. The key is what kind of information should be added. Most of the times, aseptic information is added, with the intention not to adulterate too much the problem to be solved. Other times personal information or our cultural environment is added. For this reason, in most cases the solutions are always similar (since sometimes the amount of information added is greater than that provided in the problem. Therefore, if indirectly related, chaotic or random information were added, truly creative and surprising solutions could be found.

In this regard, already existing exercises in children's literary creation are important. It is about creating stories in which certain objects or concepts appear, previously chosen at random.

6.2.8. Suggestions based on the role of the insula (and the SN)

The insula is a mediation center for dynamic interactions between large-scale networks involved in externally oriented cognition (ECN), and in internally oriented cognition (DMN) [9]. Based on the detection of salient stimuli, the insula activates the most appropriate large-scale network at all times, which is why it is essential for the correct functioning of the central nucleus of the creative process, that is, the triple-network-model.

The activity of the insula suggests that the correct interactions between the ECN and the DMN should be established based on the information available at each moment. The brain correctly performs the switching between the different networks, and this suggests that methodological strategies should be carried out in accordance with the effective activation sequence of the three networks involved, as seen in the fourth section.

6.2.9. Suggestions based on the role of the angular gyrus (left AG and IFG)

The angular gyrus is involved in multimodal integration and vividness, and in the processing of the sequences of actions to develop a certain task, integrating different types of information [10]. This allows it to get involved in concrete processes such as the production of meaningful sentences, the understanding of reading, the visuospatial processing, and coding of symbols, the theory of mind, etc. In the angular gyrus, information from the body and the environment is correctly integrated, and based on this we have a coordinated idea of our body and our environment. In fact, sometimes certain injuries can occur in the angular gyrus, which can generate an oxygen deficit, and as a consequence it does not perform a correct sensory integration of our body and environment, including the sense of balance. As a result, what are called "out-of-body experiences" can be generated, and patients have the sensation of seeing their body from the outside, or even feel that their body rises (Fig. 6.1.).

Therefore, it can be said that the AG creates the first basic structure of semantic knowledge, and therefore also performs the top-down control of the activity carried out by the DMN.

Figure 6.1. Sensation of extracorporeal experiences as a consequence of lesions in the angular gyrus

The basic suggestion of this factor is that children (and also people of any age) should be taught the basic structure of the basic processes of understanding and creating written language and graphic language, as it is done. However, if a rigid or limited structure is assimilated, freedom will be restricted. Creative people have always distinguished themselves by learning rules, applying the rules correctly, but later breaking the rules and creating new ones. Its angular rotation allows it this ability to manipulate existing rulers with some ease. And that is precisely what should be encouraged. The correct and consistent application of a varied set of rules, which can be modified at any time.

Another thing that should be taught in a complementary way is the process of integrating correctly, coherently and with meaning, different types of information, although they apparently have little in common. It is therefore advisable to carry out consecutive exercises in which a changing set of rules must be correctly applied to solve the same task. For example, make a drawing only with animals to show a certain idea, and then do it only with animals, and finally with all of them. In the drawings, the relationships between the objects drawn with the objective of the task must be taken into account and everything must be coherent. Another exercise would be to enlarge half-done drawings. For example, you can do another very stimulating exercise. You can draw an incomplete drawing on the left side of a sheet of paper, and ask the children to draw several pictures by completing the right side. What they draw must be perfectly coherent with what was previously drawn on the left side and both parts must form a complete and meaningful scene. Another exercise, establish a phrase, for example: “water came out of the backpack”, and the children must complete a story in which this fact makes sense. Another example would be to create a story, or a drawing, from some random elements that have little or nothing to do with each other. The children are told that they must use these elements and they must add the elements that they consider convenient, real or fictitious, to complete a scene, in such a way that the whole has structural coherence and meaning.

6.2.10. Suggestions based on the dynamic and fuzzy memory system for storing retrieving information

Memory is a distorted echo of reality [11], therefore, drawing on what we think we have is already a creative process. It is difficult to enhance this process, as it is very effective. Evolutionary mechanisms have endowed the human brain with the ability to create distorted copies of events that actually happened, rather than creating literal copies. This provides important clues that generalized and abstract processes are more important in creative *problem solving* than concrete sensorimotor information. And it makes sense because problems are always different, and events are always different. Even when trying to repeat certain events, they always have substantial differences. Therefore, the suggestions that are inferred from this factor is that general and abstract processes should be stimulated.

6.2.11. Suggestions based on the importance of the episodic memory

Experimental studies have shown the importance of episodic memory [12], and the suggestions based on this fact are consistent with some of the previously established. The need to have all kinds of varied experiences, far from the professional activities in which we are directly involved. The more experiences we have other than the problem to be solved, the more creative ideas we will have to solve it.

6.2.12. Suggestions based on the importance of the semantic memory

Semantic information is key in the creative process, since it creates a mapping between the concepts and their attributes [13]. The greater the number of attributes, a greater number of conceptual generalizations and more diverse analogies can be made, and thus the capacity to generate different concepts increases. In this process, the learning process is fundamental, since each concept learned must be manipulated in different contexts, from different points of view, and as a result the number of attributes is increased. For example, the concept "narrow" must be taught from a spatial, intellectual, physical, economic, etc. point of view. And for this, a multitude of examples must be given. In this way, if at one point the concept of “narrow color” were used, a greater number of attributes could be added, and analogies of a high semantic level could be established. Many great artists have referred to certain colors as having a bitter, or metallic "taste." And this is undoubtedly one of the reasons that allows them to be so creative.

6.2.13. Suggestions based on the importance of emotional information

The fact that emotional information is stored more efficiently and with many more nuances [14] is something that can be used to amplify human creative capacity. The “exciting” experiences that we may have throughout our lives should be increased, especially at an early age. Learning about matters that are considered important should be infused not only with motivation, but above all with emotion. For example, a teacher, teaching mathematics, can teach the mechanisms of the Fibonacci series. Some students will be interested, but most will be bored. If the same teacher indicated that the Fibonacci series was created to determine the number of rabbits in a litter at a given time, many students would associate the mathematical process with rabbits, and with practical utility. If, in addition, the teacher indicates that beautiful designs can be created with the Fibonacci series, and gives an example, he will surely turn something boring into something "exciting" that his students will never forget, and he will also encourage them to use what they have learned in their daily lives, or in other areas of knowledge. The same can be said for example with respect to a mathematical integral. What percentage of students, who have studied mathematics integrals, have a distant idea of what they are used for in a practical way and in their daily lives? Finally, bionic technology also has many possibilities since devices capable of inducing emotion in a certain activity can be developed, in order to provide it with an emotional bias, and thus enrich and prioritize it as far as possible.

6.2.14. Suggestions based on the increased efficiency of neural networks due to motivation

Motivation amplifies the global efficiency of neural networks, and among them those related to creativity [15]. For this reason, it is important to look for any motivating element in the education of children on the one hand, and in creative activity at any age. Motivation can be of any type, both based on a reward, or on any type of threat. In today's education systems, reward is valued above all, and threat is no longer used, although this has been an important source of motivation throughout history.

With regard to the bionic and pharmacological systems, stimulators of neuronal activity could be used, especially directed at the activation of DMN.

6.2.15. Suggestions based on the less general filtering of information. D2 dopamine receptors in thalamus

This indicator [16] suggests the importance of adding additional information in the creative process that may initially seem secondary or irrelevant to the problem. This results in the importance of having as many experiences as possible, and using the maximum amount of information to enhance the information mix. Creative people have a lower level of information filtering, and therefore care must be taken in assessing relevant information in the first years of life. Pharmacology and bionic technology are promising in this regard since it can achieve a change in the activity of D2 dopamine receptors in the thalamus, and with this, at certain times, let more information pass so that it can be used in cognitive processes.

6.2.16. Suggestions based on the relationship between creativity and cooperation, overlapping and reconfiguration of neural networks

The structure of large-scale networks includes certain areas of overlap between them [17], in order to facilitate the information flows immersed in the multimodal integration network. The only suggestion in this regard, again, is to create and maintain as many neural connections as possible, this time in the overlapping areas of the different large-scale networks, as discussed previously. In the same way, the creation of concepts based on the maximum possible number of attributes is very important. For this reason, it is important that the different concepts are continually enriched based on intellectual exercises relating to various environments and different fields of knowledge.

6.2.17. Suggestions based on the hierarchical structure of the brain. Functionally complementary top-down and bottom-up functioning of neural networks

The hierarchical structure of the brain facilitates the top-down and bottom-up control mechanisms [18] essential for human creativity. Again, a suggestion based on this factor is to maintain the maximum number of neural connections, based on performing a varied number of activities, whether creative or not. These connections should be maintained for as long as possible with the help of cognitive exercises, dietary supplements, and pharmacology. Bionics could also play a fundamental role, amplifying the activity of certain processes, and partially inhibiting those deemed appropriate.

6.3. Neurocognitive model of creative process

In chapter 2, a conceptual model of the creative process was shown, based on the analysis of the behavior of creative people, and based on the analysis of the methods that stimulate human creativity. Any conceptual model proposal will always be excessively simplified and incomplete, and as stated, the only way to advance in its definition is by having sufficient information about the neurocognitive structure of human creativity. Analyzing the neurocognitive processes on which human creativity is based, new more complete and adequate conceptual models can be proposed, conveniently refining the previous ones, based on accumulated knowledge.

Until just 12 years ago, there was hardly any research that would allow us to get a small idea about the creative neurocognitive structure of the brain[19]. However, at present, year 2022, we already have a certain cumulative amount of information. In fact, to carry out this Doctoral Thesis, more than 800 articles related to the neurocognitive foundations of human creativity have been analyzed and integrated.

Based on this study, a much more adequate and complete neurocognitive model of human creativity has been proposed (Fig. 6.2).

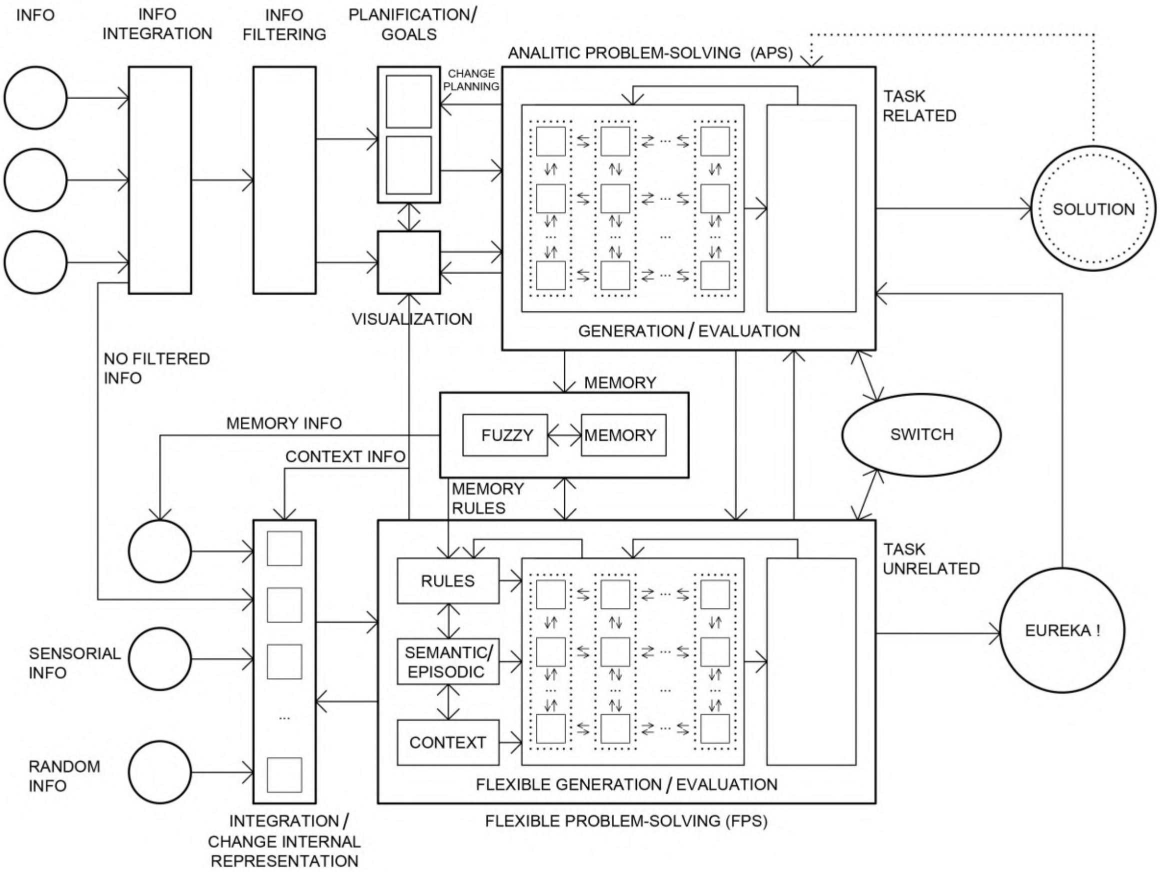

Figure 6.2. Neurocognitive model of the creative process, proposed by Luis De Garrido

The first characteristic of the proposed model is the absolute flexibility and the constant interaction of the basic structures. The model is based on an information processing system that operates both in series and in parallel. In the same way, information processing can be done at any time at various levels of abstraction, passed from one to another based on top-down and bottom-up processes.

The complexity of the model means that even if very similar problems were solved consecutively, the information processing could be carried out in a slightly different way (and in some cases substantially differently), so different solutions could be reached. Therefore, the model tries to emulate, in a block diagram, the neuronal information process (transversal and flexible) based on large-scale networks, and the continuous information flows (serial) based on cerebral gradients.

In the proposed model there are two large information processing engines. An engine performs an analytical problem-solving (APS) process, based on a complex generation/evaluation matrix. This processing engine is suitable for dealing with new problems, for whose resolution there are no previously created semantic analogies and valid operating rules in memory. In general, this engine is suitable when the problem to be solved is simple, or perfectly defined (the APS would therefore emulate the activity of the ECN). The APS feeds on all the information currently available, integrating it and filtering it conveniently. Based on this information, and with the help of the FPS, objectives are created, planning is carried out in stages, the results are visualized, the distance between the state and the solution is calculated (prediction error), and the problem contexts are imagined.

The other engine performs a flexible problem-solving process (FPS), based on a much more complex generation-evaluation matrix. This processing engine is responsible for carrying out a flexible, personal and visceroceptive generation/evaluation process, and is useful when the problem to be solved is very complex and/or poorly defined. In these cases, information must be added (contextual, sensory and random) and the fuzzy information stored in memory must also be used, as well as the rules previously generated in previous experiences (the FPS would therefore emulate the activity of the DMN). The FPS is capable of modifying the information and rules that are being used. It also uses (and modifies) the available semantic and episodic information, creating semantic parallels and associations, and creating contexts for each stage of the creative process. The FPS is especially important for graphic design and special design (painting, object design, architecture, etc.), for which complex contexts must be generated at each stage of the design process.

There is a switching agent that decides at each moment which of the two processing engines should have a leading role (in reality it can be the same processing engine with reconfigurable components that take on different roles). When an objective is set, the APS is initially activated, which evaluates the problem. To imagine the objective, the steps to follow, and the most complex scenarios, the FPS is activated, eventually. If the issue is viable, the APS remains active until resolved. Eventually the APS requires the collaboration of the FPS when it comes to deciding on a social or personal issue, or when hypothetical contexts must be imagined. The APS may come to a solution, which may be satisfactory. In that case the system terminates. However, the APS may not be able to reach a satisfactory solution after several attempts. In this case, the FPS is activated, which addresses the problem in a more abstract, flexible and powerful way (since more and more effective processes are involved). The FPS acts unconsciously in most cases, and feeds on existing information, complementing it with current sensory information, fuzzy information stored in memory, and in some cases, random information. The FPS is capable of working at various levels of abstraction, from very general levels to very detailed levels, so an adequate representation of information at various levels of abstraction is very important. In this way semantic analogies can be easily established, and both the information and the rules stored in memory can be semantically manipulated. The FPS is based on a complex information processing system both in series and in parallel. This system is based on generation-evaluation sequences in which decisions are made at various levels of abstraction, intertwined through top-down and bottom-up processes.

The FPS can reach a certain adequate solution (because it loosely meets the objectives), and at the same time surprising (because it does not resemble other more abundant and repetitive solutions). This solution is often referred to as a “happy thought”, since it seems to come out of nowhere, and seems to fulfill, albeit in a blurry way, all the objectives. When this happy thought appears we experience a burst of consciousness, and we feel an excitement (usually known as “eureka!”). The appearance of this idea causes the APS to be activated again, and consciously, and based on an analytical process, its suitability is evaluated. If the "happy thought" is adequate, the process ends. On the other hand, if this idea turns out to be inadequate, certain modifications are consciously attempted by the APS. Again, with the help of the FPS, new contexts of the problem are created, the objectives and the steps to follow are refined, and it is possible that the APS finds a solution. However, it may happen that the APS does not get a solution, so the FPS is activated unconsciously again, and the process is repeated.

Obviously, this neurocognitive model of the creative process is very simplified, and it must be refined and complemented based on successive discoveries about the neurocognitive bases of human creativity. However, it is a first proposal, which allows having a more complete global idea of the creative process, and therefore provides a framework for action so that future research can be redirected and can be more effective.

6.4. Proposal of a general strategy to stimulate human creativity based on the analysis of the neural bases of human creativity

The analysis of the main neurocognitive bases constitutes the essence of the neurocognitive paradigm of human creativity. Similarly, this analysis has suggested a set of suggestions, which together can provide the guidelines for a general strategy to increase human creativity.

This general strategy includes educational actions, change of habits, and the use of pharmacological substances, and especially the use of new technologies.

6.4.1. Education

As seen in the set of suggestions derived from the analysis of each factor, proper education is the most important mechanism for stimulating human creativity. The vast majority of educational systems used in today's overpopulated societies do not encourage creativity in any way, indeed, they restrict it considerably. To control a huge population it is important to induce in citizens a set of beliefs based on intersubjective information. This information is invented, convenient for the new ruling classes, and must be shared by a large number of people, so that they feel identified and can collaborate in a flexible way. In this way, citizens who do not know each other, having the same beliefs, are able to collaborate in large groups. Therefore, the objective of current educational systems is to camouflage among a set of basic knowledge an intersubjective ideology convenient to the ruling classes. The important thing is that the majority of citizens can believe in a created and invented account and identify with it.

With this current context, creativity is the main enemy of this generalized indoctrination process. Therefore, achieving very creative citizens is incompatible with a mass educational system, and creative individuals are, despite the enormous restrictions of educational systems. In fact, one of the characteristics of many educational people is to have achieved very low grades in the educational systems. Many of them have even avoided them.

Therefore, the first educational strategy necessary to increase creativity is to avoid the current education systems, and especially the public ones. Instead, there is some chance of success in private education.

A complementary education to stimulate creativity would only be successful if it was not hampered by regulated education. On the other hand, an education to amplify creativity could not be integrated within the current educational systems since it would probably come into immediate conflict with the rest of the educational content.

If these obstacles were overcome, something unlikely, certain strategies could be devised to stimulate creativity, such as those that have been exposed previously.

The first strategy that must be adopted to establish educational systems that amplify human creativity is to design methods intended for children's education, and other methods intended for other ages.

Throughout our first years of life, an enormous number of neural connections are established between the different parts of the human brain. These connections join different neurons together and establish certain differentiated regions, as well as large-scale networks. The establishment of these connections is determined by genetic inheritance, but in any case before the age of six is when more connections exist in the brain, and they are eliminated over time. The existence of an enormous number of neuronal connections implies that the flow of information can run along wide paths, in which different alternative paths can be established. This makes it possible to enrich and mix the available information. In a simplified and symbolic way, it could be said that to find the solution to a problem, since there are a greater number of neural connections, the number of paths through which the solution search tree can be traversed could be expanded. And as a consequence, the possible cognitive processes are much more varied, the information flows are much more varied and, as a result, the possibilities of finding creative solutions are much greater.

Once certain neuronal links have been established, and depending on the neurocognitive activity of each person, some of them are strengthened, while others are weakened, and many of them even disappear. As a consequence, the information flows are restricted, and as a consequence the number of paths to traverse the solution search tree is considerably reduced.

Therefore, it is essential to correctly establish the education of children in their first years of life, since that is when their creativity can most easily be developed. In childhood, the number of neural connections is very large, and as a consequence, based on correct activity, a greater number of connections can be consolidated. And they must be maintained as much as possible for the rest of their lives, continuously carrying out creative activities.

Many educational systems are full of prejudices, social interests, personal interests, social stereotypes, political interests, commercial interests, etc. It should not be forgotten that the current educational system is based almost exclusively on creating docile and minimally prepared citizens, but at no time has it been designed to stimulate their creativity. These educational systems can mutilate a high number of neural connections in the child's brain, which reduces their neurocognitive capacity in general, and in particular, their creative capacity.

As has been said, the creative process consists of two fundamental phases: a phase for generating creative ideas and another phase for evaluating them. This could suggest that the brain must work in two different ways, but based on the research carried out, it is known that they are two different processes, carried out by different neural networks that activate independently, although sometimes they collaborate and have small overlaps. Therefore, it is possible to amplify the creative capacity of children by increasing, on the one hand, their capacity to generate ideas, and, on the other hand, their capacity to evaluate them, without the limitations of conventionalisms, prejudices, or social interests existing at each time and place.

Children should have two different and complementary training processes: idea creation and idea evaluation.

1. Idea creation processes

The goal is to amplify children's innate capacity to generate creative ideas. The concept of “creativity” does not have the same meaning for a child as it does for an adult, since what is creative for an adult is just another idea for a child.

In adults, the number of neuronal connections has been reduced, and as a consequence certain pathways of information processing have been enhanced, to the detriment of others. As a consequence, adults have more difficulty coming up with creative ideas. In other words, the tangle of branches in the quest tree has been pruned considerably, making reaching too many points more difficult or impossible.

In contrast, children only have genetic limitations, so they can go through the search tree in many more ways, and therefore can generate so many creative ideas that seem normal to them. Therefore, the first action that must be taken is not to limit the creative potential of children.

Second, exercises such as those suggested above should be performed. These exercises should have several complementary purposes. First of all, they must carry out activities to generate associations at different levels of abstraction. They must find parallels between the different activities they carry out, trying to find common patterns both in the structure of concepts and in the structure of processes, with the aim of creating abstract, blurred concepts and processes with varied applicability. They should be asked to carry out all kinds of semantic transfer exercises, so that the concepts they are developing have as many nuances as possible, that is, they have as many attributes as possible, with the greatest possible variety of values. The more complex, extensive and varied the cognitive structure with which the concepts they are learning are formed, the greater their future creative capacity will be.

To create this conceptual richness, they should be encouraged to have as many varied experiences as possible, and they should try to identify parallels with some previously experienced experiences (at various levels of abstraction). It must be taken into account that children do not easily distinguish between sensory-induced thoughts and self-generated thoughts, so the difference must be indicated to them at all times, without restricting their development. Another type of exercise that they should do is to create stories based on the mixture of concepts, for example mixing random elements with known elements from their more familiar environment. In this regard, and involving the hippocampus, it is convenient that they carry out exercises to develop the "space vision" when imagining and drawing objects (whether existing or non-existent) and at the same time creating literary-visual stories in which concepts are related to spaces. It is also important that they exercise based on their own self-generated thoughts so that they learn to control them. Finally, they must perform three types of exercises. On the one hand, they must learn to generate goal-directed ideas, and they must be taught to reason step by step, based on generalized logic. On the other hand, they must generate ideas related to themselves, their friends, and family, giving free rein to their thoughts, but learning to control them based on previously established criteria, and their own previous experience.

b. Evaluation processes

Children must be taught to make correct evaluations of previously generated ideas. It is very important that the most appropriate criteria be chosen in the evaluation processes, without being conditioned by prejudices, stereotypes, conventions, commercial and political interests, nationalism, etc. The evaluation criteria must be based on objective information, and some intersubjective information that does not conflict with the objective. In the same way, they should be taught how to evaluate the evaluator, as a criterion to establish criteria in case of conflict, that is, to establish evaluation meta-criteria, with the highest level of abstraction possible. In a complementary way, they must be taught to design correct evaluation processes: using previously established criteria, using more personal criteria, and especially, based on the "internal connection" established with the ideas to be evaluated. Finally, they should be familiarized with the concept of failure as a special form of motivation, without affecting their freedom of action in the next cycle of generating ideas.

To stimulate both the generation and evaluation processes of ideas, different strategies must be established to develop motivation processes and emotional reward processes.

In adulthood, the same type of exercises should be performed, although to increase motivation, they should be aimed at solving problems similar to those they may have in their daily life. The important thing is to maximize the range of cognitive activities that they can perform.

6.4.2. Lifestyle and environment

Lifestyle and the environment also have an influence on the creative process since it can influence the development and functioning of its neurocognitive bases. In general, very stimulating environments should be chosen and in which emotional situations can be achieved, while allowing eventual isolation from their entire environment. This same characteristic is observed in historical periods, in places where reactive people and groups have developed. Motivation can be any type, and exciting events can be positive or negative. Well-being takes a backseat, and pleasant, comfortable, loving, etc., environments should be avoided. In the same way, happiness is also not influential in the creative process.

Above all, environments should be avoided in which indoctrination of any type is favored, unless it serves as an absolute rejection, and this is an additional stimulus. In fact, a large number of creatives have found a great source of motivation in rebelling against norms, customs, and, in general, rules that are widely accepted in their immediate environment. Creative people do not usually accept rules, laws, or ordinances of any kind, as they have the ability to question any of them and possibly seek alternatives, at least for their daily lives. Therefore, they usually live outside any kind of rules.

Social relationships should be restricted to a small number, worse at the same time very stimulating. Creative people tend to always keep their enemies in mind, since this motivates them, and at the same time they tend to surround themselves with few friends, with whom to share their anger.

Another fundamental aspect is the specific knowledge of certain cultural currents, intellectual concerns, or any type of strange and unusual information in their environment. This information, mixed with information from your environment, and self-generated information is often the source of creative activity.

6.4.3. Food supplements and pharmacological substances

Based on the analysis of the neurocognitive bases of human creativity, it can be deduced that pharmacological substances can increase it in two ways. Some substances will be able to eliminate mental situations that have a negative impact on creativity. For example, it has been commented that stress, or fear, reduce human creative capacity. Therefore, if the impact of stress, or fear, on human cognition is reduced, the creative capacity in these situations will remain unchanged [20].

Substances that amplify human creativity can also be used. For example, the use of dopamine in creativity has been seen to be important, so if it is administered properly, certain processes of human creativity will be amplified [21].

Finally, substances that directly reduce human creative capacity should be avoided. For example, substances such as Ritalin, which are usually given to treat children's attention deficit, diminish the human creative capacity. This substance is taken indiscriminately by adults in order to improve their ability to concentrate (i.e. the activity of the ECN) under the illusion that this improves human cognitive processes in general, although in reality it reduces many others, such as the effectiveness of the creative brain. In general, any substance that activates the cognitive processes of the DAN, and in some cases of the ECN, to the detriment of the MTL and the DMN activity, will diminish the human creative capacity.

In general, many substances can be developed, although based on what is known about the brain, if certain human cognitive abilities are increased by pharmacological substances, it is more likely that others will be reduced. However, it is a growing field of experimentation. In addition, they must take into account other side effects. Therefore, the use of non-invasive biotechnology is more promising.

6.4.4. Biotechnology

As has been seen, creative activity is based on a set of complementary neurocognitive processes that are activated in certain circumstances, and in a certain order. Therefore, if through technological devices certain brain regions could be stimulated and/or others inhibited, creative processes could be stimulated. For example, in the generation of creative ideas phase, the activity of the regions included in the DMN and in the MTL could be stimulated in order to generate a greater number of self-generated thoughts, while the regions of the ECN, and the DAN. On the other hand, in the ideas evaluation phase, the ECN regions could be activated (and in some cases the DMN in addition), in order to carry out an adequate and effective evaluation. In addition, motivation mechanisms or reward mechanisms can be amplified at certain specific stages of the design process. Connections to dopamine D2 receptors in the thalamus could also be controlled. Finally, certain parts of the brain could be excited to promote information mixing, as well as the stimulation of information retrieval in episodic memory, etc.

This brain stimulation could be carried out by means of portable bionic devices that could be placed around the brain, or even, in certain cases, partially implanted inside it.

There are already precedents for these bionic accessories, such as the brain helmet developed by the company *Innosphere*, which is capable of stimulating the neuronal activity of certain regions of the brain in order to correct the attention deficit of certain children. This device provides personalized treatment for ADHD by applying precise electrical stimulation signals to specific areas of the brain associated with the disorder.

Personalized treatment sessions based on machine learning are uploaded to a head from a digital health platform (proprietary by *Innosphere*) and delivered in ten treatment sessions of up to 20 minutes over a month [22]. Other technologies exist to treat the syndrome attention using random noise generators [23].

Another surprising precedent is the "transcranial direct current stimulators", popularly called "attention helmets", which are helmets that can be put on the head, as if it were a motorcycle helmet. These helmets have a set of electrodes that are attached to the scalp from the outside. The case produces weak electromagnetic fields and directs them to certain specific parts of the brain, stimulating or inhibiting its functionality.

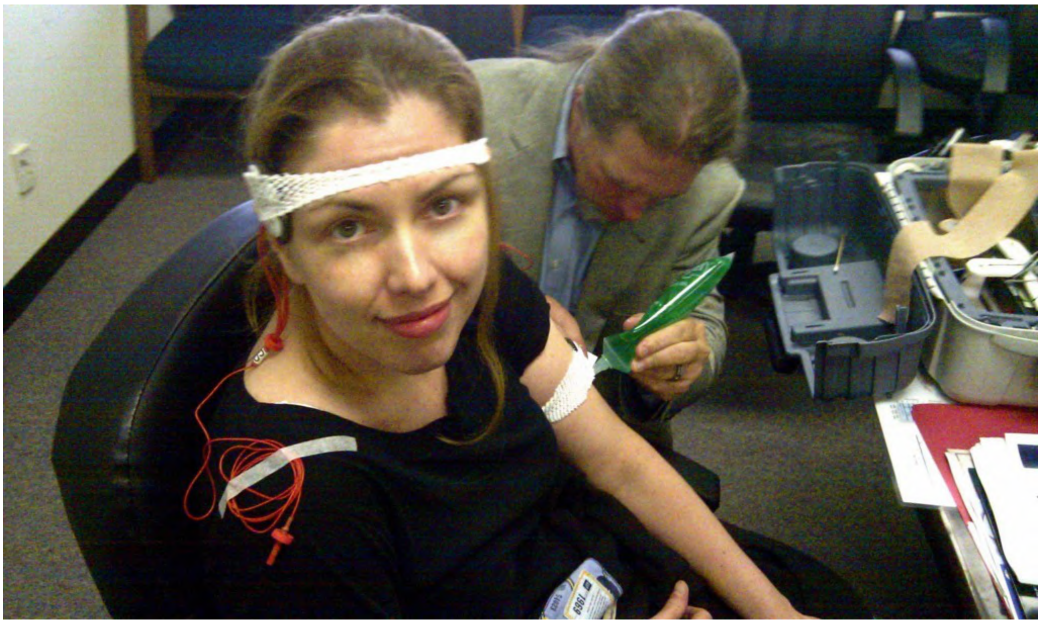

Figure 6.3. Sally Adee with an "attention helmet"

One of the most effective helmets known are those developed at the *Human Effectiveness Directorate General, Ohio Air Force Base,* which have been used to increase the effectiveness of drone flight controllers, air traffic controllers, snipers, etc. A few years ago, journalist Sally Adee [24] had the opportunity to try one of these helmets while she was shooting a series of shots at a target (Fig. 6.2.). Without the helmet she had hardly any hits, while with the helmet she hit 100% (Fig. 6.3.). Sally commented that when she put on the case she noticed her mind transformed as she did not have any sense of insecurity, and in fact for several days thereafter she had a recurring need to reconnect to the care helmet.

In the same way that helmets have been developed to stimulate attention and concentration, based on the knowledge we have of the neurocognitive processes of human creativity, "creativity helmets" could be developed, which would not only amplify human creativity, but that would integrate "augmented creativity" systems, as has been mentioned.

These attention helmets are non-invasive, and have no side effects, so they will undoubtedly become a human complement when performing certain high-level creative tasks.

Figure 6.4. Sally Adee achieving 100% of targets with the help of an "attention helmet"

6.4.5. Genetic engineering

Genetic engineering is in question in our society, but it will undoubtedly be the last station for the improvement of human cognitive abilities and creativity.

Society, at the moment, has prejudices against genetic engineering, and therefore research is slow. The global paradigm on "human rights" is the prevailing one, and based on it a conglomerate of social rules and prejudices has been generated. Most humans don't want there to be clearly better humans. Therefore, genetic engineering research is based on remedying certain cognitive deficiencies in order to create "normal" humans. However, and it is a matter of time, this paradigm will fall, and investments aimed at improving the cognitive abilities of those who can pay for the investment themselves will grow. It's just a matter of time. How do we have information about the neurocognitive processes of human creativity, we can carry out research on how to improve these processes through genetic engineering. Genetic manipulations can be developed so that brain connections are maintained longer and do not fade. The cognitive capacity of certain integrating regions of the MTL, the ECN, SN, and especially the DMN can be amplified. The activity of the large-scale networks involved in creativity can be amplified, a greater number of connections can be established, etc…

At the moment the achievements are incipient, and although a few years ago the promises were very optimistic [25], at the moment they are more modest. Currently, research on brain genetic engineering aims to remedy or mitigate certain brain disorders, as is the case especially with Alzheimer's and Parkinson's disease [26]. The use of organoids, from stem cells, to restore brain tissue is also very promising [27].

6.4.6. Artificial intelligence

Artificial intelligence will undoubtedly be the most effective mechanism to increase human creativity. In the near future, "augmented creativity" interfaces (similar to current “augmented reality” systems) may be developed. These devices will continuously collaborate with the human brain, both in generating ideas and evaluating them. In the same way, creative computational systems can be designed, capable of carrying out creative activities by themselves, taking into account criteria of human satisfaction, or general criteria. This section is so important that the next and last chapter of this work will be dedicated to it.

Notes 6

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CHAPTER 7

Neurocognitive-based computational creativity paradigm

Chapter 7. Neurocognitive-based computational creativity paradigm

As seen in the previous chapters, human creativity is modulated by social rules, prejudices, customs, etc., and its main objective is to satisfy human needs. Therefore, the paradigm of human creativity imposes limits on the creative capacity of the human brain. If these limits were removed, human creativity would be limited only by the structure of the human cognitive system. Therefore an alternative paradigm of other creative systems (such as computer systems) should necessarily be broader, since it would only be limited by the design of their processing systems.

What would a computational paradigm be free from the limits self-imposed by human beings? It's hard to even imagine. And the concept of "creativity" should be defined at a higher level of abstraction. At the moment the most general definition of the creative process is one that produces novel and valuable ideas. Ideas are novel if they did not exist before and they are valuable if they are able to solve a certain problem. The question seems simple, but surely it would have little validity for human beings, since many of the very creative ideas of the creative computer system would be rejected since they would go against certain human interests.

For this reason, computer systems are closely linked, in one way or another, to personal interests. And therefore they have conceptual limits similar to those of the human brain. Therefore creative computational systems could have a creative capacity greater than that of the human brain if some of its limits are released.

7.1. Computational creativity

Computational creativity, as it is commonly understood today, aims to create creative processes using computer systems. The creative mechanics of these computational systems are designed based on certain previously established concepts about the creative process, which in turn have been modeled by observing the behavior of creative individuals. That is, firstly, a methodological system of the creative process is designed (as a consequence of observing the behavior of creative humans), and based on this methodology, computational systems are designed (which in turn use certain simple methods). Therefore, what is actually implemented is a simplification of a simplification, which in turn is again simplified by the computational means available, the human team available, and especially by the problem to be solved (which is usually limited in an extreme way "in order to be computationally approachable"). It is not surprising that few computer systems come to show a behavior that can minimally be described as "creative".

The commonly agreed creative methodology is composed of two processes: creation of ideas and evaluation of ideas, and therefore most computer systems are based on the choice of a generation system and an evaluation system.

With regard to idea generation systems, three methods have been used in a generalized way: combination of familiar ideas (combinational creativity), taking a thinking style and tweaking it (exploratory creativity), and changing dimensions of an existing idea (transformational creativity) [1]. Some researchers distinguish between historical creativity (H), relative to the generation of new ideas that are not known to have been reported at all, and psychological/personal creativity (P), relative to the generation of new ideas for the person [2].

Many creative ideas can be created and come out of different evaluation systems, however society may see this idea as uncreative. Therefore there is a social aspect in creativity, which must be taken into account in computational creativity systems [3]. It cannot be reduced to some formal properties, but the debate can be useful to enumerate conditions under which an external observer is more likely to consider a system as creative. This criterion is similar to one of the stances when discussing what is artificial intelligence (AI), “intelligence is in the eye of the observer”, meaning that a system is as intelligent as an external observer considers it to be [4].

In order to provide the most general and varied framework possible, and at the same time allow the analysis of the concept of "creativity", different taxonomic frameworks have been created throughout history. The taxonomy commonly accepted as the most complete and accurate is the 4-P approach, that is cited frequently to analyze human creativity research, and later it was adopted as a general framework for the design of computational creative systems. These four Ps stand for *Person* (what makes the agent a creative one), *Process* (what actions need to be undertaken to be creative), *Product* (what kind of creation is expected), and *Press* (what cultural context is applied to determine something as creative or not) [5].

With regard to idea evaluation systems, numerous criticisms have been established. It is often argued that most evaluation systems make the methods uncreative, and there are numerous criticisms regarding the definition of terms, lack of autonomy in existing systems, the cultural specificity of many judgments, and the potentially domain-specific nature of creativity [6]. While operational tests (e.g. statistical analysis of the product) have been used for this purpose, questionnaires are a more frequent evaluation tool. Following its recommendations, one can address each P with some rules of thumb that include criteria to choose each P depending on the kind of impact one wants to achieve.

Another theoretical framework [7], intends to characterize the different creative systems and concepts, such as un-inspiration (failing to be creative in a valued way) and aberration (deviation from the norms) in order to support formal reasoning about creativity, and uses these two examples as illustrative ones.

Within this conceptual framework, I have personally been able to implement a computer system that emulates the creative potential of *Brainstorming* [8]. It is a multi-agent system (M.A.S.), in which two different processes are exchanged: generation of ideas and evaluation of ideas. The wealth of idea generation is ensured by the existence of several agents with different functionalities, and the same can be said for the idea evaluation phase. Each operating cycle of the system generates different criteria, both in the generation phase and in the evaluation phase, due to a different sequence of agent activation, with each time different activity. These criteria also change, depending on the problem to be solved, and due to the existence of several agents, each one involved in a field of knowledge. The *Brainstorming* structure itself implemented by a multi-agent system provides adequate criteria for the creation and evaluation of ideas.

Based on the successful implementation of this system, the conceptual structure of a much more powerful computational system was later designed, since its structure is based on the analysis of the main methods to amplify human creativity [9]. The structure of this computational system is based on the existence of two groups of agents, within which agents can have different roles.

7.2. Computational creativity based on the neurocognitive structure of the brain

Current computational systems are based on the conceptualization made based on the analysis of the creative process. And all of them are aimed at solving human problems. However, few, if any, have a behavior that can be called minimally "creative", and perhaps the main cause is the enormous amount of restrictions in the generation and evaluation processes.

So far there are no creative systems that base their architecture on the neurocognitive structure of the human brain, on which the creation of surprising, novel and valuable ideas is based. The main reason is that so far very little was known about the neurocognitive basis of the human brain. Only recently, and because of technological advances, are we able to detect and analyze the activity of the brain when carrying out a creative activity. But in addition, researchers and designers of computational systems have enormous prejudices in this regard (perhaps induced by the ignorance of the neurocognitive bases of human creativity). In fact, there are no papers that identify, classify, and relate to each other, the main known factors that support the creative capacity of the human brain. However, there are certain precedents based on previous knowledge of the human brain.

In fact, there is an updated list of the main researchers in the field of the neural bases of creativity, although it does not cite their main research and achievements, nor does it relate them to each other, nor does it comment on whether they have used their research for the implementation of creative computational systems [10].

A first precedent, although not closely related, focuses on the study of the creative process related to *Brainstorming* methodologies, based on the exchange of ideas, or information, as a basis for the stimulation of creative ideas [11].

A second precedent, equally distant, propose a neurocognitive architecture of creativity with a strong focus on various facets (i.e., unconscious thought theory, mind wandering, spontaneous brain states) of un/pre-conscious brain responses [12]. Their focus of research is based on the fact that pre-conscious creativity happens prior to conscious creativity and they propose a computational model that may provide a mechanism by which this transition is managed.

In general, the current designs of computational creative systems are not based mainly on the knowledge of the creative capacity of the human cognitive system, but on techniques based on the analysis of the conceptual creative process, developed based on the observation of human creative activity. And this is due to two reasons. On the one hand, the neural bases of human creativity have only begun to be understood in the past few years. On the other hand, some computational creativity researchers think that artificial systems have nothing to do with imitating natural systems. In this sense, it is often said that airplanes work with propellers and turbines, and do not try to emulate the beating of the wings of flying animals. However, when Leonardo da Vinci invented the propeller, he did so based on an exhaustive analysis bird flight. It was while trying to understand the mechanism bird flight that he discovered the basic conceptual structure of the activity of flying. And with the knowledge of this abstract conceptual structure that he was able to invent the propeller. That is, by trying to emulate a natural system, an even more efficient artificial system was identified.

Leonardo da Vinci was excited and intrigued by the flight of birds, and made countless studies and drawings trying to understand its physical foundations [13] (Fig. 7.1).

Figure 7.1. Drawing to find out the conceptual bases of the flight of birds, by Leonardo da Vinci

In a first stage Leonardo da Vinci made several designs and several models, to make a mechanical device, capable of directly emulating the flight of birds (Fig. 7.2). Based on these studies Leonardo also designed a gliding device, based directly on the design of the wings of birds.

But he wanted to make a truly flying artifact, capable of self-propelling. However he soon deduced that there were no materials light enough to make the wings; nor there were any thrusters small and powerful enough to allow them to flap their wings and fly. What’s more, he predicted that it might never be possible.

However, his obsession with identifying the physical foundations of the mechanics of bird flight led him to design an artifact that did not emulate the beating of the wings of birds, but was capable of moving supported in the air.

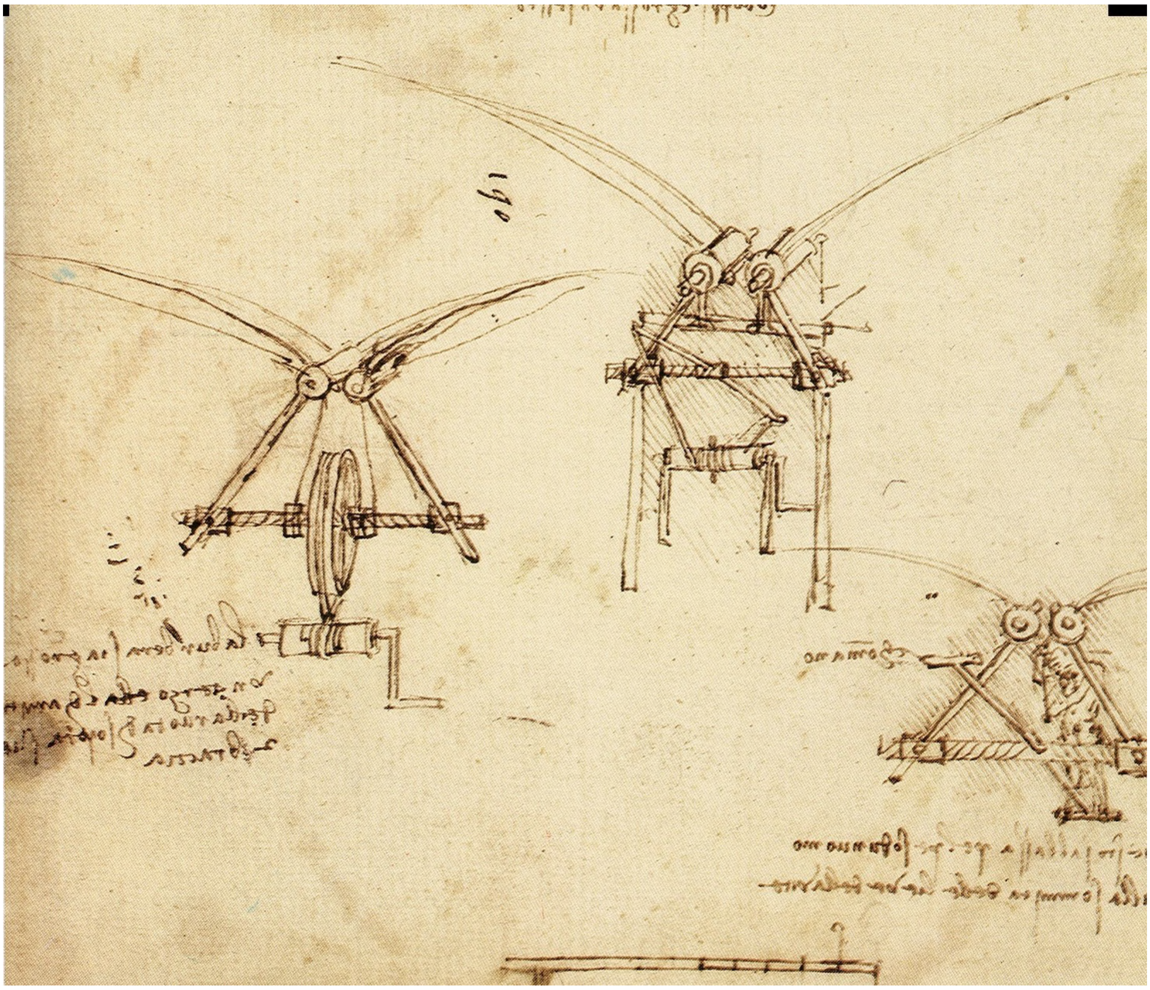

Figure 7.2. Drawing of a flying artifact trying to imitate the flight of birds, by Leonardo da Vinci

Leonardo's great passion and obsession with the flight of birds made him apprehend and internalize the enormous amount of information previously accumulated. Based on the huge number of failed proposals, his DMN was finally activated. His DMN carried out all kinds of tests, changing the usual rules previously generated, with all kinds of modifications. And it finally happened. I have designed a propeller for the first time.

The propeller is much more efficient than the flapping of the wings and is much more energy efficient, and it can be built with heavy materials, in exchange for being able to turn at high speed (Fig. 7.3). It is very likely that without trying to emulate the flight of birds, a new flight strategy would never have been designed, much more efficient, and not existing in nature.

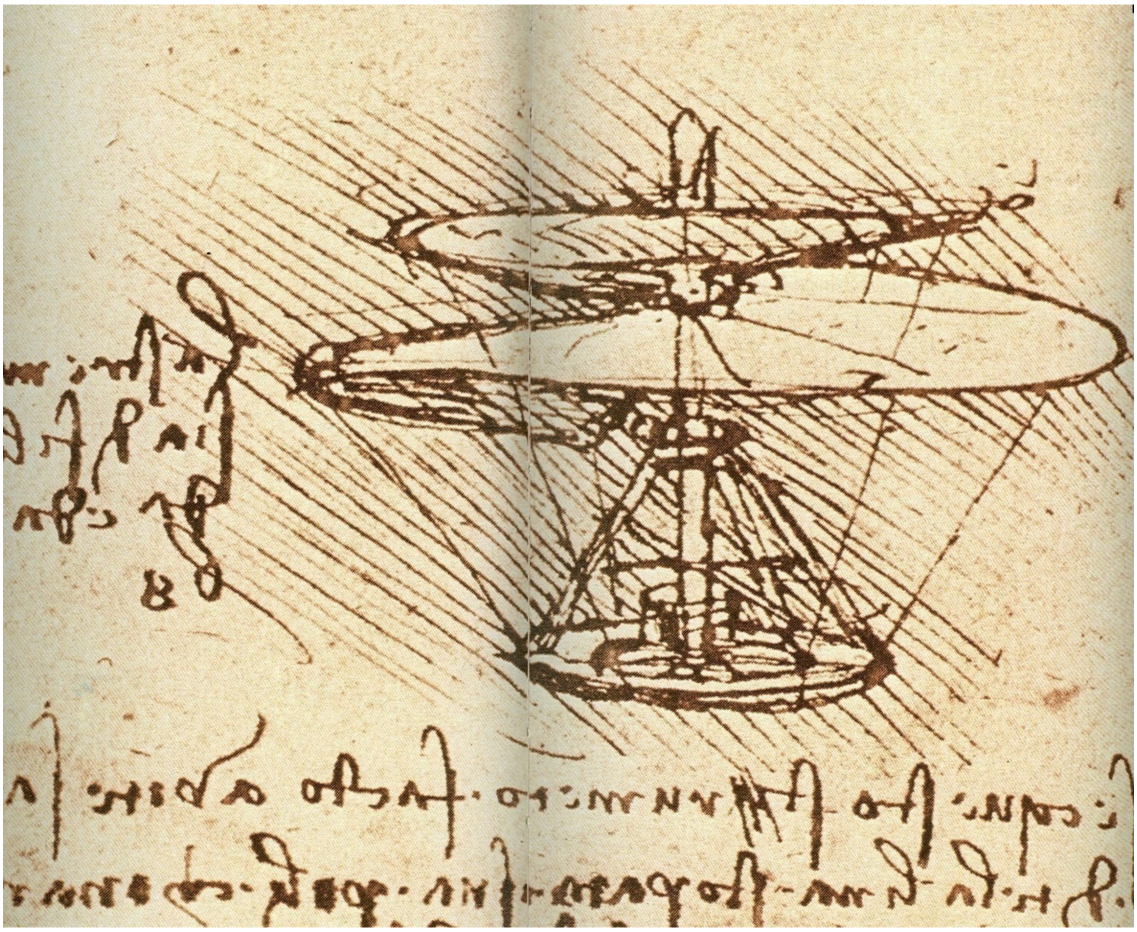

Figure 7.3. Drawing of a propeller as a result of internally apprehending the essence of the flight of birds, by Leonardo da Vinci.
The energy efficiency of a propeller is superior to the flapping of wings, but its design would not have been possible without first having studied deeply, and internalized the essence of the mechanics of flight.

By trying to emulate a natural system, an even more efficient artificial system was identified. Therefore the development of an A.I. creative system based on the neural bases of the human brain is not the final goal, but the first necessary step, so that creativity in A.I. can reach a level not even imagined today.

Therefore, the development of an AI computational creative system based on the neural bases of the human brain is not the end goal, but the first necessary step, so that computational creativity can reach a level not imaginable today. In any case, the proposed system is not intended to directly imitate the workings of the human brain but has been designed considering the neural conceptual structure that supports the enormous creative potential of the human brain, that is, the neurocognitive architecture of creativity. In this way, one is closer to identifying the general conceptual mechanisms that sustain creative activity, whether natural or artificial.

7.3. Suggestions for the design of a A.I. computational creative system, based on the neurocognitive bases of human creativity

A computational system based on the neural substrate of the creative capacity of the human brain has no precedent. In fact, the present work aims to create a new path of research in artificial intelligence, which can now be undertaken due to recent discoveries regarding the functioning of the human brain and the neural bases of its creativity.

The usual creative computational systems have been made based on observations, deductions and interpretations of human creative behavior, and based on the technological possibilities available today [14]. Conventional computational tools are usually used, supplementing them by means of extremely high computational speeds.

On the other hand, following an alternative path, the present work tries to open a new path of investigation. To do this, first, a justification for human creative behavior has been provided, analyzing the main neurocognitive factors that sustain it. Therefore, instead of considering what is observed, analyzed and interpreted about human creative behavior, for the design of an alternative creative computational system the creative structure of the human brain is considered. This new strategy makes it possible to tackle the problem directly, avoiding shooting in the dark.

To approach the design of a computational system based on the creative structure of the human brain, the different neurocognitive factors identified in chapter 5 have been analyzed. Each factor has been analyzed at a high level of abstraction in order to identify computational parallels that can emulate it. It is not about literally emulating the structure and functionality of each neurocognitive factor, but rather looking for computational analogies inspired by its structure and functionality. As a result, each factor will generate a certain set of computational suggestions of various types (system architecture, functionality, knowledge representation, etc.).

Once all the factors have been analyzed, the different computational suggestions should be grouped together. Many of them will be repetitive, which means that they are more important and should have a great impact on the design of the system, while others suggest only a few details about it. Some factors suggest ideas about the basic structure of the system, while others suggest ideas about some of its secondary aspects. Others, on the other hand, suggest ideas about the representation of knowledge, and other varied aspects that should be taken into account.

Third, based on the set of computational suggestions generated, both the system structure and its functional operability must be designed.

Fourth, the functionality of each part of the computer system must be bounded, conceptually delimiting its functions, objectives, limits, etc.

As a result, the conceptual design of a creative computational system based on the neurocognitive factors of human creativity will be obtained.

Obviously, the implementation of a similar computational system is a titanic task, so annotations and simplifications must be made, and it must be adapted for a very specific activity. In fact, and based on this structure, work is already underway on the implementation of a creative computational system, capable of designing architectural structures of Roman basilicas.

7.3.1. Suggestions based on the structure of the human cognitive system based on large-scale networks

To emulate the high creative level that human neural networks allow, flexible and dynamically reconfigurable AI algorithms must be created. This could be a multi-agent system so that groups of agents could be created, emulating the activity of each network. These groups would vary in number, with a fixed nucleus and a variable number of complementary agents, so that the group is different for each task. This structure could be implemented alternatively by means of agents who assume different roles that change according to the needs of the system.

7.3.2. Suggestions based on the multimodal organization of the brain

The multimodal organization of the human brain implies a gradual transformation of information. The transformation is initially a gigantic set of concrete data, and finally it becomes abstract information, full of meaning and widely related. This suggests that a creative computational system should be able to repeatedly transform information, changing its semantic structure. Therefore, the information must be represented in such a way that the same structure (for example: object-attribute-value) can serve to represent information at various levels of abstraction. In the same way, different mechanisms must be established to transform information from a semantic point of view. This process could be carried out by various specialized agents, which in the final system will be called as “info + agent” and “info-modifying agent”. In this way, the different computational processes developed by the agents can use some attributes or others, which means that they can manipulate the information at different levels of abstraction.

The DMN occupies one end of the main gradient within this multimodal structure, which implies that it is involved in the management of the most general and abstract information, and therefore facilitates and manages the generation of self-generated thoughts. This mechanism can be implemented using a specialized agent that generates information with various levels of randomness, the “spark agent”. In the same way, this random information can be mixed with the information in progress through another agent, the “info-modifying agent”.

7.3.3. Suggestions based on the topographic distribution of large-scale networks, and their nodes

The topographic distribution of the human brain suggests that the flow of information is progressively abstracted from different unimodal regions to the different regions of the DMN. This explains that the DMN is involved in several different processes, apparently unrelated to each other, but always with the highest level of abstraction. This process is essential, as it allows high-level semantic association of abstraction. In this way apparently different activities can be related, but with different high levels of abstraction. For example, roasted wood is related with roasted meat since both have been exposed perimeter to fire, and as a consequence their interior is protected from it. Therefore, the concept "burned perimeter" can have multiple attributes, but must include: "protect the interior", forming a protective casing. These attributes can be transferred to any other element. For example, a perimeter burned tree has its interior protected, and therefore can come back to life. Finally, the concept of "heat-treated wood" shares the same attributes, since by burning its perimeter its interior is protected from the incidents of the environment, and therefore it can be used as a much more resistant construction element.

This process of generating high-level semantic analogies requires that the information be adequately represented, with a large number of attributes, which in turn can have a large number of possible values. The information represented in this way can be filtered and restructured, choosing a certain set of attributes at each moment, and with this the same information can be represented with several levels of abstraction. The same agents suggested in the previous section can be used to adequately transform the information at various levels of abstraction.

7.3.4. Suggestions based on the collaboration between ECN, SN and DMN

Based on the previous analysis, an algorithm that attempts to emulate human creativity should have three groups of agents.

One group (“serious group”) would act rigidly, with the structure proposed in previous section, and with conventional algorithms, such as those used in searching and planning. Another group of agents (“playful group”) could filter some of the information, add new self-generated data, or mix that with other information more or less relevant to the problem. In general, there are three forms of self-generation of information. One way is to generate random information (which can have various levels of randomness). Another way is to generate information based on attributes shared with the information of the problem to be solved. Another way is to alter existing information using different techniques (using analogies, symbols, metaphors, etc.).

This process of filtering, generating and mixing information can have several levels, from a low level (where the filtering and generation is done in a way related to the problem to be solved) to a high level (in which it is done randomly), with various intermediate levels.

A third group of agents (“control group”) would decide at any given time which of the two groups should be activated, and in some cases would determine that they cooperate in certain tasks.

7.3.5. Suggestions based on the role of the DMN

The DMN has two basic functionalities in the design process, that of generating ideas and that of carrying out an evaluation related to oneself, and to close people. The generation of self-generated thoughts can be done by the “spark agent”, and it can be mixed with the information in progress by the “info-modifying agent”. The viscerospective evaluation may be carried out by the "evaluator agent", who also performs a logical evaluation, changing its role.

7.3.6. Suggestions based on the role of the MTL

The MTL performs semantic and episodic associations, recombining current information with information that it can retrieve in memory. In this way it can create integrated conceptual and spatial scenes, which are necessary for imagination processes. For this, the collaboration of the agents already described "spark agent" and "info-modifying agent" can be used, with a new agent capable of creating information based on subdividing the available information into pieces and later joining it to form a coherent story. The information generated is stored in memory by the "knowledge agent". The MTL is important for creating hierarchically organized representations and also to map complex multidimensional spaces. In fact, the MTL together with the DMN help to understand the way in which the brain represents complex task environments and the hierarchical control of behavior. For this reason, the MTL and the DMN are responsible for creating the "narrator self" of our brain, providing meaning to the actions previously carried out. For this reason, the mentioned agents must work in an organized way within the group of agents “manipulator group”.

7.3.7. Suggestions based on the relationship between *Working memory* (WM) and *Task induced deactivation* (TID)

A high WMC implies greater storage capacity and a highly detailed definition of a specific cognitive processing method. In contrast, a low WMC implies a procedural lack of definition to feed a certain cognitive process. This lack of information implies that a certain task is not carried out adequately (since sufficient information is not available), but it also implies that it is carried out creatively (because the information that it needs is generated internally, and with a different input information, the search tree is traversed by new paths). When the brain detects the absence of information, it generates its own [15].

A person with a low WMC will thus not perform a certain task in a disciplined way, but in a different way. Therefore, if the problem is fully defined, a low WMC would force it to be solved incorrectly or inadequately. However, if the problem is complex and cannot be fully defined, a low WMC would force additional information to be added by the “playful group” (with information indirectly associated semantically with the problem). This manipulation of external information could lead to a creative solution since the cognitive system would look for new ways that were not initially foreseen.

The second suggestion results from the fact that creative people do not just turn off the DMN when they need to be focused on solving a problem. Therefore creative people seem to be unfocused, as they attach importance to irrelevant information because the DMN is not completely deactivated. In this way, for a moment, both networks share their (apparently incompatible) activity and various ideas can be mixed without any apparent relationship. This mix of cognitive activity opens new avenues of exploration that would never have been explored under the control of the ECN.

All this suggests that a creative computer system must be able to reconfigure its lines of reasoning (mixing the information generated by the "serious group" with that generated by the "playful group") to feed the process and continue down new paths.

As will be seen later, the information generated internally by “playful group” is of several types: information semantically related to the problem, information semantically related to the problem indirectly, or even random information (manipulating previous experiences of the system).

7.3.8. Suggestions based on the role of the insula (and the SN)

A computer system based on the creative structure of the human brain must have a group of agents (“control group”) that is continuously monitoring the information available to detect relevant salient events. When relevant salient events are detected, it activates the “serious group” (and deactivates the “playful group”), if not, it activates the “playful group” (and deactivated the “serious group”).

When it detects relevant salient information, the "control group" initially always activates the "serious group", which could possibly come up with a novel and valid solution. The "serious group" of agents incorporates an agent (“evaluator agent”) that continuously evaluate whether the possible solution of the "serious group" is truly novel and valid (because it is compared with common and previous solutions, while it also evaluates whether the solution meets the requirements of the problem).

If in the event that the “serious group” is not able to provide a valid and novel solution, the “control group” activates the “playful group”, which has several agents capable of generating novel solutions, and exploring the search tree for unexpected paths. The "playful group" is generating a list of creative ideas, and does not have an evaluating agent, so the list of novel ideas that it generates must be evaluated by the "serious group". Therefore the "serious group" decides if any of the ideas generated is a true solution to the problem and, in that case, remains active until it solves the problem in full.

The "control group" has a double sentinel function. In the first place, it must detect external information (new requirements of the problem) in order to activate the “serious group”. On the other hand, it must monitor the list of creative ideas (most of them crazy) generated by the "playful group" to see if any of them is a candidate to be evaluated by the "serious group", as they seem to be valid. For this, the "control group" must have a “semantic agent”, capable of differentiating a possible idea generated in several possible semantic environments.

For example, an engineer at a flat glass factory was looking for a new system for making large-area flat glass, as conventional roll-belt manufacturing and cooling systems always produced ripples. One day, he was washing the dishes in his house and noticed the large oil stains floating in the water. For this reason, he decided to make flat glasses, letting them float on various heavy liquids, in order to make them perfectly flat. Therefore, he was able to recognize the solution to the problem, even though the semantic environment was completely different (therefore the left angular gyrus is of enormous importance, as will be seen in the next point).

Therefore the "control group" oversees the activation of one or the other group, and decides if they work independently, or if they collaborate.

7.3.9. Suggestions based on the role of the angular gyrus (left AG and IFG)

Within the algorithm structure of the system, “top-down” semantic control should be applied to the “playful group” of agents. Since the “playful group” of agents could have solved a problem from another field of knowledge that might initially seem to have no relation to the problem to be solved, the results must be evaluated semantically to make parallels and relate them directly to the problem at hand. The importance of the workings of the "playful group" is the unforeseen path that it travels until it reaches a solution, and therefore is independent of the specific information of a certain field of knowledge. The playful group can modify the information and create semantic parallels. Therefore, the "control group" must detect a possible solution and "wake up" the "serious group", which will perform a top-down control over imaginative processes derived from the playful group. Therefore, the "control group" must have a semantic detector ("semantic agent") that is capable of detecting a solution, although semantically masked.

An example will illustrate the concept. A manufacturer of shot for shotgun cartridges was struggling to come up with a cheap method of making shot, but he could not figure out how. One night he dreamed of an owl crying on top of a lighthouse. In the dream he could see the owl’s tears as they fell and became little regular spheres. The following day the inventor semantically “interpreted” the problem –that had already been solved– and adapted it to his field of knowledge. He decided to drop molten lead into liquid mercury, and that was the solution.

The “playful group” of agents can change the data in its cognitive process and can even solve the problem in a different information environment. However, it must be interpreted semantically for the specific environment of the problem.

7.3.10. Suggestions based on the dynamic and fuzzy memory system for storing and retrieving information

In the human brain, memory is altered at our convenience, guaranteeing our well-being. For this reason, our brain distorts information, so each time we use it is different. The fact that our brain stores modified and different information from the real thing, forces our cognitive system to travel slightly different paths and obtain unforeseen results, and this stimulates creativity.

In a computer system, memory is not altered, so it must be altered artificially. In Therefore, in a multi-agent system, although the memory remains unaltered, each time it is used a copy must be made, which must be artificially modified by an agent (the “solver group” in the serious group”, and the “info-modifying agent” in the “playful group”).

If we presuppose any type of variant for the representation of objects using an object-attribute-value list, we must first classify its attributes. Some attributes will be “essential”, others will be “necessary”, others “important”, others “insignificant”, and perhaps others may simply seem “unnecessary”. In this way every time memory is used, the “info-modifying agent” (or “the solver group”) modifies it starting with the "unnecessary" attributes, then it can sequentially modify even the "insignificant" and "important" attributes, but it should not alter “necessary” or "essential" attributes of the objects. In addition, many attributes must be associated with procedures to manipulate the values that the algorithms can assign to them. In other words, the objects can modify by themselves the values of some of their attributes, regardless of the actions of the agents.

7.3.11. Suggestions based on the importance of the episodic memory

The importance of episodic memory in creativity lies in the fact that increasing the number and variety of personal experiences, allows for a greater variety of paths to follow when solving a certain problem. These alternative paths are not facilitated due to the accumulated experience in a certain specific discipline, but due to the “abstract experience” acquired, as a consequence of having solved all kinds of problems in general.

In a multi-agent system, the information that the “serious group” provides to the “playful group” must be mixed with other types of information directly or indirectly related to the problem to be solved, stored in the database (and modified as seen in the previous section).

Conventional learning systems are not useful because initially they learn until they reach an optimal way of solving a problem, so they will always tend to solve it in a similar way.

Instead, a creative system must generate "creative ways to solve any problem". Therefore, it is essential to achieve them between the different previous experiences, in such a way that what is learned through an experience in a certain discipline can be useful to solve a different problem in a different discipline. In this way, the more experiences that have been had, different paths in the decision-making tree are facilitated. Therefore, a solution can be obtained by following an initially unsuspected path.

For example, the experience gained when cooking could be used to make a painting in a completely different way, or it could serve to better protect the wood against fire.

To achieve this objective, the design of a multi-agent system must consider two aspects. On the one hand, both the “serious group” and the “playful group” must have an abstract learning system that learns, but in an abstract and transversal way, taking into account the common attributes of the information that is being manipulated. This abstract learning system must continuously interact with an agent in charge of continuously establishing semantic parallels, providing different meanings to the manipulated information so that it can be used for different disciplines (“semantic agent”).

On the other hand, the knowledge representation system must allow for its manipulation at different levels of abstraction.

In this way, the multi-agent system can, and should, change its strategy from time to time. Therefore the "playful group" must work in a different way each time it tries to solve the same problem. Depending on the abstract learning made with its previous experience, the system must change the set of available rules to solve the same problem. Thus, when applying a series of different rules, although the initial information is the same, the result is different. The activation of a specific rule is therefore not only a question of the stage of development of the problem (the state of the information at a certain moment) but is also caused by forcing completely different search paths to be explored. One way to do this would be to rely on a Case-Based Reasoning (CBR) system to store case experiences and retrieve them for new similar problems.

7.3.12. Suggestions based on the importance of the semantic memory

Semantic memory stores the meanings of information, not related to concrete experiences. Semantic memory, along with episodic memory, is part of declarative memory, both fundamental to the creative process.

In the semantic process, the ATL is of special importance, which is a cross-modal center of representation capable of integrating different sources of specific information. Conceptual information is created through a combination of transmodal and modality-specific representations (that is, between information with different levels of abstraction). The ATL creates relationships between the different concepts and the different attributes that can be related to them. They also create cross-modal representations to create semantic generalizations based on conceptual analogies, rather than superficial analogies. Therefore perhaps the ATL is the heart of analogical creativity of a high semantic level. To implement the ATL function, the “manipulator group”, which contains the “info-modifying agent” and the “info+ agent”, capable of transforming and expanding the attributes of any concept, can be perfectly suitable.

7.3.13. Suggestions based on the importance of emotional information

The basic suggestion for implementing an AI system is that emotions must be emulated. The multi-agent system must have meta-rules to learn about prejudices, that is, satisfaction patterns relative to a certain number of responses. In this way, the system will promote the use of certain rules over others and will fill in more information in some objects than in others.

7.3.14. Suggestions based on the increased efficiency of neural networks due to motivation

Motivation generates an amplification of the general activity of the cortical networks. Undoubtedly it is an evolutionary mechanism that allows, in case of punctual need, to provide more nutrients to the brain, to amplify its general cortical activity. However, a machine always has the same motivation, so this factor is not very useful.

7.3.15. Suggestions based on the less general filtering of information. D2 dopamine receptors in thalamus

Based on the analysis of this factor, two main suggestions emerge.

On the one hand, the information available in the multi-agent system must be as exhaustive as possible, without being pre-filtered, including information that can be classified as trivial or insignificant. Furthermore, if an object-attribute-value representation of information is accepted, the system must gradually expand the number of attributes, as well as the range of its possible values. For this reason, in the "serious group" there must be an agent in charge of continuously enriching the information available in the database ("info+ agent").

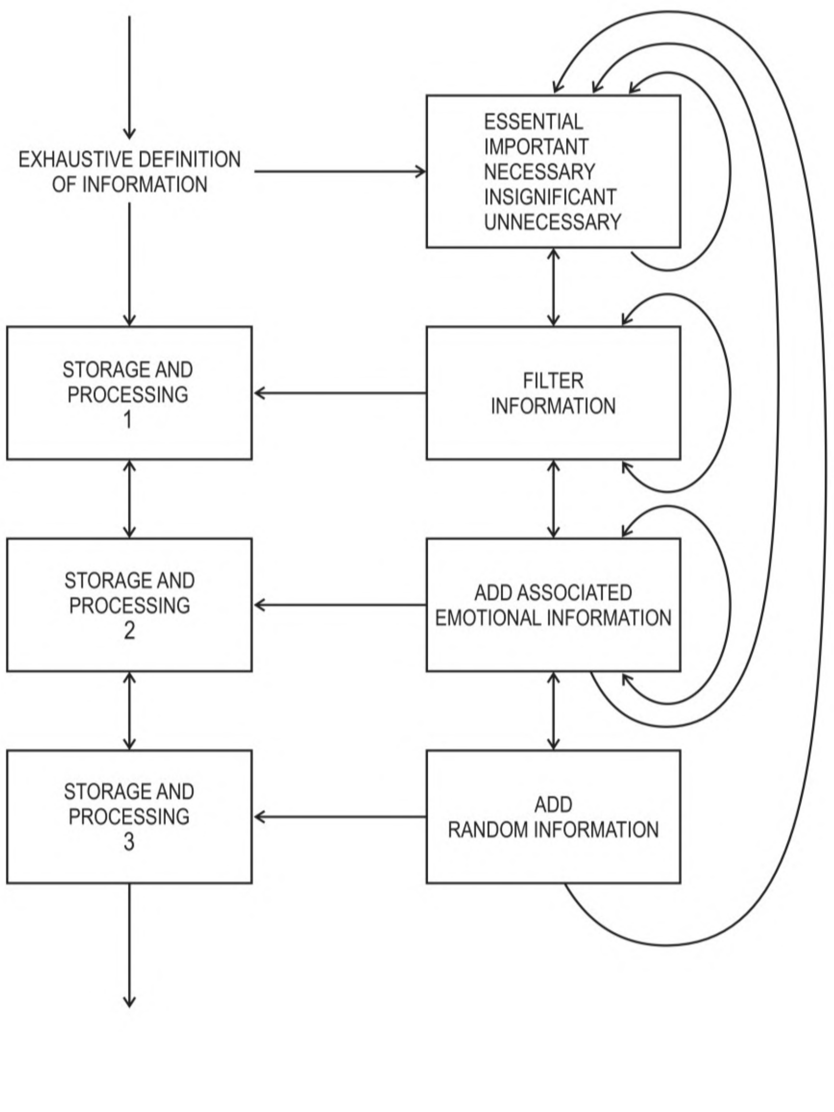

Figure 7.4. Information manipulation by a creative agent-based computational system

This is not incompatible with what is presented in section 6, since one thing is the general structure of the representation of the information, and another is the subsequent filtering that is applied to it. The information should not be filtered before the creative cognitive process, but during it. In the first place the information must be exhaustive, and in the second it must be filtered, and then it can be manipulated, or it can be mixed with semantically related information to the problem, or with random information (Fig. 7.4).

On the other hand, the information available must be divided into pieces, without establishing predetermined relationships between them, but rather suggestions. This facilitates the creation of a huge variety of possible groupings between chunks. Obviously when these groupings are evaluated many will be absurd, but others may pass the evaluation and suppose an unexpected new path towards a possible solution. Therefore, in the "playful group" there must be an agent ("chunking agent") capable of breaking the information into pieces and grouping it in different ways.

7.3.16. Suggestions based on the relationship between creativity and cooperation, overlapping and reconfiguration of neural networks

The basic suggestion for a computer system of this nature is that each agent of the multi-agent system can act differently, depending on the group to which it belongs. In other words, each agent can, and should, assume various roles. In the same way, each agent should be able to suggest that other agents join or leave the process at a certain time, emulating the overlapping and coupling of different networks. A "manager agent" will finally decide whether an agent leaves or continues.

In regard to the representation of knowledge, it must be structured in a way that allows for easy transfer of domains. For example, one day a teacher forgets to bring a ruler to draw straight lines on the board. To solve the problem, take a chair with straight legs, place it against the board and draw a straight line by pressing the chalk against the leg.

For this to be possible, the chair would have to be represented with an attribute such as the "weight" of the chair (if the weight is "heavy", the teacher would not use it). Additionally, within the "legs" attributes, another "shape" attribute would have to be created. If it were not "straight", the teacher would not choose to use the chair either. A ruler should also have the same "shape" and "weight" attributes. Thus, when searching for an object with a certain shape and weight, you could choose either one.

7.3.17. Suggestions based on the hierarchical structure of the brain. Functionally complementary top-down and bottom-up functioning of neural networks

The groups of agents in the computer system must be able to make both top-down and bottom-up decisions, depending on the creative activity that is being carried out at a given moment. The search strategy can move towards the solution, but when a dead end is detected it must go back to previous stages, restructure the information, and continue looking for a creative solution.

7.4. Conceptual design of a computational multi-agent system capable to emulate human creative activity

By integrating all the suggestions made in the previous sections, the basic structure of a computer system that emulates the creativity of the human brain can be defined.

This structure will be defined by means of an advanced agent-based information processing system, which makes use of a special information representation system. For the modeling of this system valuable precedents based on whiteboard systems and on the dynamic representation of information using an object-attribute-value scheme have been considered [16].

7.4.1. Multi-agent creative computational system, MACS

7.4.1.1. Architecture of a multi-agent creative computational system

The system is based on a multi-agent system (MAS) made up of three groups of agents: the “serious group”, the “playful group” and the “control group”, which correspond to the ECN, DMN and SN, respectively (Fig. 7.5).

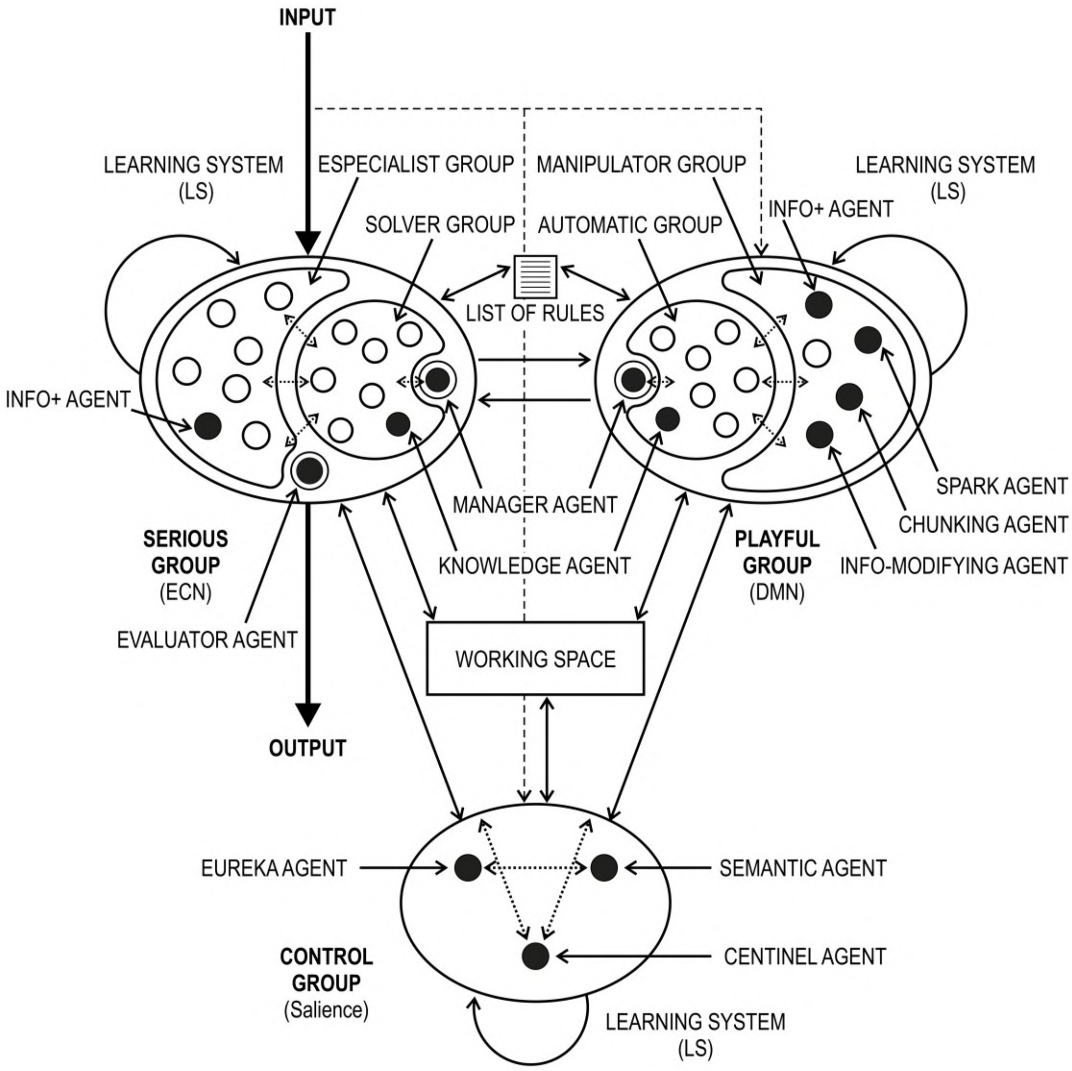

Figure 7.5. Structure of the creative agent-based computational system

Serious group

The "serious group" receives information about the problem to be solved and produces solutions to it. It is made up of two subgroups of agents (“solver group” and “expert group”), an “evaluator agent” and a “learning system”. The "solver group" is the central part of the expert system and contains experts in solving "abstract tasks". These experts, to solve a "specific task" need the help of an agent from the "expert group".

An “abstract task” (also called a “meta-task”) is understood as an essential and generic task that can be applied to an enormous variety of “specific tasks”, from several different fields of knowledge. Instead, a “specific task” is a well-defined task in a particular field of knowledge. Therefore, a "specific task" is an "abstract task" applied to a specific field of knowledge.

For example, suppose the “abstract task”: “synchronizing data”. This task consists of synchronizing any set of actions or data. If the agent in charge of this “abstract task” requests the help of an agent specialized in walking, both can synchronize the steps when walking. On the other hand, if this agent requests the help of a vision specialist agent, she will be able to synchronize the vision of two eyes (or several eyes). If this agent requests the help of agents in charge of receiving information from the senses, it will synchronize all the senses. Therefore, an agent that performs the abstract task of “synchronizing data” could synchronize how a person walks, the formation of spatial vision, the integration of data from the senses, the formation of spatial hearing, etc.

To be able to do it, each agent has a generic essential nucleus (to carry out abstract tasks), and a set of additional complements (to carry out specific tasks that have a certain abstract task in common). In other words, each agent has two complementary roles, one that serves to manipulate “abstract tasks” and another to manipulate “concrete tasks”.

The "evaluator agent" continually evaluates the solutions generated by the system and decides if they meet the requirements of the problem (that is, if they are valid solutions or not), and in the case of not complying, indicates their level of non-compliance.

The "control group" has a special learning system (learning has always been a great challenge in multi-agent systems). Every time the "control group" solves a problem (or tries to solve it) a concatenation of rules is generated. The sequence of each rule concatenation is sorted, ordered, and stored in a list. This list gives a higher or lower priority to each of the agents of the “serious group, and in this way the system learns in a way that mirrors nature rewarding the most successful concatenation of rules.

Playful group

The “playful group” is also made up of two subgroups of agents. The "automatic group" is formed by certain agents of the "solver group" who assume two new roles. One role consists in solving the problem by means of the most successful concatenations of rules from the list generated by the “serious group”, but manipulating information generated internally, without adding information about outgoing events. The other role consists of acting with a different priority than the one in the “serious group”, changing it at random.

The information generated internally comes from the "manipulator group", which manipulates and transforms the information contained in the memory of the system with various levels of intensity, depending on the level of creativity desired. The “spark agent” generates information randomly, with various levels of randomness. This agent can work with various levels of intensity, being able to generate information that is directly related to the problem to be solved, indirectly related, or random. The "modifier group" manipulates the information based on different strategies (filtering information, mixing information, changing attributes, etc.). The “chunking agent” breaks the information into pieces and joins them in different ways. The “semantic agent” is in charge of manipulating the information based on semantic associations. This agent is the only one that has access to external information, and always manipulates it semantically, in order to mix it with what is currently being used.

Both the "serious group" and the "playful group" have a "manager agent" in charge of activating the most suitable agents for each specific problem, and a "knowledge agent" in charge of expanding and modifying the information available in memory, based on accumulated experience in solving problems. The "knowledge agent" can expand and modify the attributes of each object, as well as the range of values it can have.

Control group

The "control group" oversees handing over control to the "serious group" or the "playful group" according to the existence of external events, or difficulties in solving a certain problem. The “control group” has several agents. The “sentinel agent” oversees monitoring the existence of new external information. The "semantic agent" oversees detecting semantic parallels with the information generated by the "playful group". The "eureka agent" oversees detecting a possible creative idea generated by the "playful group".

7.4.1.2. General functioning of the information processing system

The input information to the system is done through the “serious group”, although the “control group” also detects whether or not there is external information. The final solution is always generated by the "control group", since it is the only one that performs evaluation activities.

In general, when the “serious group” is active, the “playful group” is not active and vice versa. They usually work in an antagonistic manner, similarly to the ECN and DMN.

The “control group” decides which groups should be activated at each moment, depending on their analysis of the input data. If the “control group” detects an external event as “salience” and relevant, it gives control to the “serious group”, which will continue to be active until it finds a solution.

The "serious group" tries to solve the problem, through the "manager agent" that decides which agents of the "solver group" should be activated. These agents activate the necessary agents of the "expert group” and try to solve the problem. Each agent has a priority table, made by the “learning system”, which gives it its priority of execution, based on the success of previous experiences. The results of the agents are continuously evaluated by the “evaluator agent”, which decides whether or not the problem is solved. The "serious group" will remain active until a solution is found.

The "control group" continuously monitors both the "serious group" and the "playful group". If no solution is found, or if it is not satisfactory, the “control group” activates the “playful group” and deactivates the “serious group”.

The "playful group" has a greater information processing capacity than the "serious group". Initially, the "manager agent" decides which agents of the “solver group” should change their role to be part of the "automatic group" subgroup. Furthermore, this agent receives the list of successful rule sequences from the “serious group”. The "playful group" activates the "manipulator group", it can work in three modes. One mode is done using existing information, including a minimal amount of outside information. Another way is done by manipulating existing information, and without including outside information. Another way is done by changing the priority of each agent, and the sequence of successful rules. The first mode is reserved for performing tasks automatically, and very quickly (after having achieved a high level of expertise) and is also used to reinforce the learning process of the “serious group”. The other two modes generate creative solutions based on the information generated by the “manipulator group”.

The “manipulator group” is activated and its agents immediately begin to modify the available information. One agent fills the attributes of the objects with semantically related information, or with random information (“info-modifying agent”), another divides the information into pieces and rejoins them according to new semantic rules (“chunking agent”), another generates random information (“spark agent”). Therefore, it can be said that the "playful group" continually “plays” with the information, but without knowing the value and usefulness of the results. For this reason, the "control group” continuously monitors the results generated by the "playful agent" and determines if any is a candidate to be evaluated, in order to determine if it is a solution to the problem. The “semantic agent” continuously detects semantic parallels in the information generated. To detect semantic parallels, it simply detects analogies and patterns in the information structure, eliminating specific attributes and values of the different objects. Finally, the "eureka agent" detects if any of the semantic parallels is a candidate to be evaluated. If so, the "control group" deactivates the "playful group" and activates the "serious group" that evaluates each possible solution. When the “serious group” detects a valid solution, it continues with the resolution of the problem until reaching a fully defined final solution.

7.4.2. Structure of information representation in MACS

The representation of information is essential when designing a computer system that emulates the creative activity of the human brain. The most appropriate representation are the “object-attribute-value” structures for a given object, idea or thought (Fig. 7.6).

First of all, the information on each object must be as exhaustive as possible, having as many attributes as possible, with the widest possible range of values. Furthermore, both the attributes and their possible values must have a priority level, which can be modified by the "playful group" throughout the process of solving a certain problem. In addition, each object must have the greatest possible number of specifications in relation to other objects, and it must have perfectly defined restrictions. Finally, they must be perfectly delimited, but with the greatest possible number of deviations, the range of values that the attributes can have. The greater the number of attributes and values, the more creative the system can be.

```
object: chair
    is a:            furniture
    utility:                 (school (x), dining room (x), office (x), living room (x), beach (x))
    mobility:                (fixed (x), mobile (x), articulable (x), folding (x), recessed (x))
    weight:                  (very light (x), light (x), medium (x), heavy (x), very heavy (x))
    volumen:                 (very small (x), small (x), medium (x), large (x), very large (x))
    resistance:              (very low (x), low (x), medium (x), high (x), very high (x))
    reconfiguration level: (very low (x), low (x), medium (x), high (x), very high (x))
    requirements soil (ne), illumination (x), humidity (x), local size (x), environment color (x), etc.)
    relationship with other objects          furniture (in)
                                             lamps (in)
                                             doors (in)
                                             windows (in)
                                             ground (ne)
                                             walls (im)
                                             ceiling (un)
    components
        legs (im)
            without legs (in)
                hanging from the ceiling (in)
                side braces (in)
                wall anchor (in)
                furniture anchoring (in)
            with legs (im)
                relation to (im)     seat (ne)        (none (x), direct (x), indirect (x))
                                     soil (im)        (none (x), direct (x), indirect (x))
                                     arms (un)        (none (x), direct (x), indirect (x))
                type (ne)            (fixed (x), extendable (x), articulating (x), folding (x))
                number (es)          (none (x), number (x))
                shape (in)           (straight (x), curved (x), polyline (x), polycurve (x))
                length (im)          (very short (x), short (x), medium (x), long (x), very long (x))
                thickness (un)       (very thin (x), thin (x), medium (x), thick (x), very thick (x))
                texture (un)         (smooth (x), rough (x), silky (x), etc.)
                material (in)        (wood (x), iron (x), steel (x), plastic (x), etc.)
                color (in)           (white (x), black (x), red (x), blue (x), etc.)
                protection (im)      (varnish (x), chrome (x), painted (x), etc.)

        seat (es)
            without seat (in)
            with seat (im)
                relation to (im)     legs   (none (x), direct (x), indirect (x))
                                     soil   (none (x), direct (x), indirect (x))
                                     arms   (none (x), direct (x), indirect (x))
                endorsement (in)     (none (x), direct (x), indirect (x))
                folding type (un)    (fixed (x), extendable (x), articulating (x))
                shape (un)           (straight (x), curved (x), polyline (x), polycurve (x))
                length (es)          (very short (x), short (x), medium (x), long (x), very long (x))
                thickness (in)       (very thin (x), thin (x), medium (x), thick (x), very thick (x))
                texture (ne)         (smooth (x), rough (x), silky (x), etc.)
                material (im)        (wood (x), iron (x), steel (x), plastic (x), etc.)
                color (in)           (white (x), black (x), red (x), blue (x), etc.)
                protection (in)      (varnish (x), chrome (x), painted (x), etc.)

        back (IM)
            without backrest (IN)
            with backrest (IN)
                relation to          seat     (none (x), direct (x), indirect (x))
                                     soil     (none (x), direct (x), indirect (x))
                                     arms     (none (x), direct (x), indirect (x))
                                     legs     (none (x), direct (x), indirect (x))
                type (ne)            (fixed (x), extendable (x), articulating (x), folding (x))
                shape (in)           (straight (x), curved (x), polyline (x), polycurve (x))
                length (im)          (very short (x), short (x), medium (x), long (x), very long (x))
                thickness (un)       (very thin (x), thin (x), medium (x), thick (x), very thick (x))
                texture (un)         (smooth (x), rough (x), silky (x), etc.)
                material (in)        (wood (x), iron (x), steel (x), plastic (x), etc.)
                color (in)           (white (x), black (x), red (x), blue (x), etc.)
                protection (im)      (varnish (x), chrome (x), painted (x), etc.)

        arms  (in)
            without arms (in)
            with arms (in)
                relation to (im)     seat     (none (x), direct (x), indirect (x))
                                     soil     (none (x), direct (x), indirect (x))
                endorsement (im)     (none (x), direct (x), indirect (x))
                legs (in)            (none (x), direct (x), indirect (x))
                type (un)            (fixed (x), extendable (x), articulating (x), folding (x))
                number (es)          (one (x), two (x))
                shape (un)           (straight (x), curved (x), polyline (x), polycurve (x))
                length (es)          (very short (x), short (x), medium (x), long (x), very long (x))
                thickness (in)       (very thin (x), thin (x), medium (x), thick (x), very thick (x))
                texture (ne)         (smooth (x), rough (x), silky (x), etc.)
                material (im)        (wood (x), iron (x), steel (x), plastic (x), etc.)
                color (in)           (white (x), black (x), red (x), blue (x), etc.)
                protection (in)      (varnish (x), chrome (x), painted (x), etc.)
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Figure 7.6. Information representation to allow high-level semantic manipulation

Let us go back to the example provided earlier. A teacher finds that he does not have a ruler to draw a straight line on the board. He will look at all the candidate objects in the classroom that have the appropriate "weight" (very light, light, medium), "length" (average), and "shape" (straight). In the classroom there are certainly many possible candidates, such as a drawer, a notebook, a tight cable, a computer keyboard and also a chair. The chair may have straight legs. The teacher may decide to use the chair to draw on the board. The students might think that their teacher is crazy, or also that he is creative, or even a genius. The key is how knowledge of classroom objects, and specifically of the chair, has been represented. If the teacher uses it to draw a straight line on the board, the chair must have the attribute "weight" (with values including very light, light, and medium), the attribute "legs" with the attribute "shape" (with a range of values that includes the straight form), and the attribute "length" (with a range of values that includes an average length).

No matter how much diligence is applied during the design of the object-attribute-value structure to represent objects, concepts and thoughts, there will always be a lack of attributes, relationships, restrictions, and possible values. For this reason, the computer system must incorporate a "knowledge agent" that is in charge of filling in and enriching its own representations of the information based on its learning system, and on the information that is provided at all times. In this way, the system will be increasingly creative.

Moreover, the agents that manipulate this knowledge cannot filter it at any time, although they can vary or increase its attributes. In this way, the information on the available external world is increasingly complex, expanding the range of alternatives, and therefore the creative component of the system.

Finally, the attributes must be organized, grouped, and classified according to their importance. In this way, dynamic and fuzzy manipulation of the information can be allowed, grouping the attributes in different ways or changing their importance at any time. This mechanism would allow the storage of information to be encrypted and its retrieval to be dynamic and fuzzy. Therefore, the information, although apparently the same, would be reconstructed in a different way in each specific case and the fuzzy and dynamic mechanisms of human memory would be emulated.

7.5. System implementation and future work

Analyzing the different neurocognitive bases of human creativity, the conceptual structure of a creative computational system has been created. Obviously, the implementation of a computational system of this type is a daunting task, and would require the work of several years by a large team. In addition, the conceptual structure proposed here should be previously refined.

From a practical point of view, and as a previous step to the implementation of this system, experience has been gained designing and using a much simpler multi-agent creative system, capable of emulating the efficiency to stimulate creativity of the Brainstorming techniques [17], using the INGENIAS agent methodology. Subsequently, a much more complex system has been designed, drawing inspiration from the joint operational conceptual structure of the main methods that stimulate human creativity [18].

At present, the implementation of the system described in this paper has already begun, and the most pressing obstacles are already beginning to be resolved [19]. The first obstacle is the enormous complexity of the system, since many agents must be implemented, who must also change roles continuously. For this reason, known multi-agent development platform systems are not useful and a new one must be implemented. The second great difficulty is to incorporate a learning system into the multi-agent system. The third difficulty is the dynamic representation of the information, and the need to represent the different objects in several different ways (as seen in suggestions of the previous section). Finally, the fourth and greatest difficulty consists in the complex and enormous design of the agents. The proposed system is general-purpose, and must be able to creatively solve any type of problem, just like the human brain does. However, implementing a system of this caliber would entail an enormous time period (it is estimated that the described system could be ready in no less than ten years), so it has been simplified to solve architectural design problems, specifically for designing Roman basilicas. Once implemented, this system can evolve by reprogramming it so that it is capable of designing various additional types of buildings. Finally it could evolve to face the creative design of any type of building. In this way, incrementally restructuring the system at each step, it could creatively solve any kind of problem.

Such a creative computational system is of great value for the general study of creativity. Firstly, it is given that the system must have a high creative level, since its design is based on the main factors of the creative neural structure of the human brain.

Furthermore, the structure of this system is more complete and powerful than a system based on the main techniques to stimulate creativity [20]. This system must be able to create novel and valuable solutions, since on the one hand it can compare all the solutions that it is generating with all previously existing solutions and calculate the level of novelty of the proposed solutions, and on the other hand it can also calculate the degree of compliance with the client's requirements. However, it is possible that many of these solutions, despite being novel and valuable, are not to the liking of the user of the system. Consequently, it must be able to differentiate between "computational creativity", that has a broader character, and "human creativity". The fact that the user rejects a clearly novel and valuable solution means that human creativity is constrained, in a forced way, by prejudices based on the inter-subjective information shared by a certain social group. It is well known that what may seem very creative to one social group may seem of little value to a different group. Therefore, computational creativity could serve as a general frame of reference situated at a higher level than human creativity, being free from prejudices and inter-subjective social norms.

A system like the one described in this paper could learn to generate very creative solutions in a general way (computational) and also different creative solutions that may be acceptable by different social groups (human).

The difference between computational creativity and human creativity also highlights a key issue that has been avoided in the design of this system, which is the determination of the level of creativity of the solutions generated. This matter is very questionable because it is already difficult to determine it for human creations (which painting is more creative, Picasso's “Guernica” or Van Gogh's “Starry night”?). It would be possible to define some metrics for it, but they would be artificial. Some researchers seem obsessed with measuring creativity, although for others this seems nonsense [21]. If in real life no one has dared to measure creativity, why do some researchers insist on measuring creativity when implementing a computer system? In addition, it should be taken into account that if a computer system had implemented a creativity measurement system, it would try to obtain a high score in its operation, and would be forced to follow certain paths of the search tree, avoiding other paths. In other words, trying to measure creativity would be taking us away from it. However, it is possible to determine whether the generated solutions satisfy the requirements that define the problem. In the end the human watching the results will determine which solutions they like more.

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DISCUSSION

8. Discussion

In this Doctoral Thesis, the neurocognitive structure that supports human creativity has been identified based on the joint analysis of more than 800 bibliographical references that show the most important investigations carried out to date.

The research that has been carried out on the subject is very atomized, very specialized and focuses on very specific aspects of creativity, and in many cases have little relationship with each other. For this reason, and in order to have a joint and holistic idea of the neurocognitive processes of human creativity, it is necessary to study all these investigations in an interconnected way, which is an enormous task. This holistic idea would allow redirecting specific investigations in order to be more effective.

For this reason, in this doctoral thesis, the first thing that has been done has been to classify, group, analyze, intertwine and structure, in an orderly way, the most important investigations that have been carried out to date.

However, the work carried out goes much further, since by structuring and intertwining the existing investigations, it has been possible to identify certain patterns, correlations and parallelisms, and make certain deductions, which as a whole, have allowed the identification of the fundamental neurocognitive bases of human creativity. And grouping, interconnecting and structuring all of them, it has been possible to model a neurocognitive paradigm of human creativity and a computational paradigm of creativity.

Finally, the structure of a creative computational system has been established, based on a multi-agent system, based on the neurocognitive structure of human creativity.

The process followed has been structured in several stages.

In the first stage, we have reflected on the concept of creativity, showing some of the most representative definitions that have been made throughout history, collected in different bibliographical references. Based on these definitions, it can be seen that creativity is a very ambiguous and nuanced concept, although in essence it is a complex process of generation and evaluation ideas.

All the definitions compiled are different from each other, and include only some aspects of the creative process. However, among all of them, two stand out that are especially illustrative. One states that the most important component of creativity is the discovery of new relationships among different concepts, in order to transform established norms, whenever a certain problem is solved. Another is much more complete, since it proposes that creativity is a process by which the human being can voluntarily alter the functioning of his cognitive system, and therefore change the habitual way of perceiving and interacting with the environment, and the habitual way to establish concepts and processes.

Therefore, the most correct and complete definition of the creative process would be the one that includes all the definitions collected, as well as those to be collected in the future.

It is necessary to approach the definition and analysis of creativity in a different way. The most appropriate thing would be to identify an adequate taxonomic framework that contains the greatest number of nuances in the definition of the concept of creativity, and that at the same time allows it to be analyzed rigorously and in detail. For this reason, and as a result of analyzing all the taxonomies proposed to date, the most complete and appropriate has been chosen: the *4-P taxonomy* (*Person, Process, Product, Press*), devised in the 1960s, and recovered today by artificial intelligence researchers.

Person. What makes the person (agent) a creative one.

Process. The actions taken by the agent to generate creative results.

Product. The creative result (object, entity or process).

Press. The cultural environment that evaluates the result.

This taxonomy provides the most adequate and complete framework to define and analyze human creativity, and provides the most adequate reference to redirect the research on the neurocognitive bases of creativity.

Within this taxonomy, the main criteria for evaluating creativity are *novelty*, *value* and *surprise*, although there are also other secondary and complementary criteria such as *effectiveness*, *elegance*, *generalization*, *imagination*, *appreciation*, etc.

However, no matter how well the criteria are chosen, the evaluation process will always be a problem, since if their number is reduced, some non-creative ideas could be classified as such. On the other hand, if the number of evaluation criteria is expanded, some creative ideas could be discarded. Furthermore, depending on how the evaluation criteria are chosen, certain ideas may be rewarded to the detriment of others. Finally, ideas can also be more or less creative depending on their conceptual or temporal environment. Let's take an illustrative example: the idea of roasting meat (to protect its interior) is not creative since it is done on a regular basis, whereas the idea of roasting

wood (to protect its interior) could be considered very creative. Another complementary example would be Van Gogh's paintings, which were not valued at the time, but years later are highly valued.
Based on the analysis of the behavior of creative people, and based on the analysis of the methods to stimulate creativity, different conceptual models have been identified on the structure of the creative process. Taking into account all this accumulated information, in this Doctoral Thesis a conceptual model of the creative process has been proposed, completing and detailing the previously proposed models. According to this model, the creative process is a complex process of generating and evaluating ideas. This process has a sequential component, and also a transversal (parallel) component, and at all times top-down and bottom-up decisions are made. The creative process takes place at various levels of abstraction in each of its stages, making decisions of all kinds, from those that are more abstract and general, to those that are more concrete and detailed. From the beginning of the creative process, ideas are proposed, so the imagination process is fundamental, and above all it is based on the surprising association of previously known concepts and ideas. The creative process is also very flexible, and in many cases indeterminate, which means that small changes in the input information can generate very different ideas.
These conceptual models of the creative process are what have been framing the different investigations on the neurocognitive structure of creativity. In turn, the different discoveries made are substantially modeling the previously established conceptual models.

2. In the second stage, a compilation and analysis of the most effective methods that stimulate human creativity has been carried out. In the same way, the advantages and disadvantages of each one have been shown, as well as the most suitable environments to use them.
The choice of methods has been made for their differentiating character, and their effectiveness (number of valuable and novel generated ideas), under the *4-P taxonomy*. It should be said that all these methods have been designed following methodological guidelines observing the creative result of the human brain, as if it were a black box, and without knowing its neurocognitive structure.

The fact that, these methods have been created to stimulate human creativity shows that the human brain must have certain neurocognitive limitations, and that its functionality must be redirected on many occasions in order to improve their creative activity.

In general, what the methods implemented to enhance human creativity do is force the search tree for solutions to be traversed by paths different from the usual ones. We usually solve problems more or less in the same way, since we usually use the same procedures. For this reason, the aforementioned methods force us to carry out cognitive processes different from the usual ones, when it is evident that these are sterile. This shows that the creative process is much more flexible and complex than could be derived from analyzing the conceptual models of the creative process proposed to date.

The analysis of these methods provides an overview of the strengths and weaknesses of the human brain in creative problem solving. It also raises questions that have been tried to justify speculatively, but that can only be resolved by investigating the neurocognitive activity of the human brain. The methods to stimulate creativity have been proposed and modified, through trial-and-error. New methods have been proposed, and existing ones have been improved, groping in the dark, making continuous proposals and observing their effectiveness. And this has been a very slow process, and in many cases ineffective. In addition, in the most successful cases it can be verified that certain methods really work, but without knowing why. Only deductions and speculations have been made. This makes it extremely difficult to improve existing methods, or to propose more effective ones. Therefore it is absolutely necessary to know the neurocognitive and functional structure of human creativity.

Until a few years ago this has not been possible but, in recent years, with the help of new technologies, enormous advances have been made.

3. In the third stage of the present doctoral thesis, the latest discoveries made on the structure and functionality of the human brain have been studied in order to identify the *fundamental neurocognitive factors* that enable its high creative capacity.

As a result, the following have been identified:

- Capacity of the human brain to generate neurocognitive processes in series and in parallel. Creative activity requires going through the search tree for solutions in series and in parallel, at different levels of abstraction, in order to arrive at surprising and creative solutions, all of which the human brain has an enormous facility to carry out. We have identified that parallel cognitive processes develop fundamentally through large-scale functional networks, which integrate different cortical regions with varied functionality. Serial cognitive processes are based on gradients of neural activity, from sensorimotor nodes to high-level cognitive associative networks.

- Functional structure of the human brain based on the activation of large-scale networks, which integrate different specialized areas strategically distributed topographically. The operation based on large-scale networks allows the generation of high-level cognitive processes with a certain degree of fuzziness. In this way the same networks are activated to solve apparently different problems, and each time they are activated they do not involve exactly the same specialized areas of the brain. This allows the creation of analogies at a high semantic level, and the generation of general processes at a high level of abstraction, which have a common structure, but with different details for each specific activity. In order to understand the neurocognitive activity of the human brain, this section has specified and analyzed the most important networks and subnetworks identified to date.

- Existence of a *multimodal integration network* (MIN), which integrates the hierarchical flow of information between the different *large-scale networks*, at different levels of abstraction, from sensorimotor regions to multimodal associative networks with a high cognitive level. The generation of creative ideas requires parallelism and cognitive processes to be carried out at different levels of abstraction, and the multimodal structure of the brain allows this in a natural way.

- Existence of a certain topographical structure of the cortex. According to the *Tethering hypothesis*, the human brain has expanded as a result of the need for greater neurocognitive capacity to deal with increasingly complex information, in increasingly complex societies. The expansion was done in such a way that the different sensorimotor regions separated from each other, and the cortical mass grew around each of these regions, creating new concentric cortical areas. As they moved away from these nodes, the different areas could gradually engage in activities with a higher cognitive level since they freed from the restrictions of the sensorimotor systems. In this way, the different large-scale functional networks were integrating different peripheral areas of the different sensorimotor nodes, according to its functionality. Therefore, the information processed by the sensorimotor nodes is gradually processed and transformed as it moves away from them. The information is becoming more and more abstract, and is structured by levels. Therefore, the topographical evolutionary structure of the human brain allows the generation and manipulation of abstract thoughts, which is essential for the generation of creative ideas. It also enables the creation of self-generated thoughts, which are fundamental to the creative process.

- Existence of basic neurocognitive structures to support the fundamental components of creativity: *generation and evaluation of ideas*, *imagination*, and *semantic manipulation*:

- Existence of a basic neurocognitive structure to generate and evaluate ideas, fundamentally based on the interrelation of three main large-scale networks: the *Executive control network* (ECN), the *Default mode network* (DMN), and the *Salience network* (SN). This neurocognitive structure is often referred to as the *Triple network model*. According to this model, the SN is responsible for detecting salient stimuli, in order to facilitate appropriate behavior, switching the most appropriate large-scale networks. When goal-oriented tasks must be performed, the ECN is activated (and DMN deactivated). While, when no task should be performed, or when the task is repetitive, boring, or needs the application of previous experience related to oneself, (and therefore access to memory), the DMN is activated (and ECN deactivated). Sometimes both networks are activated when the DMN requires the ECN to perform cognitive monitoring of its activity.

- The creative process sometimes requires internal information and external sensory information to be manipulated together. One region, the DLPFC is responsible for performing what is called *context regulation hypothesis*, by which a context-dependent prioritization of off-task thoughts is performed. That is, the human brain prioritizes the generation of self-generated thoughts, and only when it is required to perform a task that requires special attention, the generation of self-generated thoughts is inhibited. Sometimes the DLPFC does not work correctly and self-generated thoughts are generated while a certain task is being carried out, and this facilitates the generation of creative ideas.

- The MTL memory network (a DMN component) contributes to associative processes allowing the generation of creative ideas. The DMN, that has a dual role, since it contributes to the generation of creative ideas (due to its low level of information control), and also contributes to the evaluation of ideas (since it is involved in the affective and visceral evaluation process). The ECN contributes to the process of analytical evaluation of creative activity. The DMN is also involved in what is called “inner self evaluation”, that is, in the evaluation of a problem based on the most personal components of human nature. He is also involved in aesthetic catharsis, which is experienced as a special "coupling" when looking at certain artworks that are somehow important to our inner shelf. Perhaps this has to do with the need to achieve order in human activity, achieving creative results with low entropy.

- Existence of a basic neurocognitive structure to imagine things and plan the future. Creativity involves the future creation of something that does not exist. Therefore, in the creative process, although in a blurred and ambiguous way, future plans must be made, in the same way as people project their personal goals. When imaging and planning for the future, two different processes must be carried out:

  - *Process simulation*. It is the process of visualizing the steps that must be taken to obtain a certain goal
  - *Outcome simulation*. It is the process of visualizing the effects that are obtained once a certain goal has been reached

These two processes are constantly performed throughout the creative process. On the one hand, the necessary steps that must be carried out to achieve a certain objective must be visualized, and on the other hand, the desired result must be also visualized (in order to reach a solution), to experience the pleasure of the possible associated rewards (recognition, personal achievement, academic achievements, money, etc.).

- Existence of a basic neurocognitive structure to carry out semantic processes at different levels of abstraction in order to generate concepts, and gradually enrich them. Based on recent studies, we know that semantic memory is generated based on a transmodal hub. Classic neurocognitive paradigms assumed that modality-specific regions interact directly to generate multimodal concepts. However, it has been discovered that the brain has a *cross-modal semantic center* in which semantic functions are carried out. Based on this, conceptual knowledge is created through a combination of transmodal and modality-specific representations. Of course modality-specific information is a basic source for the construction of concepts, but it is insufficient, since the different “attributes” (characteristics of objects) are combined in complex and non-linear ways when forming a concept. In this context, the cross-modal center can provide two important "semantic functions”:

  - It allows for correct mappings between the modality-specific "attributes" and a certain relevant concept.

- It allows for cross-modal representations that provide the basis for making semantic generalizations taking into account conceptual similarities, rather than superficial similarities (which constitute the central function of semantics).

4. In the fourth stage, the *Default mode network* (DMN) is analyzed in detail, since it has a main role in human creative capacity and is involved in several of its neurocognitive processes.

The DMN is involved in several neurocognitive activities that support human creativity, and among them the following stand out:

- The DMN is directly involved both in the generation of ideas (through its management of self-generated thoughts), and in the affective and visceroceptive evaluation of ideas (through its ability to manage memory, in memory-related tasks). autobiographical, episodic, and semantic, mind wandering, perspective taking, or future thinking).
- The DMN is at the end of the *main gradient*, so it handles abstract information, shared by the different tasks in which it may be involved, which only differ from each other in specific details. This allows it to also engage in high-level cognitive processes, which are apparently unrelated to each other, but share a common abstract structure. This also allows it to get involved in autobiographical cognitive processes and those related to the imagination of fictitious situations and scenarios. As a result, this fact gives the DMN a leading role in creative processes.
- DMN nodes are topographically located at the maximum possible distance from unimodal sensorimotor regions. This allows the DMN to manipulate information at the highest level of abstraction possible, with little or no relation to sensorimotor information. Likewise, it allows you to perform functions of a high cognitive level, away from the “here and now”. Among these functions, its ability to create self-generated thoughts stands out, which is the natural activity the brain prioritizes (in the absence of external tasks), and which are the basis for the generation of ideas in creative processes. On the other hand, the strategic topographical location of the DMN allows it to be involved in a wide variety of tasks that apparently have little in common.
- The DMN integrates subcortical components that allow it to develop a complex activity. It has recently been discovered that DMN integrates the basal forebrain and

the anterior and middorsal thalamus, and this implies certain additional functional characteristics:

- Allows it to be involved in memory processes, since both the anterior and mediodorsal thalamus, as well as the basal forebrain, constitute connection points of the limbic system.
- The basal forebrain produces acetylcholine, which has an important neuropharmacological effect on memory processes.
- DMN is associated with the mesolimbic dopaminergic pathway through its connection with the ventromedial prefrontal cortex (VMPFC) and the midbrain (MidB), which allows you to engage in emotional modulation.
- The basal forebrain and thalamus can act as a relay at the subcortical level, integrating primary functional networks and brainstem inputs with high-level associative networks. This explains why the activity of the DMN "seems to arise from within us", since it is related to the most intimate self-referential activity of our self (specifically the MPFC).

- The DMN has a complex functionality and a high cognitive level. It was commonly known that the DMN deactivated during tasks, and also that its activity increased when it was not performing tasks. This generated an initial idea that emphasized task-negative functions of the DMN. However, recent studies show that DMN increases its activity by performing tasks in which cognition and behavior must utilize the memory of related previous experiences. In fact, it has been proven that the DMN increases its activity (under conditions in which it should remain deactivated) on at least the following occasions:

- When the decisions to be made depend on the information that has been generated in a previous trial.
- When task-relevant stimuli should make use of long-term memory.
- When the context of a certain task is retrieved from memory.
- When a certain action rule has already been coded that can be used in subsequent actions.
- When performing very demanding semantic memory or working memory tasks.

All these circumstances occur continuously, and in an intertwined way, throughout the creative process.

- The DMN collaborates closely with the ECN, and together they have differential contributions during the different stages of the design process. The DMN is activated more strongly during the idea generation stage, and instead the regions of the ECN are activated more strongly during the idea evaluation stage. DMN is involved with a wide range of imaginative processes, such as mind wandering, mental simulation, and episodic future thinking, which have great relevance for creative thinking. Consequently, the functional connectivity (related to divergent thinking) between the inferior prefrontal cortex (IPFC) (region of ECN) and the DMN may reflect a top-down control of bottom-up processes. In other words, the cognitive control mechanisms of the IPFC may be responsible for directing and monitoring the spontaneous activity of the DMN. Creative activity could use this process of controlled attention to prevent outstanding and unoriginal ideas from getting in the way of the creative process. Therefore, the ECN, and specifically the IPFC, appears to perform certain necessary functions of supervising the generation of ideas. Therefore, the existence of greater connectivity between the right IFG and the inferior parietal cortex in highly creative people could reflect their ability to exert top-down control over the imaginative process that arises from the DMN. In summary, and based on the set of studies shown, the increase in functional connectivity between the IPFC (region of ECN) and the DMN may correspond to a greater capacity of creative individuals to control their imagination, executing complex search processes, inhibiting irrelevant information to the task and selecting ideas from a large set of alternatives.

- The DMN has patterns of meta-functionality. DMN participates in generic and higher-order activity patterns capable of supporting different and heterogeneous activities. Among these meta-functionalities observed in the investigations, the following stand out:

  - *Delayed matching*, according to which the functionality of the DMN can vary according to the way in which cognitive processes emerge within the temporal structure of the current task.
  - *Contextual modulation*, according to which the DMN can vary its pattern of neuronal activity based on previous experience.
  - *Rule-based decision making*, according to which the DMN increases its activity when internal rules are used to perform tasks

These meta-functionalities are essential in the creative process, since they make it easier for the search tree to go through unforeseen paths in the first instance.

- The DMN collaborates in the elaboration of detailed cognitive representations in the performance of tasks. The DMN integrates information from regions lower in the cortical hierarchy to form a representation of the ongoing neurocognitive context. As stated, the cerebral cortex is structured in a specific spectrum of regions ranging from unimodal to transmodal. In this spectrum, as we move away from unimodal cortex, neural activity encodes detailed thought patterns during periods of working memory maintenance. This suggests that the DMN is involved in the elaboration of detailed cognitive representations through interactions with lower regions of the cortical hierarchy. In addition, the DMN plays a critical role in detailed experiences in working memory processes during memory retrieval, and is involved in the level of information specificity, or the level of information detail. All of these characteristics are fundamental to the creative process.

- Finally, it has been discovered that DMN collaborates with other regions of the brain, enabling several basic cognitive structures for creativity. These cognitive structures include:

  - The *theory of blind variation and selective retention* (BVSR), which indicates that the DMN could generate an uncontrolled process of *blind variation* based on random conceptual combinations, and the ECN could carry out a controlled process of *selective retention*, which implies the assessment of blind variation activity.

  - The *deactivation failure hypothesis*, which suggests that the high creative ability may be based on "deactivation error" of regions of the DMN during tasks that require external focused attention. Highly creative people have been shown to be unable to suppress activity in the precuneus (DMN region) when performing working memory tasks (in which the ECN is involved). This suggests that the creative capacity, as previously stated, benefits from the coactivation of regions of the ECN and the DMN.

  - The *flexible control hypothesis*, which suggests the existence of a greater coupling between the ECN and the DMN throughout the creative process, reinforcing the idea that the creative process requires flexible cognitive control.

In summary, the DMN plays a fundamental role in high-level cognitive processes and especially in human creativity. For this reason, and based on the new functional paradigm of the DMN, supported by the new experimental discoveries, a name change to DCN (*Deep cognitive network*) has been proposed.

5. In the fifth stage, and complementing the previously identified basic factors, a total set of 17 neurocognitive factors that support the creative processes in the human brain have been identified and deduced.

This has been achieved using three different and complementary strategies:

- Analysis of recent discoveries on the neurocognitive structure and functionality of the human brain.
- Results of specific experiments related to the identification of brain activity when creative tasks are carried out (usually *divergent thinking* tests) show neurocognitive patterns such as the activation of brain areas (such as the angular gyrus, the MTL, or the insula), or the activation of large-scale networks (such as the ECN, or the DMN).
- Results of specific experiments not directly related to creativity (for example, D2 receptors in the thalamus have been studied in without suspecting that this may be related to human creativity).
- Parallels detected between neurocognitive investigations of a general nature and the behavior observed in very creative people, or with the conceptual and methodological structure of creative processes (for example, the relationship between top-down and bottom-up processes of various neurocognitive processes, with the conceptual structure of creative activity).

As a result, 17 neurocognitive factors that support human creativity have been identified:

- The structure of the human cognitive system is based on associative large-scale neural networks, which integrate different regions (specialized in certain high cognitive processes) located throughout the cortex.
- Multimodal organization of the brain that allows flows of general information, transforming it at various levels of abstraction.
- Strategic topographic distribution of large-scale networks and their constituent nodes (located at the maximum distance from sensorimotor nodes), allowing the existence of abstract thoughts and the creation of self-generated thoughts.
- Strategic collaboration between the ECN, the SN and the DMN, creating the central mechanism of human creativity (*Triple Network Model*).
- The DMN network has a special functionality, and plays a fundamental role in the processes of generating and evaluating ideas.
- The medial temporal lobe plays a fundamental role in the creation of self-generated thoughts.

- The *Task Induced Deactivation* mechanism may have operational failures, and this allows the mixture of uncontrolled information that is handled separately by the ECN and the DMN. The variability of this mechanism is directly related to the *Working Memory Capacity* (WMC).
- The insula (and the SN in general) partly control the functionality of the DMN and the ECN, when creative tasks are carried out.
- The angular gyrus is directly involved in the integration of some neurocognitive processes related to creativity. The left AG plays an important role in human creativity because it is part of two networks related to human creativity (semantic network and DMN). Creative people also have high connectivity between the DMN and inferior frontal gyrus, what is interpreted as a high ability to exercise top-down control over imaginative processes derived from the DMN.
- Fuzzy memory mechanisms do not allow for information, to be retrieved exactly. When used, in the future, the transformation it has experienced helps the creative processes.
- Episodic memory facilitates creative processes, since it implies a base of semantic memory, and it has been proven that under an episodic specific induction process creative activity is increased, since this allows the solution search tree to be traversed through alternative paths.
- Semantic memory is essential for the creative process. Concepts are created through a cross-modal structure that integrates and refines the "raw information" generated by the sensorimotor and verbal regions, and transforms it into coherent, complete and refined transmodal semantic representations. In this way, the information is structured at various levels of abstraction and with a huge number of attributes, and this is a basic condition to allow the creative process.
- The emotional mechanisms of the brain are capable of representing and storing entities, objects or concepts in a richer and more detailed way. The availability of a greater amount of information structured at various levels of abstraction, and with a greater number of relationships, allows the search tree for solutions to be traversed by more varied paths, being able to reach very creative solutions.
- Motivation increases the global efficiency of large-scale neural networks and decreases their decomposability.
- Changes in the information filtering neuronal system of the thalamus, based on the alteration of D2 receptors enable a greater amount of information to be processed.

- The large-scale networks can cooperate, overlap and dynamically reconfigure, which allows traversing the search tree by unexpected paths.
- Hierarchical structure of the brain, based on linked sequences of top-down and bottom-up processes facilitates top-down control of bottom-up emerging thoughts, when performing creative tasks.

6. Once the neurocognitive bases of human creativity have been identified, it is possible to create a neurocognitive paradigm of human creativity. This paradigm frames the creative potential of the human brain, taking into account its limitations and its intrinsic potentials. Based on this paradigm, a neurocognitive model of the creative process has been proposed, which restructures, completes and improves the conceptual models proposed so far. This neurocognitive model of the creative process must be completed and refined based on future experiments framed within it.

In general, and after analyzing more than 800 bibliographical references on the subject, a certain dispersion of research is noted, and it is observed that certain important aspects have been left aside in order to identify the neurocognitive factors of human creativity.

For this reason, in this doctoral thesis some specific experiments have been proposed, in order to provide suggestions for future research. Some of them are:

- Analyze brain activity when performing creative tasks (*divergent thinking* tests, and others) with creative and non-creative people: a) detect brain activity when a recognized creative person performs a non-creative activity, and next a creative activity: b) detect brain activity when admittedly non-creative people perform a non-creative activity, and next a creative activity.
- Sequentially analyze brain activity at different strategic moments from a real creative activity, which extends over time. Real activities are usually part of a long and complex process, so it would be interesting to monitor the brain activity at different stages of the creative process. For example, an architect takes a week to carry out the basic idea of a house design, it would be interesting to continuously monitor his brain activity throughout different moments of that week, at least from time to time, and at strategic moments. This would undoubtedly provide much more information on the neurocognitive bases of human creativity.

7. Based on the identified creative neurocognitive paradigm, it has been also possible to establish certain strategies to increase human creative capacity. For this, the main

methods that stimulate human creativity have been analyzed, as well as the different neurocognitive factors that support human creativity. Based on this analysis, different suggestions have been made to identify different strategies with which to substantially increase human creativity.

The most important strategy consists in the education of children, especially in their first five years of life, for which certain guidelines for action and a varied set of activities have been proposed.

Educators and psychologists can implement actions aimed at stimulating human creativity. Some examples would be the following:

- Promote abstract learning about the common components among the different fields of knowledge.
- Promote general knowledge of any discipline, and in-depth knowledge of preferred disciplines
- Learn to detect parallels and common patterns between the different fields of knowledge
- Avoid premature specialization, before having adequate generalized training
- Encourage hard work and exhaustive documentation on the problem to be solved
- Encourage motivation, even obsession, to solve a problem
- Increase the level of self-demand
- Forcing periods of mental relaxation after long periods of obsessive and hard work
- Increase the number of personal experiences
- Not accept any social rules
- Questioning and analyzing any type of information
- Have strong emotional experiences (both positive and negative).
- Mix the information of the problem with the sensory information of the environment.
- Avoid taking drugs that enhance the activity of certain parts of the brain, inhibiting others (for example, *Ritalin* can enhance attention mechanisms, such as the capacity for working memory, which induces a decrease in the activity of creative neurocognitive processes).

These are just a few examples of the many and varied educational strategies that can be implemented based on knowledge of the neurocognitive bases of human creativity. In fact, in this Doctoral Thesis several different educational activities have been suggested to substantially increase children's creativity.

8. In a complementary way, knowledge of the neurocognitive bases of human creativity allows us to improve existing methods to amplify human creativity and create new, more efficient methods. In this doctoral thesis several methods have been proposed to stimulate human creativity, based on the previously identified neurocognitive paradigm. In the same way, it allows to improve and complement the conceptual models on the creative process made up to now.

9. Knowledge of the neurocognitive bases of human creativity opens new paths to stimulate it with the help of chemical substances, bionic systems, and above all artificial intelligence.

Several proposals have been made, and among them the creation of "augmented creativity devices" stands out, which are electronic devices connected by sensors to the human brain, which allow the excitation of certain brain areas and the inhibition of others, in order to stimulate creative creativity of the brain. These systems would also be connected to computer systems to increase efficiency in the generation and evaluation of ideas, having at each moment a gigantic amount of relevant information.

10. Finally, a computational paradigm of creativity has been created, based on the neurocognitive bases of human creativity. Analyzing the different neurocognitive bases that support human creativity, computational parallels have been established and different suggestions established for the design of a creative computational system. By grouping all the suggestions, it has allowed for an adequate estimate of the comparative importance of each one to be made, and of its relative contribution in the overall design of the system. The suggestions are of various types, and correspond to different aspects of the computational system (system structure, system operation, limitations, information structure, information manipulation strategies, etc.).

As a result, a multi-agent computational system has been designed. This system is based on three sets of agents that interact with each other in various ways, based on the type of problem to be solved. The different agents of each group can assume different roles, depending on the design stage of the system. The system includes an evaluation system, with variable evaluation criteria, initially established by the users, but that the system can change throughout its operation. A knowledge representation system has also been proposed, which allows its manipulation at various levels of abstraction, and thus enables the system to function at the highest possible creative level.

CONCLUSIONS

9. Conclusions

1. The neurocognitive structure that supports human creativity has been identified by studying more than 800 references representing the research carried out to date.

2. A neurocognitive paradigm of human creativity has been described and the structure of a creative computational system has been proposed, based on a multi-agent system, rooted on the neurocognitive structure of human creativity.

3. The studied articles tend to focus on very specific aspects of creativity, and in many cases are just slightly related to each other. For this reason, they have been classified, grouped, analyzed, intertwined, and structured in an orderly way, creating a complete, holistic, and compact account. When analyzing the set of investigations, a set of patterns, correlations and parallelisms has been identified, which have allowed the identification of the fundamental neurocognitive bases of human creativity.

4. Since there are many definitions of the concept ‘creativity’, for its proper analysis a taxonomic definition should be chosen, based on specific points that can be precisely delimited for each specific field of creativity. We have concluded that the most complete and adequate taxonomy is the one usually called *4-P Taxonomy* (*Person*, *Process*, *Product*, *Press*). It provides an adequate and complete framework to define and analyze human creativity, as well as a suitable reference to direct the rest of the investigations. The main criteria for evaluating the level of creativity are novelty, value, and surprise. Other secondary criteria may be effectiveness, elegance, generalization, imagination, and appreciation.

5. A compilation and analysis of the most effective methods to stimulate human creativity has been carried out, including the advantages and disadvantages of each one, as well as the most suitable environments to use them. Their effectiveness is highly variable, which reveals the weaknesses when establishing the initial hypotheses of their design. This analysis also provides an overview of the strengths and weaknesses of the human brain in creative problem solving. Therefore, to understand in depth the essential nature of creativity, it, it is essential to identify the neurocognitive foundations of human creativity.

6. The fundamental cerebral factors that intrinsically sustain its creative potential have been identified:

- Brain capacity to generate neurocognitive processes in series and in parallel.
- Functional structure based on the activation of large-scale networks, which integrate different specialized areas strategically distributed.
- Existence of a multimodal network, which integrates the flow of information between the different large-scale networks, at different levels of abstraction.
- Existence of a strategic topographical structure of the cortex. Around the sensorimotor regions, new areas involved in high-level cognitive processes have been evolved and are able of manipulating abstract information and creating self-generated thoughts.
- Existence of a basic neurocognitive structure to generate and evaluate ideas, based on the interrelation of three main large-scale networks: the *Executive control network* (ECN), the *Default mode network* (DMN), and the Salience network (SN) (*Triple network model*).

7. The *Default mode network* (DMN) plays a main role in creative capacity and is involved in several of its fundamental neurocognitive processes:

- The DMN is located at the end of the main gradient, and this allows it to be involved in various types of high-level cognitive processes, which are apparently unrelated to each other. It plays a leading role in the creative processes.
- The DMN has its nodes are topographically distributed along the cortex at the maximum distance from the sensorimotor nodes. This allows it to perform high cognitive level functions, far from the 'here and now'. Therefore, it is involved in self-generated thoughts, which is a normal activity of the brain, in the absence of external tasks, and the basis for the generation of ideas in creative processes.
- The DMN is directly involved both in the generation of ideas (through its management of self-generated thoughts), and in the affective and visceroceptive evaluation of ideas (through its ability to manage memory, in tasks related to autobiographical, episodic, and semantic memory, mind wandering, perspective taking or future thinking).
- The DMN closely collaborates with the ECN, and together they have differential contributions during the different stages of the creative process. In general, when the ECN is activated, the DMN is deactivated, although sometimes both are activated. In

addition, the DMN is activated more intensely during the idea generation stage and, conversely, the ECN is activated more intensely during the idea evaluation stage.

- DMN increases its activity by performing tasks in which cognition and behavior must use the memories of related previous experiences, which happens continuously throughout the creative process.

- The DMN also integrates subcortical components, such as the basal forebrain and the anterior and middorsal thalamus, which allows it to be involved in emotional modulation. These areas may act also as a relay at the subcortical level, integrating primary functional networks and brainstem inputs with higher-level associative networks. This explains why the activity of the DMN seems to arise from within us in the creative process, since it is related to the most intimate self-referential activity of our self.

- The DMN plays a critical role in detailed experiences in working memory processes during memory retrieval, and is involved in the level of information specificity, or the level of information detail. The process of detailed concept definition is essential to the creative process.

- The DMN shows patterns of meta-functionality and participates in generic and higher-order activity patterns that support different creative activities (such as *delayed matching*, *contextual modulation*, *rule-based decision making*, etc.).

8. A complete set of neurocognitive factors that support the creative processes in the human brain have been identified, by means of three complementary strategies:

- Results of specific experiments related to the identification of brain activity when creative tasks are carried out (usually divergent thinking tests) show neurocognitive patterns such as the activation of brain areas (such as the angular gyrus, the MTL, or the insula), or the activation of large-scale networks (such as the ECN, or the DMN).

- Results of specific experiments not directly related to creativity (for example, D2 receptors in the thalamus have been studied without suspecting that they might be related to human creativity).

- Parallels detected between neurocognitive investigations of a general nature and the behavior observed in highly creative people, or with the conceptual and methodological structure of creative processes (for example, the relationship between top-down and bottom-up processes of various neurocognitive processes, with the conceptual structure of creative activity).

As a result, 17 neurocognitive factors that support human creativity have been identified:

- The structure of the human cognitive system is based on associative large-scale neural networks, which integrate different regions (specialized in certain high cognitive processes) located throughout the cortex.

- Multimodal organization of the brain that allows flows of general information, transforming it at various levels of abstraction.

- Strategic topographic distribution of large-scale networks and their constituent nodes (located at the maximum distance from sensorimotor nodes), allowing the existence of abstract thoughts and the creation of self-generated thoughts.

- Strategic collaboration between the ECN, the SN and the DMN, creating the central mechanism of human creativity (*Triple Network Model*).

- The DMN network has a special functionality and plays a fundamental role in the processes of generating and evaluating ideas.

- The medial temporal lobe plays a fundamental role in the creation of self-generated thoughts.

- The *Task Induced Deactivation* mechanism may have operational failures, and this allows the mixture of uncontrolled information that is handled separately by the ECN and the DMN. The variability of this mechanism is directly related to the *Working Memory Capacity* (WMC).

- The insula (and the SN in general) partly control the functionality of the DMN and the ECN, when creative tasks are carried out.

- The angular gyrus is directly involved in the integration of some neurocognitive processes related to creativity. The left AG plays an important role in human creativity because it is part of two networks related to human creativity (semantic network and DMN). Creative people also have high connectivity between the DMN and inferior frontal gyrus, what is interpreted as a high ability to exercise top-down control over imaginative processes derived from the DMN.

- Fuzzy memory mechanisms do not allow for information, to be retrieved exactly. When is used, in the future, the transformation it has experienced helps the creative processes.

- Episodic memory facilitates creative processes, since it implies a base of semantic memory, and it has been proven that under an episodic specific induction process, creative activity is increased, since this allows the solution search tree to be traversed through alternative paths.

- Semantic memory is essential for the creative process. Concepts are created through a cross-modal structure that integrates and refines the “raw information” generated by the sensorimotor and verbal regions, and transforms it into coherent, complete and refined transmodal semantic representations. In this way, the information is structured at various levels of abstraction and with a huge number of attributes. This is a basic condition to allow the creative process.

- The emotional mechanisms of the brain are capable of representing and storing entities, objects or concepts in a richer and more detailed way. The availability of a greater amount of information structured at various levels of abstraction, and with a greater number of relationships, allows the search tree for solutions to be traversed by more varied paths, being able to reach very creative solutions.

- Motivation increases the global efficiency of large-scale neural networks and decrease their decomposability.

- Changes in the information filtering neuronal system of the thalamus, based on the alteration of D2 receptors enable a greater amount of information to be processed.

- The large-scale networks can cooperate, overlap, and dynamically reconfigure, which allows traversing the search tree by unexpected paths.

- Hierarchical structure of the brain, based on linked sequences of top-down and bottom-up processes facilitates top-down control of bottom-up emerging thoughts, when performing creative tasks.

9. Taking into account the identified neurocognitive bases of human creativity, a neurocognitive model of the creative process has been proposed, completing and detailing the previously proposed models.

10. Several educational strategies aimed to increase human creative capacity have been proposed (especially aimed at children), based on the knowledge of the neurocognitive bases of human creativity. These strategies are aimed at the story generation, object design, and problem solving.

11. The possibility of using chemical substances, bionic systems, and above all artificial intelligence has been established. Among them, the creation of "augmented creativity

devices" (electronic devices connected by sensors to the human brain, which excite certain brain areas and inhibit others) stands out, to stimulate creativity. These devices can be connected to global networks, in order to increase efficiency.

12. This study may be useful to neurobiologists, since it provides a global vision of the neural bases of human creativity, and thereby might contribute to suggest new research pathways. Psychologists and educators might benefit from the implementation of strategies to improve creative capacities. Some of them might come from bionic engineering. Pharmacological research might be interested in synthesizing chemicals able to increase human creativity. Finally, it is also important for AI to develop new paths of research and implementation of computational creative systems.

APPENDIX

Appendix 1

Glossary

- *Alzheimer's disease* (AD).

It is a non-reversible age-related brain disorder that develops especially in advanced age. In an initial stage the symptoms are memory loss and confusion. Symptoms evolve into changes in behavior and personality, a decline in cognitive abilities, such as decision-making and language skills, and trouble recognizing family and friends.

- *Attention deficit hyperactivity disorder* (ADHD).

ADHD is one of the most common childhood disorders, and it can last through adolescence and into adulthood. Symptoms include difficulty staying focused and paying attention, hyperactivity, and difficulty controlling behavior.

- *Autism*.

Autism is a neurocognitive developmental disorder that appears in the first three years of life, and affects the normal development of the brain's communication and social skills. People with autism have difficulties with social interaction, show problems with verbal and non-verbal communication, and exhibit repetitive behaviors and specific obsessive interests.

- *Blood-oxygen-level-dependent* (BOLD).

Measure of metabolic activity in the brain based on the difference between oxyhemoglobin and deoxyhemoglobin levels due to changes in local blood flow.

- *Brain Networks.*

Brain networks can be defined either by their structural connectivity or by their functional interdependence. The structural connectivity of the brain is based on the physical union between its neurons, which can be connected to each other through synapses of short axons, dendrites and gap junctions. Different neuronal groups can be represented as nodes in a network if they have a clearly identifiable structural organization, a large-scale structural connectivity pattern, or a local functional activity pattern (which can be distinguished from the activity pattern of neighboring neurons). The functional interdependence between various nodes of a brain network is evidenced by their joint (and codependent) activity in response to changes in functional or behavioral parameters.

- *Centrality*.

Property of a node in a network that measures the relative importance of the node in the network. Nodes that occur on many shortest paths between other nodes have higher centrality than those that do not.

- *Clustering coefficient*.

The clustering coefficient measures the tendency of nodes in a graph to cluster, and is based on measures of how connected the node's neighborhood is.

- *Default mode network* (DMN).

Large-scale neural network, made up of an integrated set of brain regions, involved in high-level cognitive functions, related to oneself, including autobiographical, self-control and social functions.

- *Depression*.

It is characterized by a combination of symptoms that interfere with an individual's ability to enjoy activities that were previously enjoyable for them. Symptoms include persistent feelings of sadness, anxiety or "emptiness," feeling worthless, feeling helpless, feelings of hopelessness and pessimism, and suicidal tendencies.

- *Diffusion-based tractography* (DBT).

It is a type of non-invasive magnetic resonance imaging in which fiber bundles (tracts of white matter) are traced in the human brain based on the diffusion properties of water molecules in the microstructure of a certain area of tissue.

- *Diffusion tensor imaging* (DTI).

Non-invasive magnetic resonance imaging technique that measures tracts of white matter in the brain, in vivo, based on the diffusion properties of water molecules in the tissue microstructure.

- *Dynamic causal modeling*.

Statistical analysis, based on bilinear dynamic models, used to make inferences about the effects of manipulations on interregional interactions in latent neural signals.

- *Frontotemporal dementia* (FTD).

FTD is a clinical syndrome associated with shrinking of the frontal and temporal anterior lobes of the brain. Symptoms of FTD involve changes in behavior, or problems with language.

- *Executive control network* (ECN).

Large-scale brain network involved in goal-oriented and high-level cognitive functions such as planning, decision making, and the control of attention and working memory.

- *Functional connectivity*.

Statistical interrelation of variables that represents the temporal changes in different nodes of the network. The functional interdependence of the nodes of the brain network refers to a joint activity in different brain structures that is codependent with respect to the variation of a functional (or behavioral) parameter.

- *Functional interdependence*.

Statistical interrelation of variables that represent temporal changes in different nodes of the network.

- *Granger causality analysis* (ACG).

Statistical method that measures the degree of predictability of temporary changes in a certain brain area, and that are attributed to changes produced in another area.

- *Graphs*.

A graph is a mathematical entity that consists of nodes (vertices) and edges that connect the nodes two by two. Graphs are used to model pairwise relationships between nodes, and can be “directed” (when the edges point from one node to another), or “undirected” (when the edges have no directionality). A bi-directional grapf when the edges point in two directions between two nodes.

- *Independent component analysis* (ICA).

Computational technique that decomposes a multivariate signal into additive components based on the assumption that the components are generated from statistically independent non-Gaussian sources.

- *Intrinsic connectivity network* (ICN).

Large-scale network including several interdependent brain areas, detected at rest.

- *Large-scale network*.

Neural systems that are distributed throughout the entire extension of the brain.

- *Local field potential* (LFP).

Electrical potential generated in a certain area of neuronal tissue caused by a local group of neurons. LFPs result from current flow in the extracellular environment that has been generated by electromotive forces operating across the cell membranes of neurons, primarily at synapses.

- *Functional magnetic resonance imaging* (fMRI).

Noninvasive neuroimaging techniqu that measures blood-oxygen-level-dependent (BOLD) signals in the brain in vivo.

- *Generalized anxiety disorder* (GAD).

GAD is a pattern of ongoing worry and anxiety, triggered by different factors. The main symptom is the almost permanent presence of worry, or tension, even when there is no cause, or when the cause is not particularly important.

- *Independent component analysis* (ICA).

Computational technique that separates a multivariate signal into additive components based on the assumption that the components arise from statistically independent non-Gaussian sources.

- *Intrinsic connectivity network* (ICN).

Large-scale network of interdependent brain regions detected at rest.

- *Large-scale*.

Neural systems, involving a certain group of regions, that are distributed across the brain.

- *Network*.

A network is a physical system with graph-like properties, so the properties of the network correspond to the properties of the graph on which it is based. Networks can be characterized by their topology, which defines the way in which their different elements are arranged or configured.

- *Network edge*.

Component of a network that links the nodes.

- *Network node*.

Las componentes de ua red que estan unidas por bordes.

- *Path length*.

Number of steps between a node and all other nodes in the network.

- *Phase synchrony*.

It is the tendency of two time series to exhibit time block, or a constant phase relationship, usually in a narrow frequency range.

- *Salience network* (SN).

Large-scale brain network involved in the detection of prominent external stimuli and internal events, and switchig the appropriate large-scale networks to generate the most appropriate behavior.

- *Schizophrenia*.

Mental disorder associated with incorrect social behavior, auditory hallucinations, disorganized speech, paranoid delusions, and disorganized thinking.

- *Small-world network*.

Graph in which most of the nodes are not neighbors to each other, but are separated by only a few steps.

- *Structural connectivity*.

Physical connectivity between brain areas (detected using DTI tractography *in vivo*, or tracer studies on *postmortem*).

Appendix 2

Large-scale structural and functional brain networks

Large-scale structural brain networks. Most important definitions

There is now a consensus that cognitive activity in the brain is based on the activation of large-scale neural networks. The origin of this new network-based cognitive paradigm has its origins in the work of several outstanding researchers, from the 60s and 70s, such as Luria [1], Pavlov [2], and Wernicke [3], and has been consolidated by several recent researchers, such as Bressler [4], Edelman [5], Freeman [6], Fuster [7], Goldman-Rakic [8], Greicius & Menon [9], McIntosh [10], Mesulam [11], Mountcastle [12], and Sporns [13].

Currently, a large number of methodologies and technologies have been developed that have allowed great advances in the study of structural and functional connectivity. These studies have made it possible to consolidate the current cognitive paradigm based on large-scale neural networks.

The study of the structure of brain networks on a large scale allows us to identify the connections between the different neural regions that compose them, and also allows us to know their associated cognitive functionality.

For this, it is essential to identify the brain regions that constitute the nodes of the structural network, as well as the connecting channels that serve as its edges. In this way the possible configurations of these regions can be determined.

A recent work has carried out a compilation and classification of the accumulated information on the main methods used to define the nodes and the structural edges of the brain, and on this basis the possible functional consequences of the structural organization of large-scale brain networks were considered (14).

This study indicates that the cognitive function is generated as a consequence of dynamic process that are constrained by intrinsic structural connectivity and ongoing physiological processes.

Nodes

The nodes of large-scale structural networks can be defined in several ways:

- cytoarchitectonics
- input projection source commonality
- local circuit connectivity
- output projection target commonality

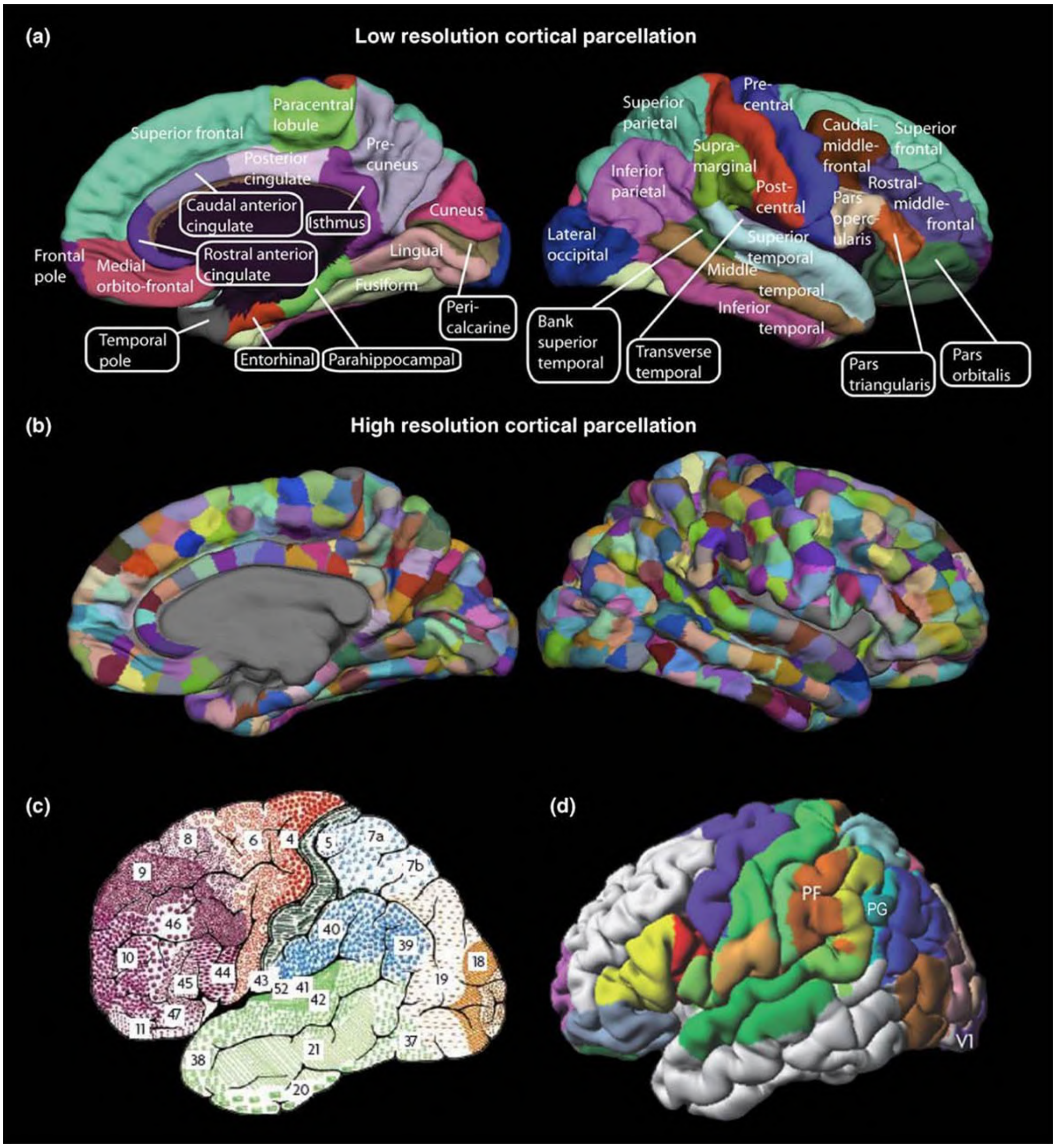

Figure A2.1. Identification of large-scale structural network nodes in the human brain by four methods currently in use.
A. Automated parcellation of a single subject's structural MRI into nodes.
B. High-resolution parcellation with arbitrary granularity.
C. Classical Brodmann atlas based on cytoarchitectonic features.
D. The Jülich-Duüsseldorf cytoarchitectonic probabilistic brain atlas.
(Source: Bressler, S., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Sciences*, 14, 277-290)

Each area of the brain can also be described as a subnet of a large-scale network. This subnet is composed of excitatory and inhibitory neuronal groups (nodes) and connecting pathways (edges). However, and for simplicity, the different areas of the brain can be assimilated into unitary neuronal masses, which serve as nodes of large-scale networks. Defining nodes is actually quite complex, and is undergoing progressive refinement as new methods are developed and understanding of structure-function relationships in the brain evolves.

In recent years, a large number of techniques have been developed to determine the structural nodes of a large-scale network from neuroanatomical data. Among them, the following stand out:

- Anatomical parcellation of the cortex of Brodmann atlas
- Neurochemical maps showing neurotransmitter profiles [15] (Fig. A2.1)
- Parcellation of standardized Montreal Neurological Institute (MNI) [16]
- Quantitative cytoarchitectonic maps [17]
- Structural connectivity divergence and convergence patterns [18]
- Subject-specific automated cortical parcellation based on gyral folding patterns [19]

Most current neurocognitive studies have focused on the cerebral cortex. Subcortical structures have been studied less, and have only been roughly identified by magnetic resonance imaging. On the other hand, the brainstem systems that mediate motivation, arousal, and autonomic function have also not been studied much because they are very difficult to identify using current non-invasive techniques. However, it is essential to analyze and delimit these structures properly, since they are fundamental and significantly influence (more than used to be believed until a few years ago) on cortical signaling and, therefore, affect cognitive function.

Edges

Edges connect different regions of the brain and create large-scale structural networks and are long-range axonal fiber pathways (white matter). The edges of the network are directional since the axonal fiber pathways have directionality from the bodies to the synapses, although they can also be bidirectional when the fiber pathways run in both directions between areas of the brain. Each area of the brain has a unique set of connections with the areas with which it is interconnected [20]. On the other hand, the edges of the network can also have variable weights depending on the number and size of axons in the pathways, as well as the number and strength of functional synapses at the axon terminals (Figure A2.2).

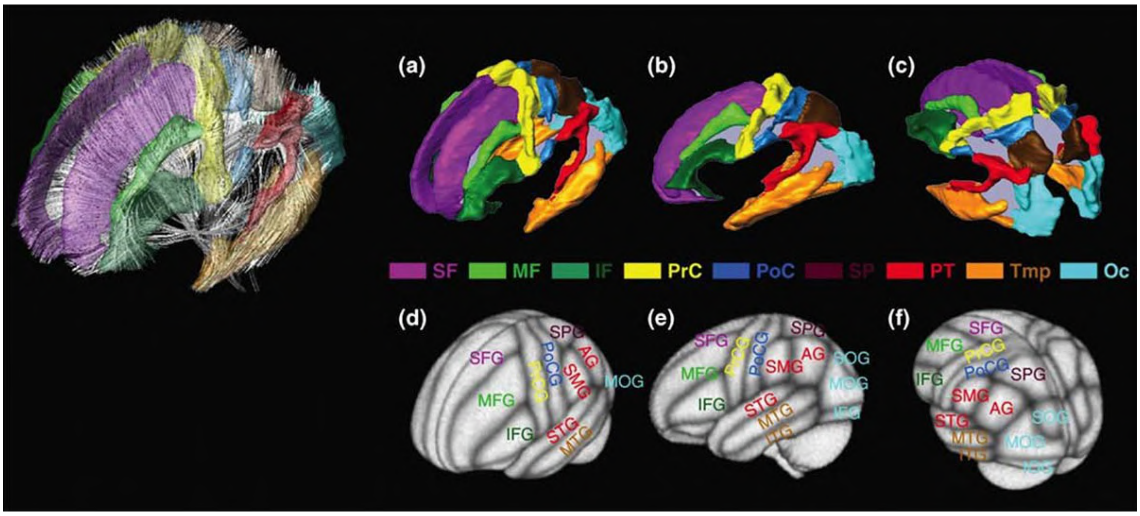

Figure A2.2. Identification of large-scale structural network edges in the human brain. Edges linking structural nodes were defined using diffusion tensor imaging.
Left. Individual fiber tracts.
A-C. Tract reconstruction and clustering.
D-F. Relation to cortical nodes.
(Source: Bressler, S., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Sciences*, 14, 277-290)

Inferring function from structural networks

Large-scale structural networks are anatomical structures within which certain functional interactions develop [21]. To structurally define a network, one must first identify the areas of the brain that are interconnected, and based on this determine what functional interactions are possible. It is also necessary to know the connectivity pattern of the structural network to identify the different types of interaction that can be generated. For example, knowing the structural organization of sensory networks facilitates making inferences about functional activity patterns once sensory stimulation has been performed [22]. In a complementary way, the knowledge of certain structural characteristics of the network (such as the grouping of nodes or the length of the path, the divergence and the convergence) also contributes important information on its functionality [23].

Large-scale functional brain networks. Most important definitions

A large-scale functional network is a set of interconnected brain areas that interact to perform certain cognitive functions. Therefore, it can be said that structural networks provide a complex framework that promotes dynamic interactions between nodes, and the set of all of them give rise to functional networks. In this way, the connectivity patterns of the structural networks determine the functional networks that can arise in them [24]. The topological structure of functional networks is constantly changing throughout an individual's life, and is determined by maturation and learning processes in its large-scale neuroanatomical connectivity matrix [25]. Large-scale functional networks in the brain exert coordinated effects on effector organs, subcortical structures of the brain, and cortical areas distributed through a set of different cognitive functions.

The component areas of large-scale functional networks play different roles. Some areas can act as controllers of the activity of other areas [26]. However, other areas can contribute with specific sensory, or conceptual, information to the functionality of the network.

Nodes

There is no consensus on what constitutes a functional brain node. The nodes of a functional network were usually defined according to the cognitive damage observed when a certain brain area was damaged. However, and based on the use of current new neuroimaging technologies, a node is defined as a region of the brain that shows the following characteristics, depending on the scanning method:

- High metabolism in *positron emission tomography* (PET) registers
- High blood perfusion on *functional magnetic resonance imaging* (fMRI) recordings
- Synchronized oscillatory activity in the *local field potential* (LFP) recordings

The participation of an area of the brain in a large-scale functional network can be inferred by taking into account its activation, or its deactivation, in relation to a certain cognitive function. In this way, a group of brain areas that are activated, or deactivated, in a joint and unique way, during a certain cognitive activity (with respect to a certain reference) can be identified as the nodes of a large-scale neural network, associated with that function. Furthermore, for a certain area of the brain to be considered as a functional network node, it must be shown that, in collaboration with other nodes, it is involved in a certain cognitive function.

Most of the investigations in functional neuroimaging use the *blood-oxygen-level-dependent* (BOLD) signal of functional magnetic resonance in order to identify the nodes of functional networks on a large scale, since it allows to relate the joint activation of certain brain areas with diminished cognitive functions.

In fact, the activation of fMRI BOLD has evidenced network nodes that are involved in cognitive functions such as:

- Attention [27]
- Emotion [28]
- Language [29]
- Motor control [30]
- Perception of time [31]
- Working memory [32]

Instead, the nodes of the default mode network (DMN) have been identified by observing the areas of the brain that are deactivated jointly, when goal-directed tasks are performed [33].

Edges

The edges of a functional network can be identified based on different types of functional connectivity analysis, which assesses the functional interactions between nodes in the network. The edges of the network, like the nodes, can be identified depending on the methodology used.

Functional interdependence analysis can identify network edges from time-series data in the time domain (eg, cross-correlation function) or frequency (eg, spectral coherence or phase synchronization measurements). In any domain, the analysis can use a symmetric measure, in which case significant interdependencies are represented as undirected edges, or an asymmetric measure, in which case they are represented as directed edges [34]. Methods that use directional measures include *dynamic causal modeling* [35], and *Granger causality analysis* [36].

Intrinsic functional brain networks

To investigate the interactions between the different areas of the brain, the methodology of *functional interdependence analysis* is usually used during the execution of tasks. However, and although functional task-based analyses have made it possible to understand the dynamic context-dependent interactions on the context, in general they do not provide sufficient information on the basic foundations of functional brain networks. Task-based analyses focus on observing the changes induced in brain interactions due to certain tasks, and for this reason they tend to ignore the anatomical connectivity and the physiological processes that underlie these interactions. On the other hand, there is currently a consensus that it is necessary to know the intrinsic structural and functional connectivity of large-scale brain networks to understand the neurocognitive mechanisms of cognition.

For this reason, alternative methods have been developed, called *intrinsic interdependence analysis*, which focus on the analysis of large-scale brain organization independent of the processing demands of the task [37]. In fact, *Intrinsic interdependence analysis* of functional magnetic resonance data acquired from resting subjects has been used to identify *intrinsic connectivity networks* (ICN) [38]. Identifying large-scale functional networks in resting state has the advantage of avoiding certain singularities present in certain cognitive tasks [39]. The ICNs identified in the brain in resting state have been shown to coincide with the networks that are activated when tasks are performed, so it can be deduced that the human brain is intrinsically organized into different functional networks [40].

In general, two different methods are used to identify ICNs.

- The most used method to identify ICN based on the analysis of fMRI BOLD data in resting state is the *independent component analsis* (ICA) [41]. This ICA method has been used to identify ICNs involved in episodic memory, autobiographical memory, executive control, self-related processing, and the detection of salient events. TUsing the ICA technique, a sensorimotor ICN anchored in the bilateral somatosensory and motor cortices, a visuospatial attention network anchored in intraparietal grooves and frontal ocular fields, a higher order visual network anchored in lateral and inferior occipital temporal cortices, and lower-order visual network, have been identified [42]. This technique has also allowed both intrinsic, and task-related (Fig. A2.3) fMRI activation patterns to be used for the identification of different large-scale networks, such as the *Executive control network* (ECN) (including the dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC)), and the *Salience network* (SN) (including the anterior insula (AI) and the anterior cingulate cortex (ACC)) [43].
- Another method used to identify ICNs is the *seed based functional interdependence analysis* (SBFIA) [44]. Like the ICA, this method has been used to examine ICNs associated with specific cognitive processes such as visual orientation attention [45], memory [46], and emotion [47]. The method has two stages. First, a specific "seed" region is identified that is associated with a certain cognitive function. Secondly, a brain voxel map is constructed that show significant functional connectivity with the seed region. This technique has shown that the same networks that are activated during the execution

of cognitive tasks are the same as those identified in the resting brain, including the dorsal and ventral attention systems [48], and the memory systems of the hippocampus [49].

Core functional brain networks

There are certain functional networks that support the fundamental neurocognitive activities of the human brain. Mesulam initially proposed that there are at least five functional neural networks in the human brain [50]:

- Working memory-executive function network, anchored in the prefrontal and inferior parietal cortices.
- Explicit memory network, anchored in the hippocampus-entorhinal complex and the inferior parietal cortex
- Spatial attention network, anchored in the posterior parietal cortex and the frontal eye fields
- Facial object recognition network, anchored in temporal and temporopolar cortices
- Languaje network, anchored in the Wernicke and Broca áreas

Since then, a number of additional networks, as well as subnets, have been identified and an enormous amount of research has been done on them.

The main functional brain networks, as well as their subnets, show a close correspondence in independent analyzes of connectivity patterns at rest and those related to the performance of tasks [51]. This suggests that resting coupled functional networks are also systematically activated during cognition. On the other hand, the fact that some major brain networks can be identified as ICN in resting subjects has contributed to a greater understanding of major neurocognitive functions.

One of the recently identified ICNs is the *Default mode network* (DMN), which deactivates when performing cognitively demanding tasks [52], and is instead activated during high-level social cognitive tasks [53]. Several studies have shown the activation and deactivation of various nodes of the DMN. For example, the PCC is involved in tasks related to autobiographical memory and self-referential processes [54]; the medial PFC is involved in social cognitive processes related to oneself and others [55]; MTL is involved in episodic memory processes [56], and angular turn in semantic processing [57]. These studies further indicate that the different component regions of the DMN have a very different functionality, but instead the DMN generally performs a set of specific functions, such as autobiographical, self-control and social cognitive [58].

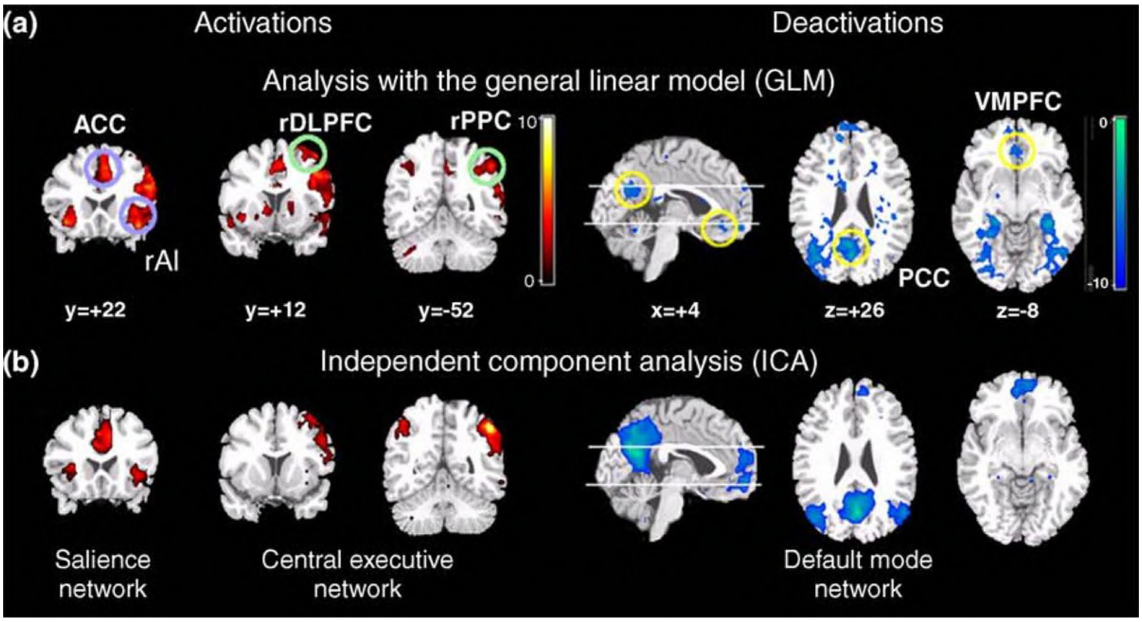

Figure A2.3. Three major functional large-scale networks in the human brain identified using converging methodologies. Task-related activation patterns in the ECN and SN, and deactivation patterns in the DMN during an auditory event segmentation task.
A. Analysis with the general linear model shows regional activations (left) in the right AI and ACC, and the DLPFC and PPC. It also shows deactivations in the ventromedial (VM) PFC and PCC.
B. Independent component analysis (ICA) provided converging evidence of spatially distinct networks: SN (rAI and ACC), ECN (rDLPFC and rPPC), and DMN (VMPFC and PCC).
(Source: Bressler, S., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Sciences*, 14, 277-290)

Another recently identified ICN is the *Salience network* (SN), which includes several cortical regions including the AI and ACC, and subcortical regions such as the amygdala, the substantia nigra or the ventral tegmental area and the thalamus. The SN is involved in the detection of the most relevant intrapersonal and extrapersonal salient events [59]. Furthermore, AI plays a causal role switching between ECN and DMN [60], two networks that experience competitive interactions between task paradigms and stimulus modalities (Fig. A2.3) and are believed to mediate attention to external and internal worlds, respectively. This network has been suggested to mediate attention to the outer and inner worlds [61]. However, to determine if this network really performs this function specifically, it will be necessary to carry out definitive studies, and validate a set of functional mechanisms, such as:

- Bottom-up detection of salient events
- Large-scale network switching to facilitate access to attention and working memory resources when a salient event occurs

- Interaction of the anterior and posterior insula to modulate autonomic reactivity to salient stimuli
- Strong functional coupling with ACC to facilitate quick access to the motor system.

Notes appendix 2

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Appendix 3

New methodologies used for the creation of new models on the functionality of the brain

Continuous fluctuations in brain activity can be measured by functional magnetic resonance imaging (fMRI) and this provides a new way to determine the functional structure of brain networks. Advances in data analysis have focused on extracting the elements that make up the temporal dynamics in terms of patterns of activity or connectivity. Based on this, brain states can be defined, and then an analysis can be performed using temporal features and computational models to capture subtle interactions between functional networks.

These new methodologies allow to deconstruct the rich spatio-temporal structure of functional components that are dynamically assembled in networks of rest state, which have been observed for a long time using conventional measures of functional connectivity. Applications of these new methodologies demonstrate that changes in functional connectivity are driven by a complex reorganization of network interactions and therefore provide valuable information to build better models of brain function.

An overview of these methodologies is provided below, as well as the main findings and perspectives for future research.

Classical methods

The discovery of functional magnetic resonance imaging (fMRI) greatly contributed to the understanding of how the brain works [1]. Just 20 years later, today's modern functional magnetic resonance imaging systems have evolved dramatically, allowing coverage of the entire brain with a spatial resolution of millimeters and a temporal resolution of less than one second.

The fMRI technique has been used in two completely different ways.

- *Task-based* fMRI. In this case, brain activity is recorded while the individual is performing a certain task. The brain activity that is recorded is a signal dependent on the level of oxygenation of the blood (blood-oxygen-level-dependent, BOLD). With this technique, a statistical *parametric map* can be performed that shows the parts of the brain that show signs of activity.

However, and beyond the extent that fMRI technology has advanced, the BOLD response is very slow and this is a limiting factor in determining the temporal characteristics of brain responses [2].

- *Resting-state* fMRI. In this case, brain activity is recorded while the individual is not performing any task and can freely engage into a process of *mind-wandering* [3]. Spontaneous brain activity in *resting-state* provides information on how distributed brain regions integrate into large-scale functional networks [4], and today it is a widely used technique.

The analysis of the data obtained is based on functional connectivity, which is a measure of statistical dependence between a couple of cycles of fMRI activity time [5], and exploratory multiveriate methods such as *independent component analysis* (ICA), and *graph modeling* (GM) are often used.

Conventional *resting-state* fMRI analyzes are based on the average behavior during a full fMRI run of several minutes, showing dissociated functional networks, thus missing important characteristics of the dynamics of network interactions [6]. Several recent studies have revealed that these ongoing interactions (for example, between high-level networks during *mind wandering*) [7], can be characterized using a new *time-resolved analysis* [8], which is based on a set of more advanced technologies.

The following is a brief summary of the different *time-resolved* fMRI data analysis methods, which have been proposed since the first reports of moment-to-moment fluctuations in *functional connectivity* [9].

All of these methods were designed for *resting-state* fMRI studies, but can also be used in *task-based* fMRI studies [10].

1. *Temporal dynamics methods*

The first time that the organization of the functional network was verified from the fMRI *restig-state* data, it was based on the functional connectivity measured by the *Pearson* correlation coefficients between pairs of fMRI *time series*. As a result, a symmetric connectivity matrix could be obtained, usually called as *functional connectome*. However, since the correlational measures reflect the average behavior during the complete execution of fMRI, moment-to-moment fluctuations in functional connectivity are lost, and these fluctuations can be very useful to understand the dynamic functioning of the brain. To remedy it three techniques have been developed:

1.1. *Sliding-window correlations* (SWC).

With this method, functional connectivity is calculated over shorter periods of time [11] (Fig. A3.1). However, this method also has some methodological problems, such as limited statistical power [12], as well as the possible false fluctuations induced by aliasing of the low frequency components [13].

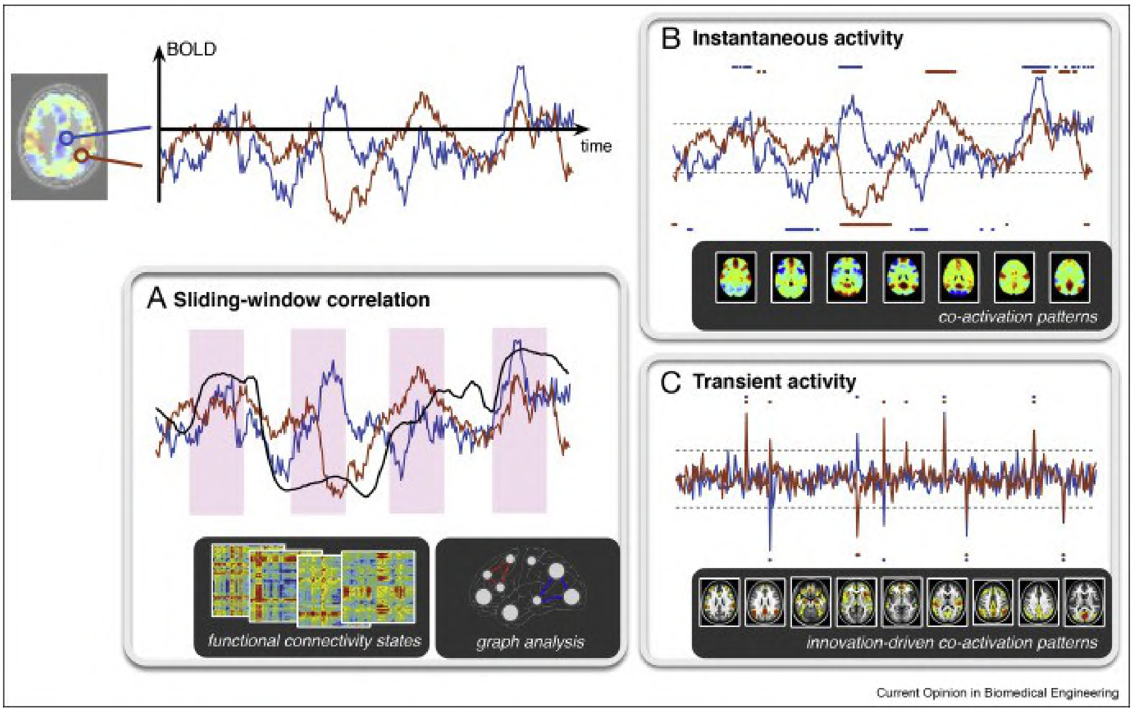

Figure A3.1. Elements of temporal dynamics.
A. *Sliding-window correlation* (SWC). With this method the functional connectivity model is transformed into time-dependent measures. For each position of the window, all the connection pairs form a *connectome* that can be analyzed in much more detail using clustering or decomposition methods.
B. *Instantaneous activity*. Clustering identifies different spatial configurations in which the selected regions are co-activated.
C. *Transient activity*. Posterior thresholds identify spatial patterns that occur at these critical times.
(Source: Karahanoğlu, F. I., & Van De Ville, D. (2015). Transient brain activity disentangles fMRI resting-state dynamics in terms of spatially and temporally overlapping networks. *Nature Communication*, 6, 7751)

1.2. *Instantaneous activity patterns*. Rather than measuring possible changes in connectivity, fluctuating brain activity can also be captured by a time-resolved analysis of instantaneous activity patterns. This new method is based on the creation of thresholds [14], to mark timepoints when activity exceeds a certain level (Fig. A3.1).

1.3. *Transient activity*. Thresholds can be applied to other representations of the activity time series. For example, a regularized deconvolution method can be used that incorporates knowledge about the hemodynamic system, and with this not only the deconvoluted activity-inducing signal can be obtained, but also its derivative, the so-called *innovation signal* [15]. This signal encodes transients in terms of positive and negative peaks for increases and decreases in activity, respectively (Fig. A3.1).

2. *Large-scale brain dynamics models*

To examine the complex dynamic interactions of the brain, including neural network docking and interactions, as well as their alterations, generative and computational time models are needed to systematically examine the richness of brain dynamics.

There are several methods for examining network dynamics, three of which stand out today.

2.1. *Hidden Markow models* (HMMs). It is a method to carry out a systematic evaluation of the sequences and temporal interactions of large-scale networks (Fig. A3.2). Currently, the HMM model is used for states of covariance in terms of a sparse base of co-activation patterns [16]. New methods have also been performed supplying SWC measurements to HMMs to study the temporal characterization of the network topology in temporal lobe epilepsy [17], and post-traumatic stress disorder [18]. In general, HMMs have been used to model activity sequences [19], including validation in large numbers of subjects [20].

2.2. *Sparely coupled hidden Markow models* (Sparely coupled HMMs). The activation patterns that characterize HMM states are typically intrinsic functional network mixtures due to temporally overlapping activity. An alternative method [21] is to use the transient activity of the iCAP framework as input to a set of parallel but loosely coupled HMMs [22], which then allows modulating influences to be explicitly captured rather than collected as mixing activity (Fig. A3.2).

2.3. *Maximum entropy model* (MEM). It is a recent method of statistical mechanisms, where local minima in an entropy-driven energy landscape form attractor states [23] (Fig. A3.2).

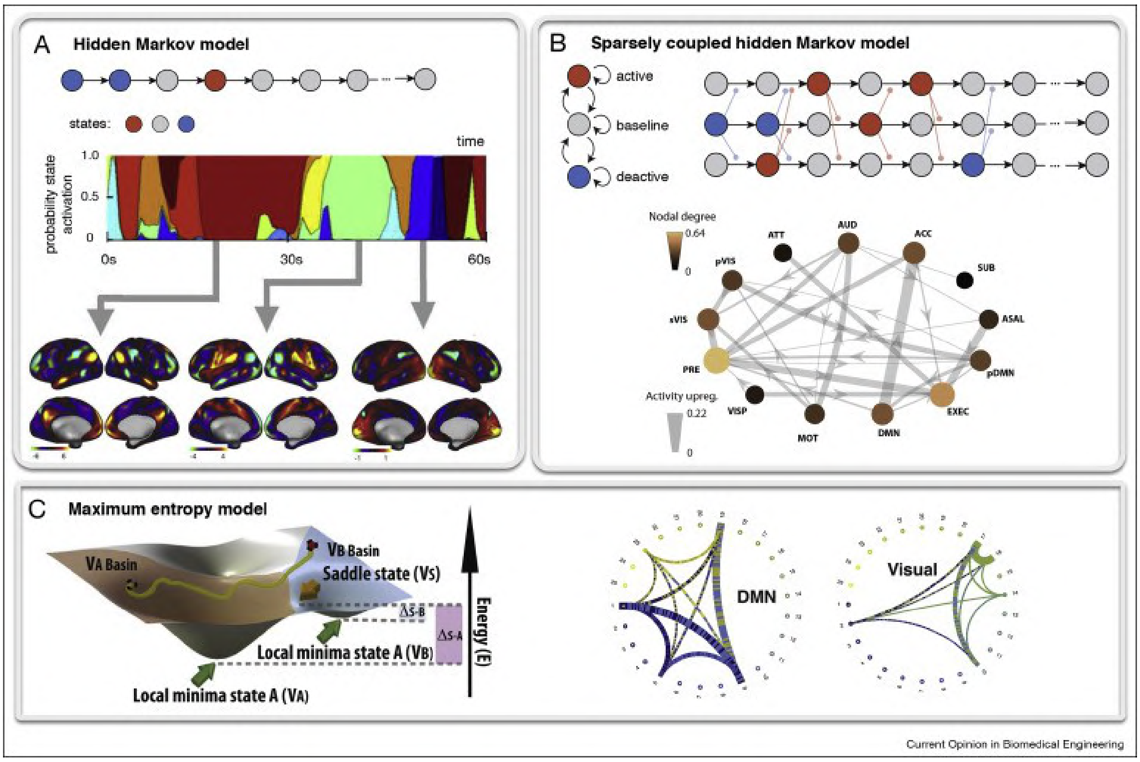

Figure A3.2. Temporal modeling approaches.
A. Hidden Markov Models (HMMs) are used to discretize the dynamic sequencing of brain states (adapted from: Vidaurre, D., Abeysuriya, R., Becker, R., Quinn, A. J., Alfaro-Almagro, F., Smith, S.M. et al. (2017). Discovering dynamic brain networks from big data in rest and task. *NeuroImage*, 10.1016 / j.neuroimage.2017.06.077). The states of the brain can be defined both at the level of activity and at the level of connectivity.
B. Sparsely coupled HMMs exploit the transient activity to model coupling between states.
C. Information theoretic approaches (for example: energy landscapes driven by entropy between different brain áreas) can be used to model the community-based interactions. The functional modules at the local minimum states drive the functional dynamics
(adapted from: Ashourvan, A., Gu, S., Mattar, M. G., Vettel, J. M. & Bassett, D. S. (2017). The energy landscape underpinning module dynamics in the human brain connectome. *NeuroImage*, 157, pp. 364-380).

Network dynamics viewpoint on brain function

Current new computational technologies have allowed new perspectives to characterize the dynamic behavior of the brain, and this in turn has opened new perspectives in research (Fig. A3.3).

These new technologies, and these new perspectives, are valid for both *task-based* fMRI and *resting-state* fMRI. Complementarily, the availability of additional behavioral, neuropsychological or clinical data should improve and optimize these new research models of brain activity.

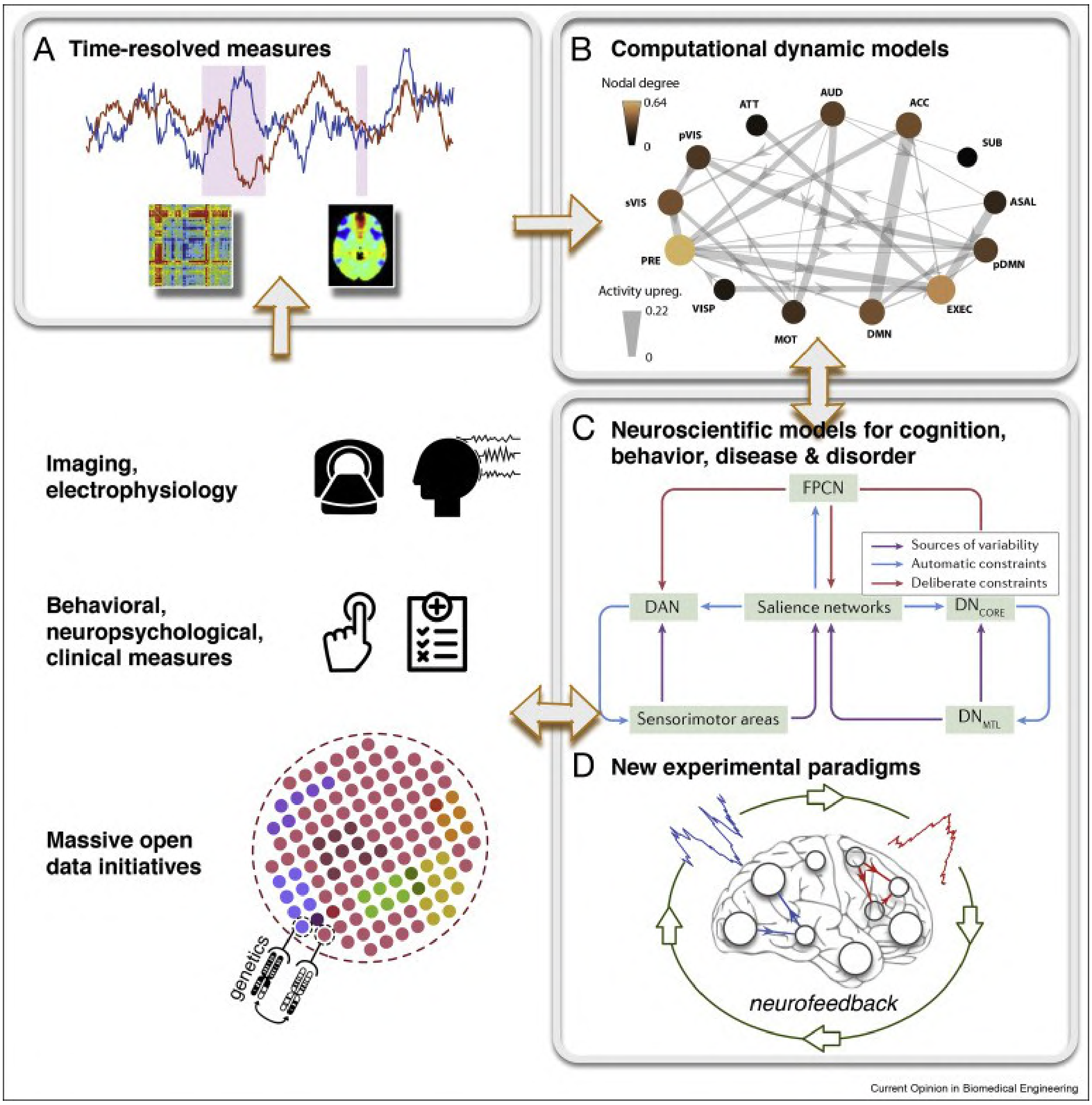

Figure A3.3. Network dynamics viewpoint on brain function
A. *Time-resolved measures of brain* activity
B. *New computational models* (support new neuroscientific models)
C. *Neuroscientific models* (inspired by computational models)
D. *New experimental paradigms* (based on computational models)
(Source: Karahanoğlu, F. I., & Van De Ville, D. (2015). Transient brain activity disentangles fMRI resting-state dynamics in terms of spatially and temporally overlapping networks. *Nature Communication*, 6, 7751)

The dynamic network interaction model must reformulate the way it supports coordinated cognition when integrating perception, attention, goal-directed thinking and learning [24]. The understanding of adapting to a constantly changing environment must also be reformulated through a flexible network organization. The interaction and balance between the three fundamental networks in human cognition (DMN, ECN, SN) could also be reformulated [25]. Recently, also a dynamic perspective has also been put forward for spontaneous thoughts based on continuously interacting networks [26].

The fMRI BOLD signal is the bottleneck of any method, since it is an indirect and slow hemodynamic substitute for the neuronal signal and, therefore, it is essential that the biophysics of the spatio-temporal hemodynamic response evolve for the realization of future fMRI data analysis [27]. In the same way, functional magnetic resonance acquisition systems should be improved, and the information should be complemented with other neuronal signals such as *electroencephalography* (EEG) or *intracortical recordings* [28]. Molecular mechanisms such as *gene transcription patterns* [29], or *cerebral Aβ* measured by positron emission tomography (PET) [30] could also be added.

Future perspectives

There are new dynamic methodologies that can undoubtedly be very useful in the coming years:

1. *Dynamic network models* to improve *neurostimulation or neurofeedback strategies* [31]. For example, real-time fMRI can be used to feedback the activity level of a single brain region [32], while network measures could target more relevant interactions on a large scale [33].

2. The resting-state fMRI methodology provides great hope by being able to define image-based biomarkers for the early diagnosis and prognosis of neurodegenerative and neurodevelopmental conditions [34]. Combined massive MRI data acquisition systems with sharing initiatives [35], better models can be achieved to accurately capture dynamic processes.

Notes appendix 3

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