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NUMBER REPRESENTATION IN BILINGUALS
THE ROLE OF EARLY LEARNING IN THE MENTAL NUMBER LINE REPRESENTATION

Tesis Doctoral

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La Dra. Elena Salillas, el Dr. Manuel Carreiras, ambos investigadores del centro Basque Center on Cognition Brain and Language y el Dr. Manuel Perea, profesor de la Universitat de València,

DECLARAN:

Que el trabajo titulado “Number representation in bilinguals. The role of early learning in the mental number line representation”, que presenta Cristina Gil López para la obtención del título de doctor/a, se ha realizado bajo nuestra dirección y cumple los requisitos para poder efectuar su defensa.

Y para que así conste y tenga los efectos oportunos, firmamos el presente documento.

Dra. Elena Salillas Pérez   Dr. Manuel CarreirasValiña   Dr. Manuel Perea Lara

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Resumen amplio en castellano en conformidad con el artículo 7.2 del reglamento que rige la evaluación, depósito y defensa de tesis doctorales de la Universitat de València (28 /2012)

Introducción

La presente tesis tiene como **objetivo** el estudio de la matemática bilingüe dentro del ámbito científico de la Cognición Numérica. El abordaje de cómo las personas bilingües representan y acceden a la magnitud es actualmente una cuestión de creciente interés que responde a la necesidad de entender el papel que desempeña el lenguaje en la adquisición temprana de las matemáticas. Esa importancia se ve reflejada habitualmente en el contexto de la educación, en donde el aprendizaje de la aritmética y el bilingüismo concurren de forma natural. Dada la importancia que tiene en nuestra sociedad tanto la adquisición de las matemáticas como el aprendizaje de una segunda lengua en edades tempranas, es necesario su estudio y abordaje desde el ámbito de la Neurociencia Cognitiva.

Con el fin de entender en mayor profundidad los mecanismos neurocognitivos que subyacen al manejo de los números en las personas bilingües, el presente estudio aborda la cuestión del papel que el aprendizaje temprano de las matemáticas en una de las dos lenguas naturales del bilingüe, tiene en la representación del número. Para ello, se han diseñado tres experimentos utilizando la técnica de electroencefalografía, la cual permite una buena resolución temporal de la actividad neuronal que acompaña a la función cognitiva. Presentaré, a continuación, una descripción breve del marco teórico que ha motivado el presente estudio, así como de la metodología, resultados y conclusiones más importantes de los tres experimentos incluidos en esta tesis y que son de gran interés para el avance teórico en la materia que nos ocupa.

Antecedentes del tema de investigación

La representación numérica parte del concepto de apreciación aproximada de la magnitud, la cual es innata e independiente de cualquier formato o código numérico. Esta representación inicial evoluciona a medida que se va adquiriendo el conocimiento exacto de las cantidades a partir del aprendizaje de la secuencia de conteo y los hechos aritméticos. La instrucción formal de las matemáticas permite la comparación y manejo de grandes cantidades de manera exacta. Sin embargo, la apreciación rápida e inexacta de la magnitud conforme al llamado "código abstracto de la representación de la magnitud" no se pierde tras la adquisición de la aritmética exacta. Más bien, se entiende que es maleable o susceptible de ser modificado por factores externos tales como el lenguaje y el aprendizaje de las matemáticas.

Uno de los aspectos más llamativos dentro de la teoría de la representación numérica es la asociación entre **espacio y número**. Se sabe que la información numérica está fuertemente asociada a una representación espacial de izquierda a derecha, análoga a una línea numérica mental (LNM). Así, los números referidos a cantidades grandes quedarían representados en el lado derecho mientras que los números de cantidades menores estarían representados en el lado izquierdo de esta línea horizontal imaginaria. Esta representación se activa automáticamente cuando la información numérica se presenta en cualquiera de las modalidades o formatos numéricos, ya sea verbal, arábico o simbólico. De acuerdo con la hipótesis de la LNM (Moyer and Landauer, 1967; Restle, 1970; Dehaene et al., 1993; para una revisión amplia ver Hubbard, 2005), dicha representación se origina a partir del código básico de la magnitud y evoluciona concurrentemente cuando el niño aprende el valor exacto que le corresponde a cada símbolo o notación numérica.

Uno de los efectos más robustos que demuestran hasta la fecha la existencia de una LNM proviene del estudio del efecto SNARC *("Spatial Numerical Association of Response Codes";* Dehaene, Bossini y Giraux, 1993): en una tarea de comparación numérica que requiere de una respuesta manual, los números pequeños activan un patrón de respuesta más rápido cuando se responden con la mano izquierda mientras que los números mayores se responden más rápido con la mano derecha. Esto ocurre incluso en tareas en donde no se requiere un procesamiento de la magnitud para ejecutar la tarea como puede ser decidir si un número es par o impar. El efecto SNARC, por tanto, sugiere que la representación numérica tiene un componente espacial sensible a las posiciones relativas de la información numérica en el lado izquierdo y derecho. Además del efecto SNARC, existen en la literatura estudios basados en los llamados e*fecto de distancia* [1] y *de tamaño*[2]. En general, los estudios que evalúan dichos efectos en tareas de comparación y cálculo numérico demuestran la existencia de una asociación del espacio con la representación interna de la magnitud (véase Moyer and Landauer, 1967; 1973; Parkman, 1971; Browne, 1906; Dehaene, 2003).

Otros estudios realizados con pacientes con heminegligencia también aportan evidencia sólida a favor de la hipótesis de la LNM (Zorzi, Priftis y Umiltà, 2002). Los pacientes con heminegligencia cerebral ignoran los estímulos presentados en el lado opuesto al hemisferio lesionado (habitualmente suele ser el derecho). En tareas de bisección de líneas o de intervalos numéricos, los pacientes cometen un sesgo a la hora de señalar el punto central. Generalmente, desplazan hacia la derecha el centro

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[1]Es un efecto conductual que se observa en tareas de comparación numérica. Demuestra que a medida que la distancia relativa entre dos magnitudes aumenta, resulta más fácil y rápido discriminar ambas cantidades entre sí.

[2]En una tarea de comparación, dada la misma distancia relativa entre dos cantidades numéricas (ej. 2-4 y 7-9), se produce una peor ejecución cuando se incrementa la magnitud de los números (i.e. se produce una mejor ejecución para los números menores).

de dicha línea o intervalo numérico. Lo que estos y otros estudios sugieren es que el concepto de magnitud se basa en una representación mental de la LNM y no en un marco de referencia espacial extracorpóreo.

Además de la relación entre número y espacio, el actual marco teórico también contempla el **papel que el lenguaje** adquiere en la cognición numérica. Los estudios que se han llevado a cabo demuestran que el lenguaje cumple una función importante dentro del procesamiento numérico debido a que los hechos aritméticos (sumas, restas, multiplicaciones) se aprenden y recuperan de forma verbal. Sin embargo, existe escasa evidencia empírica acerca de cómo impacta el lenguaje en la representación básica de la magnitud. Es decir, qué efectos tiene el lenguaje en el conocimiento numérico abstracto innato, aquel que como bien se ha dicho, es pre-verbal e independiente del cualquier formato. De hecho, lo modelos generales que explican el funcionamiento de la cognición numérica sólo contemplan vagamente el papel del lenguaje dentro del contexto de los hechos aritméticos (Campbell and Clark, 1988, 1992; Campbell, 1994; Campbell and Epp, 2004; Dehaene and Cohen, 1995; Dehaene et al., 2003; McCloskey et al., 1985; McCloskey, 1992). La conclusión actual es que el lenguaje no es imprescindible para tener acceso al sentido de la magnitud pero sí favorece la adquisición y manejo de conocimientos matemáticos más complejos (Butterworth, 2010; Carey, 2001; Delazer et at., 2005; Gelman and Butterworth, 2005; Nieder and Dehaene, 2009; Piazza, 2010; Spelke and Tsivkin, 2001; Salillas and Carreiras, 2014). Sin embargo, más allá del contexto de los hechos aritméticos, apenas hay estudios sobre cómo impacta el lenguaje en el llamado *código básico de la magnitud.* Dicho código de representación numérica está presente desde el nacimiento y es compartido con otras especies animales (Dehaene, 1996, 2001).

Una manera de conocer el papel que desempeña el lenguaje en la representación numérica es a través del fenómeno del **bilingüismo**. Las personas bilingües que han aprendido dos lenguas a edades tempranas (0-5) y tienen una competencia lingüística similar en ambas lenguas (bilingües balanceados) ofrecen un contexto idóneo para el estudio del efecto del lenguaje en la representación de los números. La investigación actual parte de la idea de que hay un código verbal preferido por los bilingües para las matemáticas (Spelke & Tsivkin, 2001). Concretamente, se ha comprobado que los bilingües activan sólo una de las dos lenguas para el manejo de los hechos aritméticos (Campbell & Epp, 2004; Rusconi et al., 2007). Este código verbal o lengua de preferencia a veces coincidía con la lengua de mayor nivel de competencia o L1 (Frenk-Mestre & Vaid, 1993). Sin embargo, estudios recientes sugieren que la lengua que mayormente se activa, no sólo para los hechos aritméticos sino también para la representación básica del número, es la lengua de aprendizaje de las matemáticas (LL^{math}). Curiosamente, la lengua de aprendizaje de las matemáticas no necesariamente coincide con la L1; por tanto, no es el dominio de la lengua lo que determina la relación entre lenguaje y el código de magnitud abstracto (Salillas & Carreiras, 2014). El aprendizaje temprano de las matemáticas favorece la conexión de una de las dos lenguas con el conocimiento básico de la magnitud. La evidencia empírica sugiere que la LL^{math} (la lengua del aprendizaje de las matemáticas) impacta en la representación básica de la magnitud dejando una huella verbal que favorece el procesamiento numérico de manera automática (Salillas & Carreiras, 2015, Salillas et al., 2015).

Otro de los pilares de interés en el estudio de la cognición numérica tiene que ver con la función que cumple la **memoria de trabajo** en la realización de tareas numéricas como el cálculo, discriminación o comparación de cantidades. La memoria de trabajo es una función ejecutiva modular que, de acuerdo al modelo de Baddeley y Hicth (1974), se compone de un bucle articulatorio fonológico, un almacén visuo-espacial y un sistema ejecutivo central. Su implicación es fundamental para el desarrollo de las habilidades numéricas como así lo demuestran los resultados de estudios sobre capacidad de memoria de trabajo y rendimiento en resolución de problemas matemáticos (DeStefano & LeFevre, 2004). De hecho, la capacidad limitada en memoria de trabajo se ha relacionado con dificultades en el desarrollo de la competencia numérica (ver revisión de Raghubar, Barners & Hecht, 2010). Además de su implicación en tareas cálculo numérico, la memoria de trabajo también cumple un papel importante en la representación numérica. Concretamente, se ha demostrado que el componente visuo-espacial de la memoria de trabajo tiene una implicación significativa en el procesamiento del componente espacial asociado a la representación del número (Herrera, Macizo y Semenza, 2008).

Hasta aquí, he ofrecido un breve repaso de las tres líneas teóricas sobre las que se basa el trabajo de investigación de la presente tesis. En primer lugar, he recordado dos conceptos fundamentales que definen la representación numérica: el código de representación básica de la magnitud y la relación entre número y espacio. He seguido con un resumen sobre las principales propuestas teóricas que se refieren al papel del lenguaje en la representación numérica. Además, basándome en la evidencia empírica reciente, he destacado el interés que suscita el fenómeno de la matemática bilingüe para estudiar el papel del lenguaje en la representación y procesamiento numérico. Por último, he querido subrayar la importancia que tiene la memoria de trabajo en el procesamiento numérico, concretamente en la relación entre espacio y magnitud numérica.

La presente investigación

El presente trabajo de investigación estudia el impacto que la LL^{math} tiene en la representación de la LNM en bilingües balanceados castellano-euskera. Dado que no hay evidencia empírica concluyente acerca de cómo los bilingües acceden y se representan la magnitud numérica y tampoco los modelos teóricos lo contemplan de forma explícita, es preciso investigar los mecanismos cognitivos que conectan el lenguaje con el concepto básico de magnitud y con ello, la representación de la LNM. Siguiendo la línea de investigación de Salillas y Carreiras (2014) sobre el impacto de la LL^{math} en el código básico de la magnitud numérica, este estudio indaga en los efectos que tienen el aprendizaje temprano de las matemáticas en la relación entre número y espacio. Por tanto, el principal objetivo ha sido la investigación de cómo los bilingües activan y recuperan la línea numérica mental cuando la información numérica coincide con la LL^{math} en comparación con la Otra Lengua (OL). Un segundo objetivo se ha centrado en evaluar cómo impactan en la memoria de trabajo la manipulación y retención de la información numérico-espacial cuando ésta se presenta verbalmente en cada una de las dos lenguas (LL^{math} y OL).

La principal hipótesis mantiene que la representación de la LNM en los bilingües está fuertemente ligada con el código verbal que corresponde con la LL^{math}, generando así un procesamiento automático de la información numérico-espacial. Por tanto, se predice que los procesos cognitivos que conectan la relación espacio-número con la LL^{math} deben ser distintos a aquellos otros que conectan con la OL. Estas diferencias pondrían de manifiesto el impacto que el aprendizaje temprano de las matemáticas tiene sobre la representación básica de la cantidad, la cual incluye el componente espacial o LNM. Puesto que los aprendizajes tempranos dejan una huella mnémica importante en la memoria a largo plazo, se espera que la recuperación de la representación de la LNM conlleve un proceso cognitivo más automático cuando la información numérica se presenta en la LL^{math}. Con respecto a los efectos del aprendizaje temprano durante la manipulación de la información numérico-espacial en la memoria de trabajo, nuestro estudio predice una mayor carga cuando la información se presenta en la OL y, por tanto, un mayor coste de procesamiento cognitivo.

Cabe reseñar, no obstante, que aunque el presente estudio contempla los mecanismos de procesamiento asociados a la memoria de trabajo (codificación, recuperación y retención), no es nuestro objetivo sacar conclusiones sobre el rol que ejerce en la manipulación de estímulos numéricos. Más bien, qué efectos tiene el factor de aprendizaje temprano de las matemáticas sobre el rendimiento de la memoria de trabajo y qué patrones de respuesta cerebral desencadena en la codificación, recuperación y retención.

Para tal fin, se han diseñado tres experimentos basados en un paradigma de memoria de trabajo usando la técnica de electroencefalografía (EEG) y el método de análisis de potenciales relacionados con eventos (ERPs). La electroencefalografía es el registro y evaluación de los potenciales eléctricos generados por el cerebro y obtenidos por medio de electrodos situados sobre la superficie del cuero cabelludo. Por medio de ésta técnica esperamos registrar el patrón de respuesta cerebral asociado a la actividad cognitiva subyacente. De hecho, existen estudios previos con EEG que comparan la influencia de la lengua de aprendizaje de la aritmética en tareas de cálculo (Salillas & Wicha, 2012) donde se aprecian diferencias en los principales componentes ERP asociados a cada una de las dos lenguas. También se ha estudiado con esta técnica, el impacto de la LL^{math} en la representación básica de la magnitud (Salillas & Carreiras, 2014; Salillas et al., 2015). En esta línea, en los tres experimentos realizados con EEG se espera encontrar diferencias cuando se activa y retiene la presentación de la LNM con la LL^{math} y con la OL.

A continuación presentaré un breve resumen de los objetivos, métodos y conclusiones más importantes de cada uno de los tres experimentos.

Experimento 1

El objetivo general del Experimento 1 fue estudiar el impacto de la LL^{math} en la representación de la LNM dentro del contexto de una tarea de memoria de trabajo. Concretamente, cómo se activa esta representación durante la codificación, recuperación y retención de la información numérico-espacial presentada en la modalidad visual. Para ello, se ha utilizado la técnica de electroencefalografía y método de ERPs que permite obtener patrones de respuesta eléctrica cerebral provocados por un determinado proceso cognitivo. En éste experimento el principal foco de interés era ver si existen diferencias en cuanto a los componentes ERPs, distribución topográfica y curso temporal durante la actividad vinculada a cada uno de los estadios de procesamiento de la memoria de trabajo.

Método

Participantes

Un total de 14 participantes adultos de edades comprendidas entre 19-30 años fueron seleccionados para participar de forma voluntaria en este estudio. Todos ellos eran bilingües balanceados Castellano-Euskera que reportaron haber adquirido ambas lenguas en una edad comprendida entre los 0 y los 4 años. La frecuencia de uso diario de ambas lenguas era similar. La competencia lingüística de cada participante se evaluó con la versión español-euskera del *Boston Naming Test* (Kaplan, Goodglass, and Weintraub.,1983; Salillas and Wicha, 2012). Con respecto a la lengua de aprendizaje de las matemáticas, la mitad de los participantes aprendió las matemáticas en castellano y la otra mitad las aprendió en euskera.

Tarea y Diseño experimental

Los estímulos que se utilizaron para este experimento fueron ocho palabras-número (del 1 al 9 sin contar el 5), cuatro figuras cuadradas y un punto de fijación. En una tarea de memoria de trabajo (v.g. match-to-sample-task) consistente en memorizar una secuencia de cuatro palabras-número posicionadas dentro de una figura – cuadrado, el participante debía retener dicha secuencia y juzgar si la localización en la figura de una palabra-objetivo presentada posteriormente, era correcta o incorrecta. Las figuras aparecían dispuestas horizontalmente. Cada palabra-número se presentaba una sola vez dentro de una de las figuras. La duración y el intervalo entre estímulos fue de 400ms. Tras un periodo de retraso de 800ms, le seguía un número-test por un máximo de 2000ms o hasta que el botón de respuesta era pulsado por el participante.

El Experimento contó con dos factores experimentales: congruencia espacial de la magnitud numérica con la LNM (Congruente vs incongruente) y el aprendizaje temprano de las matemáticas (LL^{math} vs OL). Así, en los ensayos congruentes se presentaban los números de magnitud mayor (6,7,8,9) en los cuadrados de la derecha y los números de magnitud menor (1,2,3,4) en los de la izquierda. En los ensayos incongruentes ocurría lo contrario. Cada ensayo congruente e incongruente se presentaba aleatoriamente en castellano o en euskera el mismo número de veces. La estructura y presentación de los ensayos del bloque experimental fue idéntica para cada uno de los participantes, independientemente de que su perfil de LL^{math} fuera castellano o euskera, lo que permitió que pudiera colapsarse para su análisis estadístico (i.e. LL^{math}: Castellano+Euskera).

Procedimiento

Cada participante realizó la tarea en una habitación adaptada para grabación de EEG, la cual se encontraba insonorizada y aislada de interferencias eléctricas. Se les instruyó para que respiraran de forma suave y evitaran moverse durante la sesión experimental. Su mirada debía estar dirigida hacia el centro de la pantalla. Cada ensayo comenzaba con un punto de fijación, continuaba con la presentación fija de las cuatro figuras cuadradas y avanzaba con la presentación dinámica de cada una de las cuatro palabras-número. A esta secuencia la seguía un intervalo de retraso la cual precedía a un número-test. Al final de la sesión, todos los participantes respondían a un cuestionario corto de preguntas relacionadas con la ejecución de la tarea y reportaban un feedback sobre la pauta seguida para realizar la tarea. La duración total de la sesión fue de 1h 30min incluyendo descansos.

La actividad eléctrica cerebral (EEG) se grabó con 27 canales dispuestos en su colocación según el sistema internacional estándar 10/20. Los electrodos se colocaron sobre un gorro elástico de la marca registrada “Easy-cap”. Para el registro de la actividad eléctrica producida por el movimiento de los ojos se utilizaron cuatro electrodos más: dos en el canto externo de ambos ojos y dos en la órbita ocular inferior. La señal de EEG se referenció online a los mastoides izquierdo y derecho. Las impedancias se mantuvieron por debajo de los 5kΩ para todos los electrodos. El registro de la actividad se amplificó y digitalizó a una frecuencia de muestreo de 1000Hz. Durante la adquisición de los datos, a la señal de EEG se le aplicó un filtro de banda de 0.001-100Hz. Las señales altas y bajas se corrigieron con un filtro digital de banda baja (30Hz) y de banda alta (0.1Hz), respectivamente. Se obtuvo una línea base de 200ms correspondiente a la actividad promedio de la señal que precede al procesamiento del primer estímulo.

Los análisis llevados a cabo tuvieron en cuenta inicialmente un análisis de varianza (ANOVA) global que incluyó los 27 electrodos junto con el contraste de las condiciones de Lenguaje (2) x Congruencia (2). El motivo era comprobar los efectos generales de congruencia y las posibles interacciones del factor congruencia por electrodo y lenguaje. Posteriormente, se realizaron también ANOVAs separados para la condición de lenguaje. Aquí se tuvo en cuenta los efectos de congruencia y las interacciones por electrodo, lo que llevó a explorar también los efectos individuales en regiones de interés. El objetivo fue investigar el perfil topográfico particular de cada una de las dos lenguas (LL^{math}/OL) tras conocer los efectos de congruencia. Se establecieron, por tanto, cuatro regiones de interés (Anterior-Izquierda, Anterior-Derecha, Posterior-Izquierda y Postertior-Derecha) cuya partición siguió los criterios hallados en la literatura para conocer patrones de actividad eléctrica cerebral anterior y posterior así como las lateralizaciones hacia el hemisferio izquierdo y derecho (i.e. Anterior-Izquierdo, Anterior-Derecho, Posterior-Izquierdo, Posterior-Derecho).

Resultados y conclusiones

El objetivo de este estudio era comprobar si el aprendizaje temprano de las matemáticas con un de las dos lenguas influye en el procesamiento de la representación de la LNM. Los resultados indican un patrón de respuesta cerebral (ERP) distinto para la LL^{math} en comparación con la OL. A continuación se describen los efectos mostrados asociados a los siguientes componentes ERP:

- **N1-P2p:** Interacción Congruencia x Lenguaje. Un efecto de congruencia principal para ambas lenguas aparece durante la codificación de la información numérica-espacial. No obstante, el patrón de distribución es distinto entre ambas lenguas. Vemos que en LL^{math} los efectos siguen un patrón posterior derecho mientras que en OL la distribución es más bilateral.

- **N400-like:** Se muestra una interacción Congruencia x Lenguaje. El efecto de congruencia aparece durante la etapa de recuperación de la LNM sólo en la condición de LL^{math} mientras que para la OL no se apreciaron diferencias significativas.

- **Onda lenta negativa (nSW):** Los datos muestran un efecto de triple interacción Electrodo x Congruencia x Lenguaje durante el periodo de retraso correspondiente a la etapa de retención. Este efecto aparece sólo significativo para la condición de la LL^{math} y más fuertemente distribuido en la región de interés Anterior-Derecho. Ello sugiere que efectos más duraderos y consistentes subyacen durante el procesamiento de la congruencia cuando la activación de la LNM se produce desde la LL^{math} .

A partir de estos resultados se concluye que los mecanismos que subyacen cuando se activa la representación de LNM desde el formato numérico de la LL^{math} son diferentes de aquellos otros asociados con la OL. Por un lado, la activación se produce en ambas lenguas pero se distribuye de forma distinta. Además, la activación de la LNM se mantiene durante más tiempo en la memoria de trabajo cuando los números son manipulados en la condición de LL^{math}. Ello sugiere un procesamiento de la congruencia numérico-espacial más fuerte en la LL^{math} la cual activa automáticamente la LNM. Por otro lado, el procesamiento de la congruencia con la OL es menos sostenido durante el curso temporal del periodo de recuperación y retención en memoria de trabajo. En conclusión, este experimento apoya la hipótesis de una posible huella cognitiva a largo plazo asociada a la LL^{math} que activa automáticamente el sistema de representación de la LNM de los bilingües.

Experimento 2

El siguiente experimento tiene como objetivo profundizar en las diferencias entre LL^{math} y OL en una condición de mayor carga de memoria de trabajo. Se centra en evaluar cómo afecta el incremento de la dificultad en el proceso automático de activación y recuperación de la LNM desde la condición de lenguaje (LL^{math} vs OL). La principal hipótesis predice que la representación de la LNM está fuertemente ligada a la LL^{math} como consecuencia de la experiencia de aprendizaje temprano lo que resulta en una activación automática y de menor coste cognitivo en memoria de trabajo comparado con la OL. Para ello, se utilizó la misma tarea que la descrita en el Experimento 1 pero incrementando el número de estímulos a retener, por tanto la dificultad, durante la secuencia de memorización. A continuación, se resume el método y las conclusiones más relevantes del Experimento 2.

Método

Participantes

Catorce participantes diestros (11 mujeres, edad media 22 años) participaron voluntariamente en este experimento. Todos ellos eran bilingües Castellano-Euskera parlantes, con similar nivel de competencia lingüística para ambos idiomas y una edad de adquisición comprendida entre los 0 y los 4 años. La medición de la competencia lingüística se evaluó con el BNT adaptada al Español y Euskera (Kaplan, Goodglass, and Weintraub, 1983; Salillas and Wicha, 2012). La LL^{math} era castellano para la mitad de los participantes y euskera para la otra mitad. Con objeto de controlar la posible variabilidad entre sujetos, se midió la capacidad de memoria de trabajo con la batería de habilidades cognitivas de Woodcock-Johson III (test 7: Memorización de secuencia de números al revés; test 9: Memoria de trabajo auditiva).

Tarea y Diseño experimental

Los participantes realizaron una tarea de memoria de trabajo similar a la descrita en el Experimento 1, también en modalidad visual. Debían memorizar los estímulos (números-palabra) y la localización que ocupan dentro de una figura (cuadrado) para seguidamente juzgar un número test. En la secuencia de memorización se presentaba un total de cuatro o seis palabras-número, bien en castellano o bien en euskera. El intervalo entre estímulos y la duración fue idéntico al Experimento 1 (400ms). El periodo de retraso se amplió a 1100ms con objeto de conseguir una muestra más amplia de la actividad ERP que concurría con la retención. La respuesta era emitida presionando uno de los dos botones del mando (gamepad) según el participante juzgara como correcta o incorrecta la localización del número test (2000ms)

El diseño experimental incluyó las siguientes condiciones experimentales: Congruencia (C/I) x Lenguaje (LL^{math} /OL) x Carga de memoria (Alta/ Baja). En cada uno de los ensayos, las condiciones de congruencia y lenguaje seguían el mismo criterio que el descrito en el Experimento 1. Los ensayos de la condición carga de memoria baja presentaban cuatro palabras-número y los ensayos de la condición de carga de memoria alta presentaba seis. Se utilizaron un total de 576 ensayos presentados con idéntica estructura para cada condición. Tanto los ensayos presentados en castellano como los presentados en euskera eran los mismos para todos los participantes independientemente del perfil LL^{math}/ OL que tuvieran. Esto permitió analizar el factor de aprendizaje temprano colapsando ambas lenguas.

Procedimiento

El procedimiento llevado a cabo, tanto en la parte conductual como del registro de la señal EEG, fue el mismo que el aplicado en el Experimento 1. Los participantes que no siguieron las instrucciones que se les había pedido (estrategias, ruido en el registro debido a movimientos oculares y/o musculares) fueron excluidos del análisis. Al final de la sesión todos los participantes respondían a un cuestionario corto de preguntas relacionadas con la sesión y reportaban un feedback sobre la pauta seguida para realizar la tarea. Aquellos participantes con un porcentaje de errores elevado también fueron asimismo excluidos. La sesión experimental contó con un número de pausas alto para permitir una atención sostenida mayor. La duración total del experimento fue de 1h y 45 min.

Los análisis llevados a cabo siguieron el mismo proceder que el empleado en el Experimento 1. Se tuvo en cuenta primeramente un ANOVA global que incluyó los 27 electrodos y las condiciones de Lenguaje (2) x Congruencia (2). No obstante, dicho análisis global se hizo por separado para ambas condiciones de carga de memoria de trabajo. El motivo radica en el interés de esta tesis en conocer cómo afecta el formato verbal (LL^{math} y OL) al procesamiento de la congruencia número-espacio cuando aumenta la carga en memoria de trabajo. El efecto *per se* de memoria de trabajo o las posibles interacciones por lenguaje y congruencia quedan fuera del interés de este estudio. Posteriormente, se realizaron también los ANOVAs individuales y por regiones de interés de forma idéntica al Experimento 1.

Resultados y conclusiones

El experimento 2 de la presente tesis tenía como objetivo principal evaluar el efecto del aprendizaje temprano de las matemáticas en la representación de la LNM cuando se manipulan distintas cargas de memoria de trabajo. Por tanto, comparamos los patrones de repuesta ERP en la condición LL^{math} y OL para la condición de carga alta (6 estímulos) y baja (4 estímulos). Para el análisis, las dos lenguas (castellano y euskera) se colapsan según la condición LL^{math} y OL. Los análisis muestran diferencias de amplitud en el procesamiento de la congruencia en ambas lenguas pero en distintas ventanas temporales y con una distribución del potencial neuroeléctrico también distinto. A continuación se resumen los resultados más llamativos de éste experimento.

- **N1-P2**: efecto asociado a un procesamiento temprano de la codificación de la congruencia tanto en la condición de carga alta como baja. En ambas condiciones de carga de memoria de trabajo, el inicio es más temprano siempre para la LL^{math} (150 ms antes) en comparación con la OL.

- **N400-like**: efecto de congruencia asociado a la recuperación de la LNM. Aparece en ambas lenguas en la condición de carga de memoria baja mientras que en la condición de carga alta sólo es significativo en la condición de LL^{math} . Se aprecian también importantes diferencias en el patrón de distribución topográfico hallándose una tendencia lateralizada a localizaciones Anterior-Izquierdo en la OL y más bilateral, con tendencia hacia localizaciones Anteriores y Posteriores en algunas etapas del procesamiento, en la LL^{math}.

- **Onda lenta negativa (nSW)**: efecto de congruencia en la fase de retención para ambas condiciones de carga de memoria de trabajo siendo dicho efecto más fuerte para la LL^{math}. El efecto aparece significativo para la OL sólo en la condición de carga de memoria baja pero siguiendo un curso temporal y distribución distintas. Por tanto, se sugieren efectos más sólidos y cualitativamente distintos entre ambas lenguas ($LL^{math} > OL$).

Las principales conclusiones que se extraen de este experimento se enumeran a continuación:

1) La manipulación de información numérico-espacial con el formato verbal de la LL^{math} desencadena patrones de actividad cerebral diferentes de la OL. Esto sugiere que los procesos cognitivos implicados no son iguales.

2) Los resultados apoyan la hipótesis de una influencia duradera de la LL^{math} en la representación de la LNM debido al aprendizaje temprano en comparación con la OL.

3) La información numérico-espacial que activa la representación de la LNM conlleva un procesamiento en memoria de trabajo distinto en función del factor de aprendizaje temprano de las matemáticas.

En conclusión, los resultados del presente experimento sugieren que existen diferencias (i.e. cualitativas y cuantitativas) en los procesos cognitivos asociados a la representación de la LNM entre ambas lenguas. Por tanto, es posible considerar que la relación entre número y espacio en bilingües parece estar fuertemente influenciada por la LL^{math} .

Llegados a este punto, hemos descrito los dos experimentos centrados en investigar el impacto de la LL^{math} en la representación de LNM en bilingües, cuando la información numérica se presenta en la modalidad visual. A continuación, se describirá el tercer y último experimento de esta tesis, en donde los mismos objetivos se exploran en la modalidad auditiva.

Experimento 3

En consonancia con los estudios EEG que demuestran la influencia de la modalidad perceptual en tareas de memoria de trabajo, se diseñó un tercer experimento de características esencialmente similares al Experimento 2 pero desde un paradigma de memoria de trabajo audio-espacial. El motivo de añadir un tercer experimento en modalidad auditiva se debió al hecho de que los números en el formato verbal activan el procesamiento de la estructura fonética particular de cada palabra-número de manera más directa que en la modalidad visual. Por ello, era necesario contrastar si los efectos obtenidos en la modalidad visual también se daban en la modalidad auditiva, es decir, cuando los números se escuchan y el mecanismo de procesamiento se sabe diferente. Según lo referido en la literatura, en tareas de memoria de trabajo en modalidad auditiva, el lazo o bucle fonológico facilita el acceso de la información a las representaciones previas o de la memoria a largo plazo, de una manera más directa y rápida. A este efecto se le conoce como ventaja o sesgo fonológico (Baddeley, 2000).

Por tanto, el propósito del Experimento 3 se ha centrado en investigar los mismos objetivos de los dos experimentos anteriores pero en la modalidad auditiva. Para evitar redundar en este punto, referimos al lector a la lectura de los objetivos descritos en el Experimento 1 y 2.

Método

Participantes

Se seleccionaron 14 participantes diestros (7 mujeres, edad media 23 años) que se presentaron como voluntarios para este estudio. Todos eran bilingües balanceados Castellano-Euskera, evaluados con el BNT adaptado (diferencia <10 entre el número total de respuestas correctas en Castellano y el número total de respuestas correctas en Euskera). La edad de adquisición no superó los cinco años. La mitad de la muestra seleccionada reportó haber aprendido las matemáticas en castellano mientras que la otra mitad dijo haber aprendido en euskera. Al igual que en el experimento 2, los participantes también fueron evaluados en su capacidad de memoria de trabajo con la batería de habilidades cognitivas de Woodcock-Johnson III.

Tarea y diseño experimental

El paradigma experimental se basó en una tarea de memoria de trabajo similar al Experimento 2 pero en la modalidad auditiva. Se utilizaron como estímulos auditivos los números de una cifra correspondientes a cada lengua. El ensayo comenzaba con un punto de fijación situado en el centro de la pantalla. Los números se escuchaban de forma secuencial bien por el oído derecho o bien por el izquierdo. La duración de cada estímulo auditivo era de 500ms con un intervalo entre estímulos de 600ms. Entre la presentación del último número y el número-test, se estableció un periodo de "de retraso" de 1200ms. Seguidamente, se emitía binauralmente, un sonido clave para avisar al participante de la presentación del número-test (1900ms). El participante debía prestar atención a la localización (izquierda o derecha) de la palabra-test antes de juzgar si era correcto o incorrecto con respecto a la secuencia memorizada anteriormente. La respuesta debía darse lo más rápido posible presionando con la mano derecha uno de los dos botones (correcto o incorrecto) del mando o gamepad. Tras la respuesta, el participante debía recibir un feedback visual para las respuestas correctas e incorrectas. La presentación de los estímulos en lado derecho e izquierdo fue balanceada así como cada una de las condiciones experimentales. La lengua de presentación fue aleatorizada y por tanto, variaba entre ensayos pero no dentro de un mismo ensayo. El número total de ensayos fue de 576.

El diseño experimental incluyó las mismas condiciones que las del Experimento 2: Congruencia (C/I) x Lenguaje (LL^{math}/ OL) x Carga de memoria (Alta/ Baja). La misma estructura experimental se utilizó con todos los participantes independientemente del perfil lingüístico y todas las condiciones experimentales se colapsaron por igual en los análisis.

Procedimiento

El procedimiento llevado a cabo, tanto en la parte conductual como del registro de la señal EEG siguió los mismos pasos y mediciones que los aplicados en el Experimento 1 y 2. Los participantes que no siguieron las instrucciones que se les había pedido (estrategias, ruido en el registro debido a movimientos oculares y/o musculares) no fueron incluidos en los análisis. Tras realizar la tarea en una única sesión, los participantes respondían a un cuestionario corto de preguntas relacionadas con la sesión y reportaban un feedback sobre la pauta seguida para realizar la tarea. Aquellos participantes con un porcentaje de errores elevado se excluyeron del estudio. La sesión contó con un número de pausas alto para permitir una atención sostenida mayor. La duración total del experimento fue de 2h, aproximadamente.

Resultados y conclusiones

El principal objetivo del Experimento 3 fue investigar el efecto de la LL^{math} en la activación de la LNM cuando la información numérica parte de la modalidad auditiva. Al igual que en los experimentos 1 y 2, los análisis realizados tuvieron en cuenta primeramente un ANOVA global y posteriormente análisis específicos por regiones de interés. Los resultados obtenidos se resumen a continuación:

- **Onda lenta negativa (nSW):** componente asociado al procesamiento de la congruencia número-espacio durante la fase de codificación, recuperación y retención. Los efectos de congruencia sólo resultaron estadísticamente significativos para la LL^{math} en ambas condiciones de carga de memoria mientras que no fueron significativos para la OL (LL^{math} > OL).

- La **distribución** de los efectos en LL^{math} fue generalizada en la condición de carga de memoria baja. En la condición de carga alta, los efectos siguieron un patrón de distribución generalizado en las fases más tempranas del procesamiento y una distribución más lateralizada hacia localizaciones del hemisferio derecho en la fase de retención.

El conjunto de resultados mostrados en el Experimento 3 confirman un manejo distinto de la LNM en comparación con la OL también desde la modalidad auditiva. Los patrones cerebrales hallados en la condición de LL^{math} sugieren un proceso automático de activación y recuperación de la representación de la LNM a largo plazo. En cambio, el procesamiento con la OL implica procesos más lentos que además conllevan una carga en memoria de trabajo mayor. Por tanto, los resultados de este experimento sugieren que el factor de aprendizaje temprano de las matemáticas se encuentra integrado en las redes neuronales que subyacen a la representación numérico-espacial mientras que el acceso a la representación con OL conlleva procesos soportados por redes quizás más lingüísticas o menos dependientes del procesamiento espacial.

Conclusiones generales

Los resultados del presente estudio se enumeran a continuación:

- Primero, se muestran diferencias en el curso temporal de los principales componentes N1-P2 y nSW a nivel de procesamiento temprano de la congruencia número-espacio. Además el procesamiento de la congruencia cuando se lleva a cabo con la OL implica procesos más lentos con un aparente coste mayor en memoria de trabajo (i.e. reducción significativa los efectos en condición de carga alta).

- Segundo, se muestran diferencias en la distribución topográfica de los principales componentes ERP (N1-P2, N400-like, nSW) durante la codificación, recuperación y retención de la información congruente con la LNM. Se asocia un patrón lateralizado hacia la derecha en LL^{math} y más hacia la izquierda en OL en algunas etapas del procesamiento de la congruencia.

- Tercero, el aumento de la carga en memoria de trabajo afecta a la activación de la LNM sólo cuando la información se procesa en la OL pero no cuando ésta se procesa en la LL^{math}. A lo largo de los tres experimentos, vemos que los efectos de congruencia se mantienen para la LL^{math} en las distintas condiciones de carga de memoria de trabajo y modalidades. De esto último se concluye que la relación de la OL con la LNM es más dependiente de redes visuales mientras que la LL^{math} es independiente de la modalidad perceptual (efectos de congruencia consistentes tanto en modalidad visual como auditiva).

Tomados en su conjunto, los resultados reportados de los tres experimentos aportan evidencia empírica que demuestra el impacto del aprendizaje temprano de las matemáticas en la representación de la LNM. Estas diferencias se aprecian tanto cualitativamente como cuantitativamente cuando se procesa la congruencia y a nivel de coste cognitivo en la memoria de trabajo. Es decir, tanto el curso temporal como la distribución topográfica reflejan diferencias cualitativas entre LL^{math} y OL mientras que la ausencia de efectos en la OL cuando aumenta la carga en memoria de trabajo, está relacionado con diferencias cuantitativas. En conclusión, los resultados de esta tesis apoyan la hipótesis de un posible impacto lingüístico en la representación de la LNM. Es decir, la representación de la LNM en personas bilingües conecta automáticamente y de forma más eficiente con la LL^{math}. Por tanto, este estudio predice que la representación del número en los bilingües adultos está muy marcada, no sólo por la LNM, sino además por el impacto de la LL^{math} en dicha representación.

Implicaciones y direcciones futuras

En general, el presente estudio resulta novedoso y con implicaciones importantes en el campo de investigación de la matemática bilingüe. Paralelamente a los estudios previos, este trabajo no sólo promueve la importancia de considerar la influencia del lenguaje en los Modelos Cognitivos del procesamiento numérico sino que además aporta evidencia empírica sobre los procesos de afianzamiento del lenguaje en la representación básica del número. En el ámbito educativo, considerar esta influencia en las metodologías de enseñanza, augura mayores y mejores resultados en el análisis y diagnóstico precoz de dificultades de aprendizaje de las matemáticas en contextos de aprendizaje y docencia específicamente bilingüe. Por ejemplo, saber que la adquisición de conceptos numéricos abstractos (álgebra) se ve influenciada en parte por el idioma en el que se aprenden y que además se activan mecanismos neuronales diferentes cuando se manejan en la otra lengua, demuestra una codificación distinta de dos sistemas cognitivos paralelos (lenguaje y cognición numérica), a priori independientes pero que interactúan entre sí. Por ello, la investigación futura debiera indagar acerca del peso lingüístico en el área de las matemáticas desde una perspectiva global que incluya las bases neurobiológicas del cerebro bilingüe.

Dissertation

NUMBER REPRESENTATION IN BILINGUALS THE ROLE OF EARLY LEARNING IN THE MENTAL NUMBER LINE REPRESENTATION

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General introduction

This introduction presents an overview of the Math Cognition framework that has motivated the present dissertation. **Chapter 1** introduces a general description of the foundational aspects of numerical intuition based on representative empirical evidence. **Chapter 2** reviews the most relevant theoretical and empirical aspects of the numerical-spatial magnitude representation. **Chapter 3** describes evidence related with the role of language in number representation. **Chapter 4** provides a review of the current background of numerical cognition in bilinguals. **Chapter 5** walks through literature of Working Memory and its relevance in Numerical Cognition. **Chapter 6** briefly summarizes the experiments of present study. The methods and results of three experiments are described in **Chapters 7, 8** and **9.** Finally, **Chapter 10** provides a discussion of main results and implications of this thesis.

CHAPTER 1

1. THE NUMERICAL REPRESENTATION FRAMEWORK

1.1. INTRODUCTION

Numbers build our modern society and help us to establish causal relations between entities in the real world. In today ´s world, mathematical knowledge constitutes an important aspect of human cognition development that shapes how we think in the different neurocognitive domains such as for instance, the executive functioning or learning processes. Numbers are the basic rudiments for developing more complex mathematical knowledge and influence rational aspects of social judgment or decision making (e.g. cost and rewards), already observable early in life. For instance, counting ability predicts how children would divide and distribute resources based on logical reasoning (Jara-Ettinger et al., 2015). Despite being abstract in nature, numbers reflect and translate human thinking.

Over decades, the question of how numbers are represented has been one of the central topics of research in Math Cognition (Carey, 2001; Dehaene, Piazza, Pinel and Cohen, 2003; Dehaene, 2011; Nieder and Dehaene, 2009; Spelke, 2000; Whalen, Gallistel and Gelman, 1999). All people from different cultures show an innate signature for number representation sometimes called the "number sense" (Dehaene, 1997, 2011). This numerical intuition is described as an abstract, non-verbal representation of magnitude and mostly, independent from language. However, it is susceptible to being shaped by other numerical information acquired during early school years. For instance, learning numerical symbols or arithmetic has been shown to affect an individual's ability to compare and represent certain magnitudes (Gilmore, McCarthy and

Spelke, 2007; Holloway and Ansari, 2008; Moyer and Landauer, 1967; Temple and Posner 1998). In this regard, although there is considerable evidence showing that children and adults can manipulate numerical information without using symbols (Barth, La Mont, Lipton and Spelke, 2005; Pica, Lemer, Izard and Dehaene, 2004; Whalen, Gallistel and Gelman, 1999), the use of numerical symbols increases the precision of magnitude representation (Holloway and Ansari, 2008). The main conclusion is that a pre-existing intuitive system referred to as *core quantity knowledge* is deeply anchored in human magnitude representation and constitutes the basis on which symbolic representation is developed. In what follows, I provide a description of the most basic concepts underpinning the current numerical representation framework.

1.2. An innate system for magnitude representation

Part of the current knowledge about how numbers are represented is centered on the perception of magnitudes using either a symbolic or non-symbolic system. The ability to roughly estimate magnitudes is based on the so-called *Approximate Number System* (ANS). This system is an essential foundation for numerical skill development and is universally present in all human and non-human species (Butterworth, 2010; Cantlon, Platt, and Brannon, 2009; Nieder and Dehaene, 2009). Comparative studies have shown that a variety of non-verbal animals and human infants are able to detect the approximate difference in magnitude between two sets and perform elementary calculations (Dehaene 1999; Piffer et al 2012). During the course of numerical knowledge development, the ANS plays a critical role in the human capacity for estimating and comparing approximate numerosities (Feigenson et al., 2004; Gallistel and Gelman, 2000). However, this system is also involved in more complex numerical knowledge acquisition, which presumably includes arithmetic (Butterworth, 2010;

Gilmore, McCarthy and Spelke., 2007, 2010). The ANS has been assessed in several studies using non-symbolic number comparison tasks (e.g. the identification of the larger amount between two arrays of dots or objects). These studies evaluated infants' abilities to compare small and large numerosities and concluded that the perceptual capacity to discriminate non-symbolic quantities was limited to set sizes of four or less (Gilmore, McCarthy and Spelke., 2010; Xu and Spelke, 2000). This perceptual mechanism of small magnitude appreciation was labeled as "subiziting" (Piazza and Izard, 2009; Starkey and Cooper, 1980). Numerical symbols are built on this foundational capacity allowing the exact representation of large magnitudes (Feigenson, Dehaene and Spelke, 2004). This capacity to represent exact magnitudes needs to be learned as it is not part of preverbal human core quantity representation. According to this perspective, magnitude information is encoded or mapped in various symbolic notations (e.g. Arabic, verbal) allowing a more precise manipulation of quantity.

The way that this sense of approximate magnitude operates is based on *Weber's law* which states that the discriminability of two numerosities varies as a function of the ratio between them. In other words, Weber's law refers to the "smallest noticeable difference" necessary to discriminate variations in continuous quantities such as weight or size (see Fechner, 1860; Gallistel, 1990; Levi et al., 1992). In the context of Numerical Cognition, it has been shown that discrimination of magnitudes is based on a nonverbal representation that follows the mentioned Weber´s law. The most appealing demonstration is the existence of numerical *distance and numerical size effects* (Moyer and Landauer, 1967; see definition in footnotes 1 and 2). Both effects have been observed in animals and humans and they index the activation of the non-symbolic system (ANS) during magnitude estimation and comparison tasks (Dehaene, 1992, 2001; Gallistel and Gelman, 1992). This means that although numbers can be represented as discrete entities (i.e. numerical notations) a non-symbolic analogue magnitude format underlies the human sense of magnitude. This claim was first demonstrated by Moyer and Landauer (1967) in the context of a numerical comparison task. They showed that the accuracy of magnitude discrimination was influenced by both, the linear distance and the absolute magnitude value. For instance, we know that discriminating the relative magnitude of 2 versus 9 is faster than for 2 versus 4 or that discriminating the relative magnitude of 2 versus 9 is faster than for 22 versus 29. Hence, the imprecision increases in proportion to the number being represented. Generally speaking, the universality of Weber's law is taken as reference framework to indicate the presence of a non-symbolic number representation system, that is, the core knowledge of numbers (Dehaene, 1992, 2001; Gallistel and Gelman, 1992). Later on, other processes connect numerosity and symbolic notations with an internal analogue representation (Moyer and Landauer, 1967).

1.3. The numerical formats

Another important concept present in Numerical Cognition framework refers to the different numerical notations or formats in which magnitude can be accessed. The influence of number codes in magnitude processing has been a main focus of interest in numerical cognition research in the past decades (Cohen Kadosh et al 2008; 2009; Damian, 2008; Dehaene and Cohen, 1997; Nathan and Algom, 2008; Noël, Fias and Brysbaert, 1997; Reynvoet, Brysbaert, and Fias, 2002; Seron and Noël, 1995). With the acquisition of number symbols, different *numerical codes* map each magnitude to a verbal or symbolic notation. Further, numbers can be perceived visually or aurally and ultimately understood in at least two forms: Arabic-digits (1, 2, 3…) and number words (one, two, three…). This enables the acquisition of a more sophisticated numerical knowledge. The main reason is because it provides the exact representation of numerosities and facilitates the cognitive manipulation of large quantities. To better understand the bases of human numerical competence, it is important to distinguish between *exact* and *approximate* magnitude systems. While the approximate system is present from birth, the exact system develops from childhood mostly instigated by cultural and linguistic factors that boost with the acquisition of the counting sequence (Dehaene, 1997; Feigenson et al., 2004; Gordon, 2004; Pica et al., 2004). Unlike core magnitude knowledge (i.e. basic magnitude representation), symbolic numerical codes are culturally established (Ansari, 2008) and thus learned and retrieved from long-term memory (e.g. Arabic digits, number words, Roman numerals). For instance, Arabic digits can be characterized as a logographic system (i.e. the phonological code is not specified), mainly because the visual symbol that represents the magnitude has been arbitrarily related to its specific verbal format within the culture of reference. In general, it is assumed that number codes can influence the way in which numbers are represented and thus directly affect the manipulation of numerical information (Noël and Seron, 1997; Zhang and Norman, 1995). The nature of this influence and its impact in the architecture of numerical cognition is a fundamental topic of debate in Math Cognition.

The influence of numerical formats in the magnitude representation

The way in which different notations and symbolic systems (numerical codes) connect with the core magnitude representation is a critical research topic in Math Cognition. In this regard, comparison studies between infants and mathematically educated adults have tested non-linguistic processing of numerosity and demonstrate the maintenance of non-verbal representation of magnitude in adulthood (Whalen, Gallistel and Gelman, 1999). Along the same lines, data from behavioral studies suggest that in situations where human adults are prevented from using numerical symbols or strategies like counting, whatever the task is (e.g. estimation or production), they tend to use an analogue representation to process numerosity (see Barth, Kanwisher and Spelke, 2003). These results are just simple examples that demonstrate that adults keep the non-verbal magnitude representation of small quantities as infants and animals do, even after learning the symbolic system. The extent to which symbolic and non-symbolic number processing play different roles and whether or not numerical codes modify preverbal number representation, has been one of the most important research topics in last decades within the field of Math Cognition.

Currently, there are numerous **cognitive models** in the literature that explain the functioning of the numerical system. All of them provide a comprehensive account of the numerical representation system based on different numerical format and modalities considering in particular, the verbal format to be a crucial part for the development of exact arithmetic. One this representative model is the **Abstract Code Model** (McCloskey et al., 1985; McCloskey, 1992). This framework proposes a modular architecture of the numerical representation system based on three modules (comprehension, production and calculation) each connected with a central magnitude code defined as abstract and amodal. The model conceives that the arithmetic fact retrieval from long-term memory is built upon the abstract semantic representation level. Further, retrieval of arithmetic facts is independent from any input format (Arabic, verbal) and is processed through the abstract semantic representation system (e.g. 2x5 and *two times five* are processed in the same central system). The abstract semantic module constitutes a mandatory bottleneck engaged in all number processing operations and calculation mechanisms. Albeit with some empirical limitations, the Abstract Code Model has provided unquestionable value to experimental research and has been considered pioneer in one of the most influential theories in the field of numerical cognition.

A further math cognition model is the **Encoding Complex Model** proposed by Campbell and Clark (1988, 1992). This model assumes that multiple formats (verbal, visual, analogue, symbolic…) are connected in a sort of encoding-decoding network for numerical computations. The strengths or weakness of those connections will depend directly on the task and individual idiosyncrasies which are mediated by learning experiences. The heart of the Encoding-complex Model resides in the amount of effective networks available to operate efficiently at the comprehension, production and arithmetic-fact retrieval level, which is directly proportional with the practice and familiarity with the specific formats (Campbell, 1994; Campbell and Xue, 2001; Campbell and Epp, 2004). To exemplify the functioning of the model, the authors explain that when a numeral is presented, different formats of representations are activated at the same time like an "associative network". All information associated with the type of code (format) within the specific task, becomes more or less active depending on inhibitory and excitatory mechanism. For instance, during the Arabic-to-verbal transcoding, the model allows direct associations between both codes (i.e. reading aloud implies transcoding from visual- Arabic code to verbal articulation format) combined with indirect associative connections (e.g. mental number lines, visual-motor procedures) (Campbell and Clark, 1992, *"The nature and origins of mathematical skills"*, p. 451-490).

The termed **Triple Code Model** offers an intermediate view to explain the functioning of the number representation system (Dehaene and Cohen, 1995; Dehaene et al., 2003). It postulates that numerical information is based on three representational systems: visual-Arabic, verbal-auditory and analogue quantity or magnitude code. The three distinct systems exchange numerical information during arithmetic operations that, depending on the task, will recruit one specific code. Indeed, the model predicts that due to the fact that multiplication tables and some additions operations are learned and stored verbally, problems presented in Arabic code *(*e.g. *7x3)* are converted into a verbal format (e.g. *seven times three)* and thus, retrieve through direct verbal route. Conversely, the analogue magnitude representation is independent from language and accounts for the semantic of numbers. In this regard, the access to quantity would not be mediated by any format since it is assumed that only the analogue code has the inherent meaning of magnitude spatially represented in a mental number line (MNL) (Dehaene, Bossini and Giraux, 1993; Gallistel and Gelman, 1992; Restle, 1970). This assumption is one remarkable pillar that supports the research of this thesis since it apparently would determine the nexus between number and space.

Although the three models constitute the representative framework of Numerical Cognition, the Triple Code Model has received considerable empirical support. One of the major strengths of Deheane´s Triple Code Model resides in the neuroanatomical substrate (Dehaene, Piazza, Pinel and Cohen, 2003). What the authors initially propose are three neuronal circuitries coexisting in the parietal lobe to account for each of the three numerical systems. On the basis of neuroimaging data, this tripartite parietal organization predicts selective activation depending on the type of numerical information to be processed. Some of these brain imaging studies will be reviewed in next section.

1.4. Neuroimaging evidence

The numerical knowledge acquisition is built on the basis of a core magnitude system, which also has a neural substrate. As Dehaene (1997, 2011) claims in his seminal book *"The number Sense",* the organization of number representation at the neural level emerges through the connection between numerical symbols and the core magnitude system (Dehaene, 2001, 2004). This indicates that the acquisition of a symbolic counting system would not be a requirement for having a sense of magnitude. Empirical evidence supporting the notion of a notation-independent magnitude representation comes from already mentioned size effect[1] (Parkman, 1971), distance effect[2] (Moyer and Landauer, 1967; 1973) and ultimately from the SNARC effect[3] (Dehaene, Bossini, and Giraux, 1993; Hubbard et al., 2005). These effects are indexes of core magnitude knowledge, and can arise independently from language. Consistently, the neuroimaging support the hypothesis of an abstract neural substrate for magnitude representation.

Based on neuroimaging data, it is assumed that digits and number-words operate in different brain substrates. The common view is that independent networks are active as a function of the numerical format. Dehaene´s neuroanatomical version of the Tripartite model proposes three parietal circuits for number processing (Dehaene et al, 2003): the intraparietal sulcus (IPS), the Angular Gyrus and the Posterior Superior Parietal system. Previous studies have used functional magnetic resonance imaging[4] (fMRI) to investigate the representation of numbers as a function of modality or

[1] In a numerical comparison task, for the same numerical distance (i.e 2-4 and 7-9), as the size of the numbers increases, performance decreases (Dehaene, 2003).
[2] For a numerical comparison task, as the relative numerical distance between the two numbers increases, performance is faster and more accurate (Moyer and Landauer, 1967; Dehaene et al., 1990).
3 Responses to relatively larger numbers are faster when associated with the right hand while relatively small numbers are faster for the left hand (Dehaene et al., 1993).
4 Functional magnetic resonance imaging of the brain is a non-invasive way to assess brain function using magnetic resonance imaging (MRI) signal changes associated with functional brain activity. The most widely used

notation in the intraparietal sulcus (IPS) (Dehaene and Cohen, 1995; Cippoloti and Butterworth, 1995; Dehaene et al., 2003; Cohen Kadosh, Henik and Rubinsten, 2008). The IPS was strongly activated during numerical processing independently of number notation, being more active in approximate magnitude comparison tasks than in exact arithmetic computation (Arsalidou and Taylor, 2011; Chocon et al., 1999; Dehaene, 1996; Dehaene, et al., 1999; Pinel et al., 2001; Piazza et al., 2002). Thus, the main hypothesis is that numbers are represented in an abstract fashion engaging this region of the parietal cortex (IPS) which is considered the neural substrate for numerical representation (Dehaene et al., 1998; 1999; Cantlon et al., 2009; Cohen Kadosh and Walsh, 2009; Eger et al., 2003; Nieder and Dehaene, 2009; Rosenberg-Lee, Tsang and Menon, 2009; Piazza et al., 2007; Pinel et al., 2001; Venkatraman, Ansari and Chee 2005). Other studies show that another circuitry of the parietal cortex (i.e. Angular Gyrus) is to some extent affected by the numerical format. Specifically, this network appeared more active during the performance of exact problems such as multiplications, wherein the verbal format was needed for arithmetic fact retrieval (Deheaene, 1992; Lee, 2000). In this regard, studies comparing notational effects (e.g. Arabic versus verbal) during the performance of simple arithmetic show that difficulty tends to increase in the verbal format condition (Damian, 2004; Campbell, 1994; Campbell and Alberts, 2009; Cohen Kadosh, Henik and Rubinsten, 2008). Consistently, event-related potentials [5](ERPs) have also provided evidence of parietal activations during performance of simple arithmetic in different modalities and for-

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method is based on BOLD (Blood Oxygenation Level Dependent) signal change that is due to the hemodynamic and metabolic emanation of neuronal responses.

[5]The ERP is a record of electrical brain activity that is associated with external events. It involves a sequence of waveforms characterized by specific deflections that index the brain activity associated with the processing of information in a particular time point. Further, it allows extracting differences in timing and topography for a specific component (ERP) in order to make inferences about the time course and overall scalp topography of the aimed cognitive processes (Luck, 2005; Luck and Kappenman, 2011). In contrast with the high spatial resolution of fMRI technique, EEG offers a high temporal resolution to track the cognitive functions of interest.

mats (Dehaene, 1995; 1997). Furthermore, common scalp topographies for the distance effect have also been shown in numbers presented as Arabic digits or as dots matrices (Dehaene, 1996).

Once symbols are acquired, classical language areas in the left hemisphere are active during the processing of numerals in verbal notation but without affecting the quantity code (Dehaene and Cohen, 1991; Dehaene et al, 1999). In this respect, the main claim is that numerical symbols might be incorporated into the numerical system but would not modify its core representation. How this process takes place and how this integration occurs remains unspecified. In fact, recent neuroimaging findings are beginning to demonstrate more directly that the analogue magnitude representation can be somehow affected by verbal-notation systems (Nuerk, Iversen, and Willmes, 2004; Salillas and Carreiras, 2014, Salillas, Barraza and Carreiras, 2015). On the basis of this open debate, the question of the possible influence of language in magnitude representation arises with an important focus of attention in the impact of the verbal format (Dehaene, 1992, 1996; Salillas and Carreiras, 2013). Indeed, important differences between the processing of number words and digits have been already demonstrated (Cohen Kadosh, 2008), thus consistent with a linguistic modulation in the numerical representation.

The main conclusion drawn from these studies is that there is a unitary modality-independent system to appreciate symbolic and nonsymbolic numerosities, but the automaticity in retrieval of numerical magnitudes can be affected by the notation (e.g. Arabic, verbal). Thus, the general agreement is that not all numerical formats access or activate equally the magnitude representation system. A number of factors like experience (e.g. math learning experience) and context of the task has been shown to modulate the degree to which one specific format access to the magnitude representation (Campbell and Epp, 2004; Cohen Kadosh et al., 2007, 2008, 2009; Fias, Reynvoet, and Brysbaert, 2001; Ito and Hatta, 2004).

The following chapter examines the concept of the analogue magnitude representation considering the numerical-spatial association. The representative theories concerning the connection of space with number magnitude are laid out based on the most representative empirical evidence.

CHAPTER 2

2. SPACE AND NUMBER REPRESENTATION

2.1. INTRODUCTION

This chapter focuses on the link between numbers and space. I will describe the most striking empirical evidence supporting the numerical-spatial representation of number magnitude, defined and conceptualized as positions on an oriented "mental number line" (MNL). I will also review the main influential factors that may determine this numerical-spatial conceptualization.

One recurrent question of interest in the field of Math Cognition refers to the spatial component of number representation. A generally accepted idea is that number representation can be seen as spatially organized. Evidence supporting this claim came initially from Galton´s (1881) studies in the late 19th century. Based on the author's observations on mental imagery, he stated that numerical information tends to be represented or visualized as a left to right oriented Mental Number Line (MNL). Therefore, an important visuo-spatial role has been attributed in numerical abilities development. However, such numerical-spatial association constitutes an internal representation, not limited to mathematical reasoning that overall constitute the basis of basic number representation (Galton, 1880). Since these first observations, extensive behavioral and neuroimaging research has been developed and further strengthened with subsequent studies of verbal and non-verbal populations (non-human animals and preverbal infants). At the behavioral level, the most striking evidence of a numerical-spatial link is the SNARC effect (Numerical Spatial Association of Response Code; Deahene et al,.1990) followed by further support from neuropsychological studies (e.g. Rourke and Conway, 1997). Brain imaging studies also support the link between numbers and space by demonstrating the activation of numerical processing areas (parietal cortex) in tasks that require either number processing or spatial computations (Dehaene et al., 2003; Gőbel et al., 2001; Milner and Goodale, 1995). In general, current empirical evidence supports an early and intuitive association of numbers with spatial features (Gallistel and Gelman, 1992) that appears functionally connected in the brain.

2.2. The Mental Number Line hypothesis

The mental number line hypothesis has been conceptualized as an analogue representation of magnitude, independent from any format or symbol (Dehaene, 1992; Hubbard, Piazza, Pinel and Dehaene, 2005; Moyer and Landauer, 1967; Restle, 1970). Moreover, is thought to be an evolution of the "core numerical representation" that accounts for the most basic numerical intuitions (Catlon et al., 2009; Dehaene, 1996, 2001; Feigenson, Dehaene and Spelke, 2004). This numerical-spatial relationship is considered to be automatically activated during simple numerical processing operations (for instance when solving small calculations, number estimations or approximations, or in a parity task[1]. This idea is also based on mathematicians' reports who describe the use of visuo-spatial imagery in mathematical reasoning and symbolic calculations (De Hevia et al., 2008; De Hevia and Spelke, 2010; Fitzgerald and James, 2007; Tall, 2005; Tall and Mejia-Ramos, 2006). In fact, many people describe anecdotal experiences of "vivid mental number lines" when imagining numbers.

Throughout the literature, a wide range of modulating variables has been proposed to explain the significant association between number and space, such as se-

[1] Participants must judge with a button press whether a presented number, ranged from 0 to 9, is odd or even

mantic memory, task execution or cultural habits reflected in different mathematical educational contexts (Dehaene et al, 1993; Fias and Fischer, 2005; Shaki and Fischer, 2008; Umilta, Priftis and Zorzi, 2009; Verguts et al., 2005). Also part of numerical abilities acquisition relies on a normal development of the MNL representation. In this regard, it has been shown that the spatial component of the core numerical representation (Dehaene, 1992; Wynn, 1998) is affected in children with visuo-spatial disabilities which was attributed to an abnormal development of the mental number line representation (Bachot, Gevers, Fias and Roeyers, 2005). It seems plausible therefore that such numerical-spatial representation connects with the foundation of basic number representation (Galton, 1980; Seron et al, 1992; Van Dijck and Fias, 2011). In the following lines, empirical evidence that supports the MNL hypothesis will be provided.

2.3. The SNARC effect

A robust empirical demonstration of spatial-numerical associations is the so-called **SNARC effect** (Spatial-Numerical Association of Response Codes). During a binary parity classification task of single numbers (in Arabic or verbal format), faster responses are elicited with the left hand for small numbers while faster responses are elicited with the right hand for large numbers. The SNARC effect is very consistent since it has been observed under a large variety of tasks, stimulus manipulations and experiment designs (see Fias and Fischer, 2005). Congruent with the MNL hypothesis, the SNARC effect reveals a critical spatial codification of number representations according to their magnitude (Dehaene et al, 1991, 1993).

A large part evidence of numerical-spatial interactions comes from studies using the *line bisection bias* paradigm (Calabria and Rossetti 2005; Fisher, 2001; Longo and Lourenco, 2010; Zorzi et al 2002). In this type of task it has been consistently demonstrated that when lines are composed of numbers either in the Arabic or verbal format, participants are less accurate at indicating the midpoint in comparison with lines composed of “x”s. More precisely, the bisection of the line deviates to the left or to the right depending on the position of the target-number in the MNL, thus suggesting that numerical formats automatically activate the numerical spatial representation of magnitude (Calabria and Rosetti, 2005). Moreover, numerical cues can induce the numerical-spatial associations even when the magnitude of the number is irrelevant to solve the task. The most prominent evidence of such an automatic activation of the numerical-spatial link is perhaps the so-called *attention bias effect*[2]. In a detection task, by simply presenting a digit, it automatically shifts attention to either the left or right visual field according to the relative size of the number, even though the magnitude information is irrelevant to perform the task (Fisher et al 2003). In other studies, the SNARC effect has been demonstrated in nonnumerical tasks such as judging phonemic content of number word (Fias et al. 1996). Taken together, evidence suggests that the association between number and space is automatic and that awareness of numerical magnitude is not necessary to activate the SNARC effect (Fias et al.. 1996, 2001; Fischer et al. 2003; Hubbard et al, 2005; Lammertyn et al. 2002).

One important aspect that characterizes the SNARC effect is its flexibility. It has been demonstrated that the SNARC effect could be influenced by the *horizontal* reading-writing direction. For instance, the reverse SNARC effect was found by Dehaene et al. (1993) with Iranian adults who write and read from right-to-left suggesting a spatial bias linked to cultural habits. However, the direction of the SNARC effect can be also altered. In a cross-linguistic comparison study with bilingual Rus-

[2] The main assumption of the attention bias paradigm is that, although the presentation of digits is irrelevant for solving the task, spatial representations are either way activated.

sian-Hebrew readers, a SNARC effect was present after reading Russian (in a Cyrillic script from left to right) but after reading Hebrew (from right to left), the spatial mapping of numbers was significantly reduced (Shaki and Fischer, 2008; Shaki, Fischer and Petrusic, 2009). Thus, the hypothesis of habitual reading direction and SNARC effect association seems to be robust for the horizontal dimension but is not clear yet for the vertical dimension.

In this regard, the research evidence indicates that apparently there is a *vertical* spatial organization bias for number magnitudes, with small numbers being responded faster with the bottom key and large numbers with the top one (Gevers et al., 2006). Using saccadic latency measures, Schwarz and Keus (2004) found an association between numbers and vertical arrangement in space, with large numbers eliciting faster upward saccades relative to small numbers, but the opposite pattern was found for small numbers. Similarly, Ito and Hatta (2004) reported a vertical SNARC effect with Japanese participants with small numbers associated with the bottom and large numbers associated with the top. These results were inconsistent with the reading-written direction hypothesis since they did not match the top to bottom direction of Japanese reading.

In light of these findings, proposals have been made for other possible magnitude mappings compatible with this vertical association such as distance, weight or temperature scales (Lourenco and Longo, 2010, 2011; Walsh, 2003). Nevertheless, evidence supporting Dehaene's (1993) reading orientation hypothesis has been provided by studies with Arabic population (Zebian, 2005) who read in the reverse direction (from right to left). Results showed a variation in the orientation of the SNARC effect as function of the respective reading direction (see other data in Hung et al., 2008). Thus, the general conclusion is that although the SNARC effect is highly influenced by reading habits for words and numbers, is consistently present whenever the reading direction for numbers and words matches or not (Shaki, Fischer and Petrusic, 2009; Fischer and Shaki, 2010).

Another aspect to consider is *when* this link between magnitude and space develops. Some studies support the proposal that the age at which this numerical-spatial association is formed seems to be related with the acquisition of Arabic numerals. However, according to current studies is not that clear. Using a parity task (see footnote 4), Berch and colleagues (1999) demonstrated that children do not exhibit the SNARC effect before age 9. In other study, the SNARC effect was found in younger ages (7-year-old) but only when participants performed a task that involved magnitude processing (e.g. magnitude judgement task[3)] and not when the numerical magnitude was irrelevant to perform the task[4] (van Galen and Reitsma, 2008). This age-related variability led authors to infer that the SNARC effect was absent in younger children because they do not have yet automatic access to magnitude information when perceiving Arabic numerals. Thus, the main suggestion is that the spontaneous association between small magnitudes and the left side and between large magnitudes and the right side arise when children start to get familiar with the counting sequence which is before learning the Arabic symbols and before learning to read (Opfer and Thompson, 2006; see also de Hevia and Spelke, 2009). However, the proneness to process more efficiently large numbers on the right side and small on the left side (as demonstrated by the SNARC effect) emerges once Arabic numerals are learned. Due to an extensive exposure to external spatial-number associations over the course of

[3] Participants must judge with a button press whether the magnitude of a presented number is larger or smaller compared with a given number.
[4] In Galen and Reitsma experiment, participants performed a detection task based on Fischer et al., 2003 paradigm. A digit is presented between two boxes is followed by a target (a dot presented within one of the boxes). The perception of the number is irrelevant to detect the target.

learning math (graph axis, rulers, measuring templates, etc), children will get more experience with numbers and thus, will automatically activate the spatial information (Berch, Foley, Hill, and Ryan, 1999; Hubbard, Piazza, Pinel and Dehaene, 2005). Concurrently, the internal representation of numerical magnitude in a left-to-right MNL is reinforced by reading habits (Zebian, 2005). Taken together, the current view is that a basic mapping of space to numbers is present initially but the directionality emerge later mostly influenced by the experience of reading and formal instruction (Bulf, de Hevia and Macchi Cassia, 2015; Dehaene et al., 1993; De Hevia et al, 2014; Fagard and Dahmen, 2003; Itto and Hatta, 2004; van Galen and Reitsma, 2008; Zebian, 2005; Zhou et al., 2007).

The SNARC effect reflects an internal space-related number representation but also evidence suggests an influence of overlearned number-to-hand motor associations (Glover and Dixon, 2001; Milner and Goodale, 1995). In this respect it should be noticed that the majority of the existing evidence seems to be more in line with the MNL interpretation of the SNARC effect. For instance, Dehaene and collages (1993) demonstrated that the SNARC effect was independent of a hand-based spatial code. Authors showed that in a parity task in which participants had their hands crossed, small numbers were responded faster with the right hand and large numbers with left hand (see also Wood and others, 2006 for a different discussion). The authors concluded that the MNL is left-to-right oriented with respect to representational or conceptual associations rather than with respect to the spatial position of the hands. Therefore, the SNARC effect would not be determined by an extracorporeal spatial reference but rather, by an internal spatial representation. Nevertheless, still some questions remain unanswered concerning the manual association hypothesis (see Wascher, Schatz, Kuder, and Verleger, 2001).

Overall, we know that numerical spatial associations can be influenced by a great amount of factors like the learning context, finger counting strategies (Di Luca, Granà, Semenza, Seron and Pesenti, 2006), task demands (Bächtöld et al, 1998; Galfano, Rusconi and Umilta, 2006) or cognitive strategies (Fischer, 2006; Lindemann et al, 2008). On this basis, different interpretations like motor associations with extracorporeal spatial reference (Bachtöld et al., 1998; Corbetta et al., 2000a; Glover and Dixon, 2001; see also Wascher et al.2001 for a contrary view) have arisen as alternative explanations to account for spatial numerical associations. As already mentioned, the majority of the existing evidence supports the mental number line interpretation (e.g. specifically the fact that the SNARC effect mirrors the congruency of external responses with an internal representation of magnitude; Dehaene et al., 1993, p. 384). In addition, a spatial coding has been observed in the processing of non-numerical magnitudes (Walsh, 2003) such as the height, luminance or tonal information. One of such examples can be found in music cognition research with the so-called SMARC effect (Spatial-Musical association of response codes) (see Lidji, Kolinksky, Lochy and Morais, 2007; Rusconi et al., 2006). Therefore, the spatial coding interpretation has been the dominant framework for studies on the SNARC effect. However, it should be mentioned that alternative interpretations questioning the unequivocal spatial interpretation of the SNARC effect have been put forward. One of this alternative makes reference to a possible linguistic coding or verbal account (Gevers and Verguts, 2006; Gevers et al., 2010). The main explanation is rooted in those universal verbal concepts that refer to different opposing dimensions like "top"-"down", "left"-"right", etc., which are thought to be associated with positive or negative classifications known in the literature as "polarity coding" (Proctor and Cho, 2006; Santens and Gevers, 2008). According to this framework, the SNARC effect would result from a dual coding between verbal concepts of magnitude with positive and negative labels (see Paivio, 1986). For instance, the magnitude concept “small” is often associated with “negative” and “large” with “positive” in the same manner that the spatial concepts “left” and “right” do, respectively. Recent research has tested behaviorally spatial and verbal engagement in the SNARC effect, and supports the hypothesis of a likely contribution of a “verbal-spatial coding” within the context of a parity judgment-task and magnitude comparison-task (Gevers et al., 2010; Imbo et al., 2012). In light of these results, it might be tempting to completely reject the visuo-spatial account of the SNARC effect. However, while it is possible to say that the nature of the SNARC is not solely spatial, the available evidence does not allow to completely discard the spatial implication hypothesis. Therefore, in the absence of more conclusive empirical evidence, the current view is that both accounts have apparently the same (complementary) probability of inducing the SNARC effect.

So far I have provided a brief theoretical and empirical review of the numerical-spatial association account. The MNL hypothesis has been highlighted as a pivotal component within the numerical-spatial representation theory together with the SNARC effect as the most prominent empirical demonstration. In what follows, I will complete this chapter with neuroimaging studies that account for the neural basis of numerical-spatial association.

2.4. Neuroimaging evidence: parietal basis of numerical-spatial representation

The neural basis of the association between number processing and space is a central question in current numerical cognition research. In Hubbard et al. (2005) review, authors provide a comprehensive overview of neuroimaging evidence supporting the link between number and space. Overlapping neural circuits within right posterior parietal cortex, appear to be implicated in numerical-spatial processing which is suggestive of a functional relation with the abstract representation of quantity (Dehaene et al., 2003; Hubbard et al., 2005; Pinel et al., 2001). As already pointed, the key region of the brain associated with numerical processing is the parietal cortex but also activations in prefrontal cortex have been found in different numerical task (Dehaene, 1996; Nieder and Dehaene, 2009). Here, I will review some of the core findings that address the issue of common brain regions of spatial-numerical magnitude processing.

Consistent with Dehaene et al. (2003) neuro-anatomical version of the Triple code model, the involvement of parietal regions in number processing has been observed in a variety of arithmetical tasks such as mental calculation, magnitude comparisons or approximation (Chochon et al., 1999; Eger et al., 2003; Gerstmann, 1940; Rueckert et al., 1996). Specifically, the activation of the left and right intraparietal sulci (IPS) has been observed in fMRI experiments with a high correlation with the behavioral distance effect (Ansari et al., 2005; Pinel et al., 2004). For instance, shifts of attention along the MNL activate specific regions intraparietal areas (Dehaene et al., 2003). Functional magnetic activity in fronto-parietal regions has been reported in numerical tasks (Zago et al., 2001), the same areas that are also involved in visuospatial functions such as spatial attention (Fischer, 2001) or mental rotation (Kosslyn et al., 1998; Vingerhoets et al., 2001).

Additional evidence comes from neuropsychological studies based on brain damage patients (Marshall and Halligan, 1990; Vuilleumier et al., 2004). Most of this studies show evidence of an internal relation between number and space For instance, it has been demonstrated that neglect patients with right-hemisphere damage neglecting their left-hemifield (focus the attention only to the right visual field), show rightwards bias when asked to bisect the midpoint of both, a line or a numerical interval (Zorzi, Priftis, and Umiltà, 2002). Vuilleumier et al., 2004 study demonstrated that neglect patients have unilateral spatial difficulties to process numbers depending on the digit taken as reference in a number comparisons task (e.g. when patients were asked to compare the magnitude of “5” with “6” and “4”, they were much slower to make a judgement in “4” than in “6”), thus suggesting the construction of different spatial representations. Moreover, some fMRI studies have reported dissociations between brain regions implicated in numerical processing (e.g. brain areas engaged in spatial attention and verbal knowledge of numbers) in neglect patients with right-hemisphere damage when bisecting both numerical intervals and horizontal lines (Doricchi et al., 2005; Hubbard et al., 2005). Similar results have been reproduced in normal subjects. They tended to misbisect the spatial midpoint of a numerical interval or physical line (see Zorzi et al, 2002, 2006). This phenomenon is known as pseudoneglet (Bowers and Heilman, 1980) and indicates common networks between spatial attention and the numerical system.

Consistent to these fMRI studies, it has been shown that deficits in performance of visuo-spatial and numerical comparison tasks can be induced with TMS[5] (Transcranial Magnetic Stimulation). For instance, when a repetitive TMS pulse was applied over the left angular gyrus, the mental number line organization was altered during the performance of a numerical comparison task (Gobel et al., 2001). In other experiments, when repetitive TMS was applied over the right-posterior parietal cortex, a left-neglect effect in number interval and line bisection tasks was induced (Bjoertomt et al., 2002; Fierro et al., 2000, 2006; Göbel, Calabria, Farne, and Rossetti, 2006).

5 Transcranial magnetic stimulation (TMS) is a noninvasive procedure that uses magnetic fields to stimulate nerve cells in specific brain locations to enhance cognitive processes. The most notable advantage of TMS is its ability to directly stimulate the cortex with little effect on intervening tissue.

Brain correlates of numerical-spatial interactions have been also demonstrated with event-related potentials (ERPs). Amplitudes of early components have been shown to reflect the processing of numerical-spatial congruencies after the access of number semantics (Gut et al., 2012; Ranzini et al., 2009). For instance, in a parity judgment task, Gut el al., (2012) found early brain signatures (N1-N2) indexing processing of congruency in centro-parietal sites. In other previous studies, specific left-right posterior topographies in early latencies (N1-P1p) have been related with the numerical distance effect in numerical comparison tasks (Dehaene, 1996). In the context of the attention bias paradigm, other ERP components (P1-P3) distributed over centro-parietal sites have been shown to be modulated by the relation between number and space (Gut et al., 2012; Ranzini et al., 2009; Salillas et al., 2008; see also Hillyard et al., 1995; Hopfinger and Mangun, 2001 Mangun et al., 1998). Crucially, the amplitude of such components was determined by the congruency of the number size with the target location (small numbers-left side vs large numbers-right side). Thus, even when digits are irrelevant to the task, numerical-spatial representations remains from left-to-right according to the relative magnitude of numbers (small or large).

Taken together, these studies conclude that similar neurocognitive mechanisms underlie the numerical and spatial processing, thus reinforcing the MNL hypothesis (Corbetta et al., 2000b; Hubbard et al 2005, Pia et al., 2009; Vuilleumier and Rafal,1999; Vuilleumier et al., 2004). At the neuroanatomical level, fMRI and TMS data are consistent with common neural substrates mostly localized in the right inferior parietal cortex, for space and magnitude processing domains (for a review see Hubbard et al., 2005; Cohen Kadosh et al., 2008). Brain dynamics associated with distance effect and processing of numerical-spatial congruency (e.g. N1-P2p, P300) also corroborate the MNL hypothesis. The involvement of centro-parietal ERP patterns in numerical-spatial processing is consistent with fMRI studies showing modulation of parietal regions during semantic processing of numbers (see Dehaene et al., 2003).

Up to this point, we have walked through some of the neuroimaging findings supporting the spatial-numerical proposal. The studies reported here are just a small sample of the impressive neurobiological evidence supporting the association between numerals and space, conceived as the MNL. In sum, the neural evidence of such connection can engage extensive brain networks but critically, the parietal and prefrontal cortex seem to be the most involved structures. Namely, the same neurobiological bases encompassing the basic numerical competences (for a general review see Nieder, 2005). In the next section, the role of language in number representation will be described together with the most relevant empirical support.

CHAPTER 3

3. LANGUAGE AND NUMBER REPRESENTATION

3.1. INTRODUCTION

Language constitutes the basis of human communication. In fact, it is considered an important social and cultural tool to share not only intentional actions or ideas, but also to manipulate abstract concepts such as time, magnitude or algebra. In relation to math cognition, the role that language plays in the evolution of the innate sense of magnitude is not yet well-defined by any of the existing theories. The current view is that some basic aspects of number cognition development (e.g. arithmetic facts, counting) strongly depend on language (Butterworth, 2010; Carey, 2001; Delazer et at., 2005; Gelman and Butterworth, 2005; Nieder and Dehaene, 2009; Piazza, 2010; Salillas and Wicha, 2012; Spelke and Tsivkin, 2001). It is well-known that solving simple arithmetic problems involves language processing. However, there is also evidence in support of the notion that numerical ability and language have different underlying processes and thus are independent (Cappelletti, Butterworth, and Kopelman, 2001; Cipolotti, Butterworth, and Denes, 1991; Varley, Klessinger, Romanowski, and Siegal, 2005). Therefore, the pervasive question that arises in current lines of research is whether language influence numerical knowledge development and how this connection is reflected in the brain.

3.2. THE LINK BETWEEN LANGUAGE AND NUMBERS

The role of language during development of number representation has constituted a main focus of research interest in recent decades (Carey, 2004). In the first stage of development, it seems obvious that language is part of the process for acquiring more complex numerical knowledge, beyond the approximate numerical sense that all human and non-human animals share (Dehaene, 2004; Gordon, 2005; Hodent, Bryant and Houde, 2005; Pica et al. 2005). For instance, the ability to solve complex calculations (e.g. the rules for transforming equations) relies on our capacity to manage numerical procedures which are ultimately mediated by language (e.g. verbal reasoning). In order to acquire a high level of mathematical reasoning, it is crucial to first develop an exact quantity representational system and this is not possible without language (Dehaene, 2004; Carey, 2004). However, there are specific non-linguistic influences on the process of magnitude development to be considered beforehand. The link between language and number intuitively appears early in life, before any mathematical learning or formal instruction (Gelman and Gallistel, 1978; Wynn, 1990; Dehaene et al 1999, 2004). Relevant insights on this question are found in cultures with a very limited range of number words to refer numerical concepts. The most illustrative example comes from ecological studies. Gordon (2004) investigated how Amazonian tribes refer to large and exact numerosities given the fact that they only have three magnitude concepts (one, two, many). Similarly, Pica et al (2004) explored this issue in a different Amazonian tribe (Munduruku) with only a range of five number words. What these authors observed was that despite lacking words to identify exact magnitude, these tribes are able to manipulate approximate large quantities fairly well. Conversely, they were not able to process exact quantities accurately (Gordon, 2004; Pica, Lemer, Izard, and Dehaene, 2004). The main conclusion derived from these studies was that one basic number representation system accounts for approximate numerosities and this system is present before language acquisition. Therefore, it is thought that a verbal counting system should not a priori be essential for having a core numerical representation but learning verbal numbers is fundamental to develop the representation of exact quantities (see Carey, 1998, 2004; Dehaene et al., 2004, 2007; Spelke and Tsivkin, 2001). The conclusion to be drawn from these studies is that development of exact magnitude is based on the acquisition of numerical verbal forms but once they are mastered, language (verbal format) is not imperative to manipulate exact quantities. Indeed, exact arithmetic, contrary to approximate number processing, is thought to be represented in a specific language-coded format. This assumption has been examined through the distinction between exact and approximate arithmetic (Butterworth et al., 2008; Dehaene et al., 1999; Spelke and Tsivkin, 2001). Whereas exact calculations are learned by rote, approximate estimations or comparison do not rely on language as are supposed to be held through the quantity code (Dehaene, 2009).

Understanding the role of language in accessing magnitude is essential to acquire a full picture of how numbers are represented and stored. Whether language connects with the basic aspect of magnitude representation (i.e. core magnitude knowledge) is a question of further research (Dehaene et al, 1993; Von Aster and Shalev, 2007). In this respect, it has been proposed a role of language beyond the context of exact arithmetic. Recent findings suggest a linguistic permeability of quantity code originated during early learning math that would remain in adults' magnitude representation system (Salillas and Carreiras, 2014; Salillas, Barraza and Carreiras, 2015). This proposal raises the possibility of a crucial role of language in the core numerical knowledge that would become linked during early math learning with the acquisition of numerical verbal symbols. This topic will be followed up in Chapter 4 within the context of numerical cognition in bilinguals.

3.3. Neuroimaging evidence

In this section, part of the neuroimaging empirical evidence supporting the influence of language in Numerical Cognition is presented according with two important streams. On the one hand, I provide a general description of neuroimaging studies that support the role that language plays in exact arithmetic. On the other hand, we present fMRI and EEG evidence of the linguistic traces in the core numerical knowledge as result of early learning processes beyond the arithmetic facts retrieval.

A large number of imaging studies have led to the view that human number cognition is based on the integration of two distinct systems: a non-verbal representation of approximate quantities and a language-related system of number words. In some fMRI studies, results showed that performance of exact arithmetic facts like single-digit addition or multiplications strongly correlates with activation of Left Angular Gyrus (LAG) (Dehaene et al., 1999, 2003; Chochon et al., 1999; Grabner et al., 2009; Zago et al., 2001). Bear in mind that arithmetic facts are learned and long-term stored verbally and thus, retrieved by rote. Therefore, it is not surprising that overlapping activation in language and number processing regions emerged during visually presented exact calculations (Pinel and Dehaene, 2010). Based on studies with patients presenting left-frontal and inferior-parietal lesions, exact and approximate systems are supposed to be associated with different anatomical sites (Dehaene et al., 2003; Delazer and Benke, 1997; Lemer et al., 1997; 2003). A systematic finding of those brain imaging studies was the dissociation between both systems during numerical computations. For example, patients with left frontal cortex lesioned resulted in deficits in performing exact calculations such as multiplications whereas the ability to perform approximate computations such as magnitude comparison was unaffected. The reverse pattern was observed for patients with lesions in parietal regions. Moreover, brain imaging studies in healthy adults confirm distinct contributions of left and right inferior parietal areas underlying performance of simple arithmetic operations like multiplication and subtraction (Chochon et al., 1999; Cohen et al., 2000; Dehaene et al., 1999; 2003). For instance, it has been reported that performance of multiplications is associated with language processing areas in left parietal lobe (i.e. LAG) whereas performance of subtractions entailed bilateral activations of intraparietal and prefrontal pathways. In a numerical comparison task, activations are observed lateralized to right parietal lobe (Chochon et al., 1999; Pinel et al, 2001). The involvement of verbal codes in simple arithmetic seems to interact with those number facts that are typically represented in verbal long-term memory such as multiplications. A similar dissociation was found in ERP studies showing different neural correlates associated with multiplications as compared with subtraction operations (Dehaene, 1995; Zhou et al, 2006; 2009). Overall, the results of these studies evidence two important facts : 1) left and right parietal circuitries have distinct functional contributions in number processing apparently modulated by the type of numerical task and 2) the involvement of language in simple arithmetic is associated with those arithmetic facts learned by rote.

Apart from the influence of language in exact arithmetic, the linguistic traces in the quantity code as result of early learning processes of numerical verbal symbols has been recently addressed with ERP technique. Salillas and Carreiras (2014) explored the permeability of the quantity code to language and the influence of early learning in the core numerical representation with balanced bilinguals. The reported data showed an early N1-P2 distance effect during a number comparison task, modulated by linguistic variables. Thus, suggesting possible verbal signatures in the quantity representation system by early learning. Their experiments based on magnitude processing in early balanced bilinguals are taken as a novel starting point and reference framework to address important questions about how language interacts with the most basic level of magnitude representation.

In summary, the reviewed brain imaging evidence suggests firstly, that the role of language in numerical cognition is conditioned to the exact arithmetic system but possibly also on most fundamental numerical knowledge. Secondly, arithmetic facts are integrated within language cortical networks mainly because they are learned verbally and retrieved by rote. Thirdly, the link between math and language apparently is not restricted to the context of arithmetic facts. Finally, a possible linguistic shaping of the basic quantity representation system is proposed as a main topic of research in Math Cognition which further includes its impact in the spatial magnitude representation (Dehaene, 2009; Nieder and Dehaene, 2009; Salillas and Carreriras, 2014). Over this latter conjecture, the main topic of research in present dissertation is grounded.

Next chapter provides a review of the role of language in numerical representation considering the particular case of bilingualism. I will describe the main framework of math acquisition in bilinguals and the empirical evidence supporting a general influence of language in math performance and beyond the context of exact arithmetic.

Chapter 4

4. Bilingualism in Math Cognition

4.1. Introduction

The effect of bilingualism in cognitive development is a continuing discussion in the literature (Bialystok, 1999; 2009; Bialystok, Craik, and Luk, 2008; Duñabeitia et al., 2015; Rodriguez-Fornells, de Diego Balaguer, and Münte, 2006). Within Math Cognition domain, the case of bilingualism has been investigated in relation to language (Bernardo, 1998; Gordon, 2004; Miller, 1996; Saalbach et al, 2013; Spelke and Tsivkin 2001). As Ellen Bialystok argues in her seminal book *"Bilingualism in Development: Language, Literacy, and Cognition"* (2001, pp 195-206), cognitive effects of bilingualism in mathematics can occur in the same manner as in language mainly because both systems share critical features like abstract representations or conventional symbols. In this regard, cognitive and educational lines of research converge that language plays an important role in math learning. From literature reports about bilingual's arithmetic performance, it has been emphasized that several elements concerning the language of math instruction and the relative mastery of languages (i.e. language proficiency) directly modulate bilinguals' numerical processing. Relevant behavioral and neuropsychological data concerning these two aspects would be described later in this review. But before that, in next section, I will provide a brief description of some multidimensional factors frequently used in psycholinguistics to label and classify bilingualism.

4.2. Definition of bilingualism and assessment methods

From a cognitive perspective, the term bilingualism refers to those individuals who have learned more than one linguistic code for oral and written communication (Grosjean, 2010). The Bilingualism field has been framed by the definition of a wide range of categories related with fluency and other linguistic abilities (Centeno and Obler, 2001; Hamers and Blanc, 1961; McNamara, 1967). It is important to emphasize that bilingualism cannot be simplified only to the single fact of speaking two languages. The existing literature addresses a wide range of multidimensional aspects with the goal of delimiting and categorizing the phenomenon of bilingualism. Interacting dimensions are the following: age of acquisition, context, percentage of use locus of the ability, and cultural identity (Baker, 2011; De Houwer, 2009; Flege, MacKay and Piske, 2002; Grosjean, 1982, p.231; Grosjean, 2010b, pp 18-27; Grosjean and Li, 2012; Hazan and Boulakia, 1993, p.22; Hernandez, 2013; Kroll et al., 2012; Valdés et al., 2003). Due to its relevance for this thesis, I will consider two of them bellow, as the crucial dimensions that define the relative performance in the two languages: *age of acquisition* and *relative proficiency*. To a lesser extent, the *percentage of use* in daily bases will be contemplated as an influential factor in determining language dominance.

Bilingual categorization

1. The *age of acquisition* (AoA) qualifies the distinction among types of bilingualism according to the simultaneous exposure to second (L2) and first language (L1). When both, L2 and L1 are acquired from birth, this is often labeled as *simultaneous bilingualism*. Contrary, when the L2 is acquired later on time, after the 'sensitive period'[1]

[1] The term refers to the developmental moment in which a child is more receptive to certain kind of learning acquisition knowledge or experience.

for language acquisition has exceeded then, it is referred as *consecutive bilingualism* (Baker, 2011; DeKeyser, 2005, 2013; De Houwer, 2009; Flege et al, 1999, 2002; Hamers and Blanc, 1987). The influence of the age of acquisition in the level of competence has been challenged in many studies (Bosch and Sebastian-Gallés, 2003; Gandour et al., 2007; Kim et al., 1997; Perani et al., 1998, 2003) some of them supporting the notion of a critical period (DeKeyser, 2005; DeKeyser and Larson-Hall 2009, pp 88-108; Lenneberg, 1967). In this regard, special difficulties in learning L2 after puberty and greater ease in children for L2 acquisition in comparison to young adults have been observed (Johnson and Newport, 1989; Flege et al., 1995; Weber-Fox and Neville, 1996). It is well-known that the phonological and morphological aspects of language do not reach native level when L2 is learned in adulthood (Bialystok and Miller, 1999; Long, 1990; Pinker, 1994). At the neuroanatomical level, separate representation networks of bilinguals´ L1 and L2 has been related to differences between both languages age of acquisition (Perani et al., 1998; Chee et al., 2001). There are fMRI studies showing, for example, different Broca´s sub regions activations in late bilinguals groups for L1 and L2 in comparison to other groups of early bilinguals that showed an overlap in Broca´s area for L1 and L2 (Abutalebi, Cappa and Perani, 2001; Kim et al., 1997; Gandour et al., 2007; Perani and Abutalebi, 2005).

2. The next important dimension is the *level of proficiency*. Commonly, *balanced bilingualism* refers to speakers who have the same competence in both languages while *unbalanced bilingualism* refers to a dominance of one of the two languages (often the mother tongue) over the other (Grosjean, 1982, p.234; 2001; Lambert, 1990, p.201-220; Cook, 1992). However, the term of “balanced” is interpreted in literature of bilingualism research as an “appropriate competence for both languages” and not liter-

ally as an exactly equal level of proficiency (Baker, 2011). This is a very important issue to consider when assessing the degree of bilingualism for research purposes (Hazan and Boulakia, 1993, p.22; Flege, Mackay and Piske, 2002) but also, for many other social and cultural reasons like school or work successfulness (Baker, 2011; Grosjean, 1982, p.231; Valdés and Figueroa, 1994). Indeed, the level of proficiency has an impact on brain computational demands or workload. Some fMRI studies reported differences between L1 and L2 in the degree of brain activation related with the early or late age of acquisition. That is, in individuals with similar levels of proficiency, higher amount of activation in L2 compared to L1 was observed in late bilinguals but not in early bilinguals (Perani et al., 2003; Perani and Abutalebi, 2005; Kovelman et al., 2008).

3. Percentage of use is another informative measure of dominance and proficiency. Scores on language tests can be influenced by the frequency of use of each language in the daily bases but it does not seem to be decisive. For example, bilingual adults do not lose their proficient production in one of their languages even when it is less used than the other (Luk and Bialystok, 2013). Analogous to the age of acquisition, the amount of daily exposure to a language also influences the degree of regional activation. According to neuroimaging data, the larger the frequency of the exposure to the L2, the smaller was the differences between L1 and L2 (Perani et al., 2003). Therefore, it is important to further explore the influence that percentage of use might have, to characterize better proficiency.

The common procedures to assess the level of bilingualism include self-reported measures and linguistic competence tests. The latter is considered as a more objective estimator tool. Self-reported measures such as questionnaires and interviews (Dunn and Tree, 2009; Li, Sepanski and Zhao, 2006) are often used to collect information about the AoA, speaking context and percentage of use (i.e. *The Hoffman bilingual Schedule*, Hoffman, 1934). In addition, in order to obtain a standardized measure of the linguistic proficiency, a common way is to evaluate the performance by mean of the tests. One of the most frequently used techniques is the confrontation naming task, which requires the individual to name pictures of objects, graded in difficulty, in both languages. The English-Spanish *Boston Naming Test* (BNT) by Kaplan, Goodglass and Weintraub, (1983) is one of the most frequently used to assed bilingual dominance (see also Ferraro and Lowell, 2010). The association between bilingual proficiency (Spanish-English) and performance in the BNT was examined by Gollan and colleagues (2007). In their study, the level of linguistic competence was determined by the smaller English-Spanish score differences, distinguishing this way between balanced and unbalanced bilinguals (see also Acevedo and Loewenstei, 2007). The BNT offers a standardized measure based on the performance criteria and enjoys widespread use in clinical and experimental research, adapted to at least nine different languages (Kim and Na, 1999; Kazt et al., 2000; Roselli et al., 2000; Moreno and Kutas, 2005; Salillas and Wicha, 2012).

4.3. Number Cognition in Bilinguals

During the last decades, consequences of bilingualism in numerical skills development has been investigated considering critical factors such as age of acquisition, language of instruction during early learning math or language proficiency (L1 vs L2). This has allowed researchers to more thoroughly inquire in the basic aspects of the role of language in bilinguals´ numerical cognition. Based on current evidence, it is assumed that mathematical development in bilinguals normally involves one of the two languages. It is also well-known that bilinguals often translate or switch languages when carrying out simple arithmetic facts or for mathematical thinking in general (Moschkovich, 2007). This preferred language for number processing usually agrees with the language of instruction as has been shown in early studies (Bernardo, 2001; Clarkson, 1992; Frenck-Mestre and Vaid, 1993; Geary et al., 1993; Kolers, 1968). However, the question of the language preference for magnitude representations in bilinguals requires other important considerations related with how and when language connects with magnitude representation (Salillas and Carreiras, 2014).

Most of the studies about the influence of language in bilinguals' numerical cognition have been developed based in two different approaches. The most typical approach is to compare the arithmetic performance of bilinguals and monolinguals, and test whether bilinguals hold one or two storage systems for arithmetic retrieval (Domahs and Delazer, 2005; Frenck-Mestre and Vaid, 1993; Geary et al., 1993; Rusconi, Galfano and Job, 2007). A second interesting approach, test bilingual individuals in arithmetic tasks-solving, with or without previous training in their L1 and/or L2 (Bernardo, 2001; Campbell, 1999; Dehaene, 1999; Marsh and Maki, 1976; Salillas and Wicha, 2012; Spelke and Tsivkin, 2001). Particularly, comparisons have been made in bilingual children and adults in terms of stronger and weaker language impact (L1 vs L2) during problem-solving tasks (Campbell and Epp, 2004; Frenk-Mestre and Vaid, 1993; Rusconi et al., 2007; Secada, 1991). More recently, it has been shown that the processing of verbal numbers is influenced by the bilingual´s proficiency. Specifically, bilinguals with less L2 proficiency are affected in greater extent by the linguistic structures of number-words (decade-unit order) compared to bilinguals with similar proficiency between L1 and L2 (Macizo et al., 2010b, 2011). Thus, in light of this evidence, it seems likely that proficiency modulates bilinguals' processing of verbal numbers suggesting an important role of language in determining the access to the number system. In the following lines, I will depict the current empirical and theoretical framework about the role that language plays within the context of arithmetic facts and its implications in bilingualism.

The role of language in the context of exact arithmetic

In the present literature, the case of bilingualism has taken as an optimal way for testing the link between exact arithmetic and language (Frenck-Mestre and Vaid, 1993; Marsh and Maki, 1976; Salillas and Wicha, 2013; Salillas and Carreiras, 2014; Spelke and Tsivkin, 2001; Rusconi et al, 2007). It is well-known that bilinguals tend to perform *arithmetic facts* in one particular language (Spelke and Tsivkin, 2001). The majority of Math Cognition research shows bilinguals performing faster and with less error rates in the language they learn to perform arithmetic rather than in their other language (Marsh and Maki, 1976). In some cases, this language preference matched the most proficient or dominant language. This proposal was put forward based on early studies showing worse performance when numerical problems were posed in bilinguals´ weaker language or L2 (Frenk-Mestre and Vaid, 1993; Morales, Shute and Pellegrino, 1985). Therefore, for a long time it was assumed that the language of math instruction should necessary take place in the L1 or dominant language in order to facilitate the better development of numerical skills. However, such association is not clear yet given the fact that in those studies direct comparisons were made without controlling differences in linguistic proficiency (L1 vs L2) (Frenck-Mestre and Vaid, 1993). Thus, it was possible that relative high fluency of L1 compared with L2, explained the differences in numerical performance.

The influence of learning experiences in setting a preferred verbal code for arithmetic has been vaguely contemplated in the Encoding-Complex Model (Campbell and Clark, 1988; see also Campbell 1994; Campbell and Epp, 2004; Campbell and Epp, 2005). In short, the model claims that the bilingual arithmetic memory system keeps a relatively strong link with the language used for learning and retrieve arithmetic. However, the connection between one of the two languages and the arithmetic memory networks will depend, not on the proficiency but on the prior experience in direct retrieval of the arithmetic facts. The influence of math learning experiences with one of the two languages has been tested in bilingual children (Clarkson and Galbraith, 1992; Cummins, 1974, 1984; Kempert et al., 2011; Moschkovich, 2007; Spelke and Tsivkin, 2001). In Spelke and Tsivkin (2001) study, three experiments were conducted to investigate the influence of language in bilinguals´ numerical representation. Exact and approximate math problems were used (e.g. additions, cube roots) presented in the numerical verbal format. Russian-English bilinguals were trained to solve these problems in one of the two languages (either English or Russian). After the training session, participants tended to better perform exact problems with the trained language rather than with the non-trained thus, suggesting the idea of exact arithmetic being represented in a more language-specific form. Thus, language and math interact during children´s learning of arithmetic.

Another pertinent question highlighted in literature refers to the consequences of early learning in adults´ magnitude representation. In an educational bilingual environment, the language of formal instruction has enormous influence in knowledge representation (Clarkson and Galbraith, 1992; Malt and Wolff, 2010). In the case of math, consequences can affect early numerical knowledge development as well as math competence later in life. The impact of early learning in arithmetic processing networks has been recently investigated also in adult bilinguals. Salillas and Wicha (2012) tested arithmetic memory networks in adult bilinguals who only learned arithmetic in one of their two languages. Independently of the language dominance, bilinguals performed better (faster and more accurate) in the language of learning exact arithmetic. These results led authors to conclude that math and language connection is maintained in adulthood and language proficiency does not alter the arithmetic networks established during early learning.

In light of these reports, it is concluded that language plays an important role in those number task that require the retrieval of exact arithmetic (Dehaene, 1999; Rusconi et al, 2007; Salillas and Wicha, 2012; Van Rinsveld et al., 2015). To clarify and in line with Dehane ´s Triple Code Model, exact calculations (e.g. multiplication and addition) contrary to approximate number processing, are thought to be coded in a specific language. The reason is because they are learned and retrieved by verbal rote. In a similar way, associative network models explain (e.g. Ashcraft, 1992) that simple facts are stored in long-term memory and solved through automatic retrieval due to the fact that a link between each operand-node and the solution remains (Baroody, 1994; LeFevre and Morris, 1999; Rusconi et al, 2006). Thus, until very recently the association between language and numbers was conceived in relation to the management of exact arithmetic (Rusconi et al., 2007, pp.153-174; Salillas and Wicha, 2012). Very little research has considered the specific role of language beyond the context of arithmetic facts. In what follows, the hypothesis of the impact of the *language of learning math* in the quantity code will be described, since this question motivates the most notable aspects of the present dissertation.

The early learning impact in the core magnitude representation

The early learning impact in the core numerical representation system has been investigated considering the flexibility that the quantity code has after learning the counting sequence that is when math knowledge is acquired. The referred role of language, rise from the idea that in an early learning stage the numerical concepts are manipulated verbally (e.g. carryover additions and subtraction, multiplication tables, equation rules, etc.) and subsequently storage in long-term memory. Until Salillas and Carreiras (2014), this relation was understood as limited to the context of arithmetic facts. In light of recent reports, the possible **role of language in the quantity code** arises as a new alternative explanation in the bilingual math case. More precisely, this new proposal suggests that language should play a role in the more basic magnitude representation level. In bilinguals, this basic quantity system could have been shaped by one particular language. In line to this view, a broader concept to define the language preference for magnitude representation has been postulated as independent of the language proficiency and beyond the arithmetic fact retrieval. This concept is referred in literature as "*language of learning math*"[2] (LL^{math}) and is a very recent proposal that has questioned part of the current theory of numerical cognition in bilinguals (Salillas and Carreiras, 2014; Salillas et al., 2015). The assumed lack of linguistic influence on the quantity code in the models studying the math case in bilinguals (Campbell and Epp, 2004) has been investigated by examining the neural basis regulating such connection during early numerical development. In fact, neuroimaging techniques with high spatial and temporal resolution (fMRI, MEG, EEG) have been successfully used in bilinguals to explore the neuroanatomical and functional networks behind the linguistic trace in the core number representation (Salillas and Carreiras, 2014; Salillas, Barraza and Carreiras, 2015). Such connection between one of the two languages and the core system, it is hypothesized to occur during early learning math (Salillas and Carreiras, 2014; Salillas et al, 2015). In support of this claim, a

[2] It is a broader concept to define the language preference for magnitude representation beyond the arithmetic fact retrieval and is different from the so-called L+ or language for arithmetic (Salillas & Wicha 2012). The LL^{math} connects with the core numerical representation and its role is not only restricted to the exact arithmetic.

recent study provides ERP evidence of a possible linguistic shaping of the quantity code as a result of early learning factor. Since this topic is the motive of the present dissertation, in what follows, the very recent neuroimaging studies related to the impact of language in the most basic level of magnitude representation will be described together with the preceding studies of the neural basis of exact arithmetic.

4.4. Neuroimaging evidence

Based on above review, a critical factor that has been considered is how the learning process of numerical knowledge is influenced by language, determining the brain organization and functioning of the numerical system. Neural correlates underlying the process of learning exact arithmetic has been extensively explored in many studies (Dehaene and Cohen, 1997; Delazer and Benke, 1997; Dehaene, Piazza, Pinel, and Cohen, 2003; Delazer et al., 2003; Venkatraman et al. 2006). The common finding was a dissociation effect between arithmetic calculations involving exact and approximate processing on language-related networks (AG, left inferior frontal gyrus). For instance, in Venkatraman et al. (2006), a group of English-Chinese bilinguals were trained in solving exact and approximate calculations in one of their languages to further test them in an fMRI session. The main findings of this study revealed differential language switching effects depending on exact or approximate number processing localized in linguistic related areas. The involvement of one important language region (LAG) in well-learned arithmetic facts supports the hypothesis of a verbal rote rehearsal process before (verbal) automatic retrieval. Approximate estimation problems, were shown to rely less on language neural circuitries and more on visuospatial processing areas since problems were solved without a verbal strategy. This finding reflects changes in the neuronal reorganization according to the type of the numerical input that, in the case of bilinguals demonstrate that the trained language used to perform arithmetic has an effect in brain activity. Other bilingualism studies without explicitly experimental training, aimed to characterized the impact of the language of learning arithmetic facts in the exact arithmetic system using event-related potentials (ERPs) methods (Bernardo et al., 2001; Salillas and Wicha, 2012). In one of these studies with English-Spanish bilinguals, arithmetic facts solutions were presented in what the authors called the "Language of Learning Arithmetic"(L+) [3]vs. the "Other Language" (L-). Results showed differences in the ERP brain pattern as function of whether the presented problem was in (L+) or (L-) input.

Apart from the influence of language in exact arithmetic, the linguistic traces in the quantity code as result of early learning processes of numerical verbal symbols has been study with ERP technique. Salillas and Carreiras (2014) explored the permeability of the quantity code to language and the influence of early learning in the core numerical representation with balanced bilinguals. Using a simple comparison task, authors tested two groups of balanced Spanish-Basque bilinguals differing in their LL^{math}, for a possible association between a particular number wording system (vigesimal vs decimal) and the quantity code (i.e. core numerical knowledge). The results showed that a different ERP pattern was associated to the Basque wording system (vigesimal) as a function of the LL^{math}. In particular, the reported data showed an early N1-P2 distance effect during a number comparison task, modulated by linguistic variables (LL^{math}). This led the authors to suggest verbal signatures in the core magnitude representation system due to early learning math. In a subsequent experiment using EEG oscillatory analysis, authors provided consistent evidence supporting the same hypothesis. Specifically, the results suggested that a different neural network could be implicated when performing magnitude comparisons in the LL^{math} (Salillas,

[3] In the context of simple arithmetic task, is the language in which bilinguals learned to solve exact arithmetic.

Barraza and Carreiras, 2015). Overall, these series of studies demonstrated that the early linguistic context of learning math might have printed bilinguals´ long-term magnitude processing networks.

In summary, the reviewed empirical evidence suggests first, that the role of language in numerical cognition is conditioned to the exact arithmetic system but possibly also on most fundamental aspect of numerical knowledge. Secondly, arithmetic facts are integrated within language cortical networks mainly because they are learned verbally and retrieved by rote. Third, the link between math and language apparently is not restricted to the context of arithmetic facts. Finally, a possible linguistic shaping of the basic quantity representation system is proposed which further might include the impact in the spatial magnitude representation (Dehaene, 2009; Nieder and Dehaene, 2009; Salillas and Carreriras, 2014; Salillas, Barraza and Carreiras, 2015). This latter conjecture is the main topic of research in the present dissertation.

With the purpose of better define the functioning of the numerical system we address in next chapter the relevance that working memory (WM) has as an important element to the correct development numerical skills. Despite its importance, WM is not currently contemplated in general math cognition models. Given its relevance for this study, in the following section I will provide a brief review related with the role of Working Memory in Math Cognition.

CHAPTER 5

5. WORKING MEMORY AND MATH COGNITION

5.1. INTRODUCTION

Besides the described components of the essential math system, the performance of math operations such as calculations, reasoning or comparison, imply a variety of conceptual and procedural cognitive functions. One of these cognitive domains refers to Working Memory, defined as a "multi-component short-term storage with limited capacity to hold and manipulate different types of information" (Baddeley and Hitch, 1974; Conway, Cowan and Bunting, 2001, Cowan, 2010). There is a diverse variety of cognitive models that attempt to explain the functional structure and cognitive mechanism underlying WM. Within this cognitive framework, Baddeley´s Multi-component model (2000) has been the dominant theory in the recent decades. The model offers a modular explanation based initially on three functional components, each one specialized in one type of information: *Visuospatial Sketchpad*, *Phonological Loop* (verbal) and *Central Executive* (control function). In a later reviewed version, a fourth component was added termed *Episodic Buffer*, responsible of integrating information coming from the other three storage systems (Baddeley, 1986, 2000; Baddeley and Wilson, 2002). This model has been extensively used in research and educational practice aiming to test working memory, for instance, in children population with arithmetic disabilities (Dehaene, 1997; De Smedt et al., 2009; Meyer et al., 2010). Overall, Working Memory is essentially a significant construct and widely studied in the definition of complex cognition. Hence, understanding the mechanism that modulates a wide range of human number cognitive processes includes the understanding of the specific role that Working Memory (WM) has in Math Cognition (DeStefano and LeFevre, 2004).

5.2. The relevance of working memory in Math Cognition

Working memory is characterized by a short-term memory storage that can be divided into separate subsystems. Information is first encoded into memory, actively maintained and subsequently retrieved. These isolated processing stages delineate the way information is managed and bound with long-term representations (Baddeley et al., 1984; Anderson, 2000). A fundamental aspect of working memory is the limited capacity to maintain information active for a long span of time. Serial recall is one important feature for measuring Working Memory. According to Miller studies (1956), the recall limit of meaningful items is not greater than 7 (Baddeley and Hitch, 1974; Miller, Galanter and Pribram, 1960). But this capacity can vary among people and depends on verbal factors like number of chunks or task demands. This is what Nelson Cowan (2010) describes in “The magical mystery four” referring to the capacity of the Working Memory system to retain no more than 5 items at once (3-5 chunks in adults). Importantly, this was under a limited contribution of the phonological rehearsal. Not only task demands but *individual differences* in the capacity of these subcomponents would determine the nature of the WM limitations (Baddeley and Lieberman, 1980; Logie et al., 1990; Raghubar et al., 2010; Rose, 2013). Hence, it seems that the phonological loop is crucial for the rehearsal when the amount of information increases (Baddeley and Logie, 1999). This is notably experienced in common cognitive activities like language comprehension or mental arithmetic. Similarly, the visual imagery system would be helped by the visual and spatial component of WM.

With regard to Math Cognition, none of the current models explicitly contemplate the role of WM. This lack of a clear definition is perhaps due to the complexity and the variety of aspects (task, paradigms) that entail the use of working memory in math cognition research. It could also be that the integration of WM into any of the numerical models is rather complicated since there are factors difficult to combine within one general model of numerical processing (LeFevre, DeStefano, Coleman and Shanahan, 2005). In any case, it should be one part of future math cognition advances, to enquire in a greater depth into the WM aspects engaged in number cognition. In the following lines, I describe the theoretical framework concerning to the role of verbal and spatial working memory in Math Cognition.

Verbal WM in numerical cognition

The Baddeley and Hitch (1974) multicomponent model offers a structured view of WM that partially allows a possible connection with Math cognition theories. In LeFevre, et al. review (2005) it was postulated that although a relation between WM and number processing has long been proposed, the evidence connecting the two fields appears to be sparse. To what extent different subsystems of WM are implicated in mental arithmetic (Logie et al., 1994) and other mathematical tasks such as magnitude inferences or problem solving, are ongoing research topics (see review of DeStefano and LeFevre, 2004; LeFevre et al., 2005).

Concerning to the specific role of verbal working memory, outcomes in math cognition research have been frequently associated to math difficulties. Specifically, studies show that deficits in WM are causally related with poor math development skills (Duverne, Lemaire, and Vandierendonck, 2008; Hecht, 2002; LeFevre et al., 2005; Passolunghi and Comoldi, 2008). Indeed, difficulties in memorizing arithmetic facts are observed in many children with math disabilities persisting over development (for a review see Coleman , 2005; Hanich et al., 2001; Jordan and Hanich, 2000). One explanation is that verbal WM limitations cause this sort of difficulty mainly because during early learning the associations between the arithmetic problem and the solution has not been stored properly through the verbal code (DeStefano and LeFevre, 2004; Geary, Brown and Samaranayake 1991; Geary 1994, 2004; LeFevre, 2003; Shrager and Siegler, 1998). Additionally, there are factors related with the modality of presentation (visual vs. auditory) and spatial arrangement (vertical and horizontal) that determine to what extent verbal WM is recruited (see review in DeStefano and LeFevre, 2004). In this regard, many studies suggest that verbal WM storage is involved in multi-digit calculations presented either in visual or auditory format. The general conclusion was that when numbers are auditory presented the access to the temporary phonological storage is more direct than when are visually presented (Noël et al., 2001). Further, this is supported by neuroimaging data showing that factors such as the input-format and rate of presentation, affect numerical information processing (Simon and Rivera, 2007, pp. 283-305).

Despite the fact that WM is critical in math competence development (for a review Raghubar, Barnes, and Hecht, 2010) general models of mathematical cognition do not explicitly contemplate the role of WM in number processing. According to these models and the available evidence, is clear that exact arithmetic facts are retrieved verbally from Long Term Memory (LTM). It has been suggested that the intervention of verbal WM in arithmetic fact retrieval depends on different factors such as computation strategies (e.g. counting) (Imbo and Vandierendonck, 2007), the input modality (Trbovich and LeFevre, 2003) and the way in how arithmetic facts were taught/ learned (LeFevre and Liu, 1997; LeFevre et al , 2001). For instance, using a dual-task paradigm, a study with Korean speaking individuals showed that the verbal load significantly impaired the performance of multiplications but not subtractions (Lee and Kang, 2002). In line with the Triple Code Model (Dehaene, 1995), authors concluded that storing and retrieval of multiplication is more closely related to verbal codes than subtractions. Thus, the main suggestion is that the exact arithmetic store is more related with verbal WM in a specific manner, highly dependent on the type of numerical information that needs to be manipulated (see also Trbovich and LeFevre, 2003). Great demands of verbal WM in approximate arithmetic have been also demonstrated by Kalaman and LeFevre (2007). In their study participants had to solve either approximate or exact two-digit additions problems together with a verbal WM task. Results showed that WM load impaired performance of both types of additions, although the performance of exact problems was affected in greater extend.

In summary, the connection between numerical cognition and verbal WM seems to be modulated by several conjointly factors mostly related with the task (e.g. stimuli arrangement), number format (e.g. Arabic vs number-words) and problem complexity (e.g. single-digit vs. multi-digit).

Visuospatial WM in number representation

Visuo-spatial working memory constitutes a very important piece in number processing and math abilities development (Kyttälä et al., 2003; Meyer et al., 2010). Based on Baddeley´s model (1974), the nature of the visuo-spatial WM (VSWM) component is fragmented, which means that two separate storages coexist for visual and spatial information. The proper way to define VSWM is by distinguishing three separate representational formats: a visual representation of perceptual information of objects (refers to its appearance), spatial coordinates referring to where the stimuli are located, and object store representing bound information. According to the revised multicomponent model (Baddeley, 2000), spatial WM seems to represent information independently of the input modality (see also Paivio, 2014). Indeed, several studies suggest that the same processes are operating the spatial coding for visual and auditory modality (Lehnert and Zimmer, 2006, 2008; Saults and Cowan, 2007).

In relation to number representation VSWM is known to be implicated in several aspects of number processing. For instance, VSWM plays an important role in calculation or mental arithmetic (DeStefano and LeFevre, 2004; Heathcote, 1994; Lee and Kang, 2002). Furthermore, mathematical symbols constitute part of the visuo-spatial material that functionally organizes number processing (e.g. 3456, 34+78). Without the visuo-spatial implication, it would be difficult to understand for instance, the value of one digit in relation with other group of digits or numerical symbols. Indeed, the Mental Number Line (MNL) is spatial by definition and exemplifies the importance of visuo-spatial features in the internal magnitude representation (Ansari, 2008; Cohen Kadosh and Walsh, 2009; Dehaene, 1992; Feigenson, Dehaene and Spelke, 2004; Friso-van den Bos et al., 2013; Zorzi et al., 2006). In this regard, spatial number representation has been related with mathematical performance and problem solving (Booth and Siegler, 2008; Rotzer et al., 2009) further suggesting a significant implication of the spatial component of working memory (Fias et al., 2011, pp. 133-148). Moreover, there is evidence suggesting a strong engagement of visuospatial representations during approximate arithmetic computations while performance of exact arithmetic facts seems to rely more on verbal knowledge (Dehaene et al., 1999; Kalaman and LeFevre, 2007). Thus, it is reasonable to infer that different WM resources will be recruited in exact and approximate numerical problem solving. Moreover, it has been found strong correlations between VSWM abilities and numerical skills (Bachot, Gevers, Fias and Roeyers, 2005; Keeler and Swanson, 2001; Reuhkala, 2001). In one of these studies it was suggest that the correlation between visuospatial and numerical disabilities might be influenced by an abnormal development of the core representation of numerical magnitude on an oriented MNL (Bachot et al., 2005).

Another critical idea extracted from recent research indicates that VSWM is partly engaged in numerical-spatial coding processes. For example, in a magnitude comparison task in single and dual-task conditions, it has been shown that the visuo-spatial component of working memory has important implications in the processing of spatial representation of numbers (Herrera, Macizo and Semenza, 2008; van Dijck, Gevers and Fias, 2009; van Dijck and Fias, 2010). Specifically, some of this studies showed that the SNARC effect disappeared under WM load suggesting that the availability of WM resources is necessary for the numerical-spatial coding to occur. Further, the ordinal position of numbers in WM seems to correlate with the SNARC effect during maintenance stage which facilitates the efficient execution of the task (van Dijck and Fias, 2010; see also Monsell, 2003). This data led authors to suggest that at some point, numerical-spatial magnitude representation is coded as a function of its serial position in a WM task and not based on long-term MNL representation. Although it seem plausible that WM resources might influence the SNARC effect at some point, this evidence is by itself not sufficient to discard that the long-term MNL representation is not what originates automatic numerical-spatial associations especially in light of previous neuroimaging data (e.g. line bisection bias effect in left hemineglect patients; Priftis et al., 2002; Umilta et al., 2009; Zorzi et al., 2002).

An effective way used in research to investigate how VSWM modules operate during the execution of numerical tasks is by means of the specific WM stages of processing: *encoding, retention and retrieval* (Anderson, 2000; Baddeley et al., 1984). Maintenance and rehearsal mechanisms operate for instance, in MNL retrieval. In turn, the spatial configurations of magnitude stored in long-term memory would represent spatial positions that are also used for encoding information in a variety of numerical WM task. Through the use of neuroimaging designs (e.g. EEG, fMRI), it has been possible to study the dissociate activity engaged in each WM processing stage (e.g. D´Esposito, Postle and Rympa, 2000). For instance, the maintenance of visuospatial information over short delays as well as those cognitive processes engaged during encoding and retrieval at the time of stimulus presentation (or probe presentation) has been studied in delayed response task (Courtney et al. 1997; D´Esposito et al., 1999; Zarahn et al. 1999; see data reviewed in D´Esposito et al., 2000). A more systematic look to how these operations are connected at the neuronal level might provide some advances to understand how number cognition and VSWM are interrelated.

Overall, the implication of VSWM in number representation allows the successful development of numerical representation from an initial stage of mathematical skill. Assuming that the basic numerical representation (Dehaene, 1992; Wynn, 1998) has a spatial component, it is likely that this central representation might be at least initially affected by VSWM. Thus, in light of the VSWM implications observed in the vast majority of studies, current research is beginning to focus on the influence of spatial WM in numerical processing. In the following section, empirical evidence from brain imaging research will be reviewed focusing mainly on the relation between number processing and the different Working Memory stages.

5.3. Neuroimaging evidence

Working memory research has taken advantage of fMRI spatial resolution to identify the networks of brain regions associated with the maintenance of visual/auditory stimuli over shorts delay intervals (Druzgal and D'Esposito 2003; Ranganath and D'Esposito 2001). A substantial number of human fMRI *studies* identify a *delay activity* during the maintenance of the to-be-recalled information in a variety of WM tasks. In such studies, this activity seems to be allocated in certain regions of the prefrontal cortex (Miller et al., 1996; Pessoa et al., 2002; Postle et al., 2000; Rowe et al., 2000; Kane and Engel, 2002) and the inferior temporal cortex (Ranganath, Cohen, Dam and D'Esposito, 2004). Some of these studies have shown significant correlations between regions of the prefrontal and parietal cortex during the delay period supporting interactions of higher-order association areas with sensory regions during the encoding and maintenance of information.

Furthermore, increases in memory demands (memory load) have been associated with an increase of hemodynamic signal in several frontal regions like dorsolateral and ventrolateral prefrontal cortex (Duncan and Owen, 2000). It is also known, that the amount of sustained brain activation during the delay period apparently correlates with accuracy in WM task performance at the behavioral level. The main suggestion is that the activity during the delay is critical for a successful working memory execution in a given task (Pessoa et al., 2002). This is mostly related with the capacity of the WM system to efficiently retain and retrieve the information under different *memory loads*, considered crucial in WM research. For instance, in a typical n-back[1] or Sternberg task[2] under high-load and low-load conditions, the magnitude of brain activations during the delay shows a variation that is proportional to the working memory load (Braver et al., 1997; Cohen, et al., 1997; Jensen and Tesche, 2002). Similarly, prefrontal activation under high and low loads has been found to increase

[1] The n-back task requires participants to decide whether each stimulus in a sequence matches the stimulus that appeared *n* items ago.

2 The Stenberg task involves presentation of a list of items to memorize, followed by a memory maintenance period. The subject must answer whether a 'probe' item was in their memorized list or not.

according with the level of participants' performance. Hence, the delay activity seems to partially reflect the effects of memory load during the retention of information as shown in the majority of the studies (McCollough, et al., 2007; Rypma and D'Esposito, 2002; Todd and Marois, 2004; Vogel and Machizawa, 2004).

In relation with *spatial WM*, frontal and posterior parietal activations have been reported in a wide variety of fMRI studies (D'Esposito et al., 1998; Diwadkar, Carpenter and Just, 2000; McCarthy et al., 1996; Smith, Jonides and Koeppe 1996; Smith and Jonides, 1997). Evidence suggests that spatial working memory is supported predominantly by a network of *right-hemisphere* regions that include areas in *posterior parietal, occipital, and frontal cortex*. In one of these studies conducted with Positron Emission Tomography (PET)[3] technique, results showed different brain pattern activity depending on whether the material was spatial or verbal (Jonides et al., 1993). While the spatial task showed significant activations in right-hemisphere regions (included posterior and parietal cortex, occipital cortex, premotor area, inferior prefrontal cortex), the same task but with verbal stimuli, *showed left-hemisphere activations* (areas involved language production: Broca´s area and premotor areas) (Smith et al., 1996). Indeed, most functional brain imaging studies of *spatial* WM in humans have found activation in dorsal and posterior frontal areas and more precisely, in the superior frontal sulcus during the delay activity (Courtney et al., 1996, 1998; Curtis and D´Esposito, 2003; Owen, Evans and Petrides, 1996; Smith and Jonides, 1996). However, the specialized implication of this latter region in mnemonic functions needs more investigation as it is located in the premotor cortex and thus suscep-

3 A positron emission tomography (PET) scan is a specialized nuclear imaging procedure that shows the metabolic activities released in brain to map functional processes. Areas of high radioactivity are associated with brain functional activity.

tible to be attributable to motor responses preparation activity (Courtney et al., 1996, 1998; D´Esposito, 2007; Postle et al, 2000).

Moreover, electrophysiological studies have provided time resolution data to account for WM activity at each processing stage (Lang et al., 1992; McCollough, Machizawa and Vogel, 2007; Klaver et al., 1999; Ruchkin et al., 1992, 1997a, 1997b). One of the most common approaches is the Event-related potential (ERP) analysis. The ERP activity elicited during WM operations has been tested during the *encoding-retrieval, retention and recall stages*. By this means, researchers have been able to quantify at each WM phase, the electrophysiological activity elicited during a variety of WM tasks. For instance, the brain dynamics during encoding as a function of subsequent memory performance has been explored: items that were successfully recognized (i.e. hits) showed greater amplitude differences in the interval between 400-1200ms offset than the unrecognized items (miss/fails) (see Friedman and Trott, 2000). In addition, consistent with fMRI data, successful encoding has been related with left inferior frontal areas as shown in topographical analysis (voltage and current source density maps; Friedman and Johnson, 2000; Werkle-Bergner et al, 2006). A variety of studies have provided evidence of ERP components that are systematically associated with specific WM operations (Mecklinger and Muller, 1996). The commonest finding is a *negative slow wave (nSW)* component broadly distributed depending on the type (verbal, spatial) and modality (aurally, visual) of the to-be memorized information (Patterson et al, 1991; Ruchkin et al., 1988; 1995, 1997). In some of these studies, the negative slow waves are correlated with rehearsal/retention operations during the delay period. Several aspects such as polarity, timing and scalp distribution characterized this nSW, often indexing mnemonic processes during the retention interval and highly affected by the memory load (Ruchkin et al., 1988, 2003). That is, the more demanding WM resources, results in an increase of the nSW amplitude (Berti, Geissler, Lachmann and Mecklinger, 1999; Ruchkin et al., 1995). Further, it has been observed that these long lasting slow waves produce different topographies depending on whether the information is spatial or verbal. For instance, it has been show that *left-frontal topographies* are related with verbal processing material while bilateral distribution over parietal sites is consistent with processing of spatial information, thus suggesting different neural generators (Rösler et al., 1995, 1997). The amplitude and topography of the slow event-related potentials have been also shown to be sensitive to the perceptual modality of input information. For instance, some WM studies show a bilateral distribution elicited when material is presented in the auditory modality while a left-lateralized activity tends to be common for both modalities (Ruchkin et al., 1997). Finally, a non-linguistic *N400-like* component has been related is some studies with *retrieval* of long-term representations thus, suggesting specific binding mechanisms in response to a cue stimuli (Friendman and Jonhson, 2000; Kutas and Federmeier, 2000; Rugg et al., 2002).

OVERVIEW

6. THE PRESENT STUDY

6.1. OUTLINE

The review of the main theoretical and empirical insights contemplated in Math Cognition framework aimed to provide a walk through the state of the art of the main topics of interest that concern to the present thesis. Evidences of the connection of space and numbers have been strongly remarked consistent with classical and recent research findings. The impact of language in the MNL (impact of reading, categorical dimensions, etc.) has been postulated as an ongoing research question in literature and several neuroimaging studies. In order to understand the role of language in the core magnitude system, advances in math cognition research have been followed by bilingualism research, leading to the core question of which of the two languages the bilinguals prefer not only for arithmetic but for basic magnitude representation. Finally, implications of WM in number processing have been demonstrated in multiple math performance experiments in children and adults. Considering Baddeley´s Multicomponent WM model (1974) as the vehicular theory, we have outlined the main conclusions from working memory studies demonstrating verbal and visuo-spatial implications in a variety of WM task with numerical material at the behavioral and neurocognitive level. This entire framework is relevant to motivate and ground the experimental part of this thesis.

6.2. BILINGUALISM, MNL AND WORKING MEMORY COME TOGETHER

In the present study, I investigate **the linguistic impact that the Language of Learning math LL^{math} might have in the spatial-number association.** Consistent with the reviewed literature, this study aims to inquire whether the preferred language for math (LL^{math}) impacts the management of the spatio-numerical representation. This is a question not contemplated yet in the bilingual math cognition research. We know from literature that numerical spatial representation connects with the core numerical representation (Dehaene et al, 1993; Hubbard, Piazza, Pinel and Dehaene, 2005). In line with Salillas and Carreiras (2014), here a possible relation between the LL^{math} and the numerical magnitude is hypothesized. This connection is proposed to take place during early math learning. At the same time, development of the spatial component of numerical representation (MNL) co-occurs with a context in LL^{math} and could be likely stored in that code in long-term memory. Consequently, it is hypothesized that bilinguals would automatically activate the MNL representation with the LL^{math}. Thus, a general aim of this study is to explore whether **the language of learning math (LL^{math} vs. Other Language) is the preferred verbal format in adults' bilinguals for the management of the MNL or even to its representation**. If so, an unbalance between languages (LL^{math} vs Other Language) is expected during retrieval of the spatial-numerical representation. Taking into account the previous literature this is a very likely possibility never tested before. This language preference could be detected in a Working Memory (WM) task wherein both, language and space are required. Therefore, this study is based on three WM experiments that combined with EEG recordings, aimed to characterize the neural bases underlying the influence of each language (LL^{math} /OL) in the numerical-spatial representation. In the next lines, I will briefly summarize the three conducted experiments of this study.

Experiment 1 investigates the impact of the language of learning math (LL^{math}) in long-term representation of Mental Number Line (MNL) when both, verbal and visuo-spatial working memory components are engaged. A group of Spanish-Basque balanced bilinguals (young adults) were selected to complete a working memory task wherein the numerical information was presented verbally in both languages. We manipulated two variables with four experimental conditions: Congruency (C) defined as congruent or incongruent with the MNL layout; and Language (L) defined as LL^{math} vs de OL. Our major goal was to characterize the pattern of ERP activity (time course and topography) associated with each language as a function of early learning during encoding, retrieval of the MNL at the processing level and retention. Thus, critical comparisons were made between experimental conditions (Congruency and Language).

Experiment 2 aimed the same goal as Experiment 1 but considering the impact of early learning across different memory loads (low/high). A group of bilinguals with the same linguistic profile as Experiment 1 was selected. The design was similar as Experiment 1 but in addition to Congruency and Language conditions, we manipulated a third factor: Memory Load (ML) defined as low (four items) and high (six items). Our major interest here was to compare possible brain differences (ERPs components, time course and topographies) as a function of early learning when the cognitive demand of the task increases. This allowed us also to characterize the WM efficiency when numerical-spatial information is managed in LL^{math} and OL. Thus, comparisons between experimental conditions (Congruency and Language) were made in low and high WM loads.

Experiment 3, has the same objective and experimental design as Experiment **2** but numerical and spatial information was presented in the auditory modality. Selected participants had the same linguistic profile as both previous experiments. Our major goal was to test the impact of early learning in the activation to the MNL representation considering the influence of the auditory modality in neural activity. Thus, we compared ERP components, time course and scalp topographies across critical conditions.

Together, the three experiments provide a measure of the behavioral (delayed RTs /accuracy) and brain response (ERP) to spatial-numerical information presented in LL^{math} and in the OL. In next section, the methods and results of the three presented experiments will be described together with the fundamental conclusions and implications that this study has in the field of Math Cognition and Bilingualism.

EXPERIMENT 1

1. INTRODUCTION

One remarkable question in Bilingual Math Cognition research is which language bilinguals prefer for number representation. Bilinguals have two verbal codes for the same magnitude, so that the one-to-one mapping between number words and magnitude knowledge becomes more complex. Some studies have shown that one verbal code is preferred during specific numerical tasks, such as fact retrieval or even number comparison, regardless of proficiency (Salillas and Wicha, 2012; Salillas and Carreiras, 2014; Salillas, Barraza and Carreiras, 2015). Moreover, it has been suggested that arithmetic memory networks could have been shaped differentially by each of the two languages (Salillas and Wicha, 2012) but also, the basic number representations might have been influenced by language (Salillas and Carreiras, 2014). The present study aims to further investigate whether the early use of one number word system impacts differentially on specific components of the magnitude code. That is, whether the language used for learning math (LL^{math}) is the bilinguals´ preferred verbal code for basic magnitude representation, attending to its spatial component.

Number representation might entail **spatial** features in the form of a left-to-right oriented Mental Number Line (Dehaene et al., 1992; Fischer, 2003; Galton, 1880; Gevers et al., 2006; Gobel et al., 2001; Hubbard et al, 2005; Previtali et al., 2010; van Dijck et al., 2014). Such stable association between numbers and space has been observed across different tasks, formats (i.e. Arabic, number-words, dot- patterns, etc.) (Dehaene et al., 1993; Fias, 2001; Nuerk et al., 2004; Reynvoet et al., 2002) and modalities (i.e. visual, auditory, tactile) (Brozzoli et at., 2007; Di Luca et al., 2006; Fischer et al, 2003; Nuerk, Wood and Willmes, 2005; Proctor, Yamaguchi and Vu, 2007). The MNL hypothesis is clearly supported by the SNARC effect (Spatial Association of Response Codes) (Dehaene, Bossini and Giraux, 1993). Spatial association reflects the access to an abstract representation of magnitude regardless of the format or numerical notation (Restle, 1970; Moyer and Landauer, 1967; Dehaene, 1992; Hubbard et al., 2005). The spatial component is integrated in the magnitude representation however, can be influenced by external factors such as reading/writing directions (Dehaene et al., 1993; Zebian, 2005).

Additionally, the relationship between **Math and Language** is a question of intense debate (Dehaene and Cohen, 1995; Dehaene et al., 2003; Campbell and Epp, 2004; Gordon, 2004McCloskey, 1992). This relation has been shown through the study of cultures with a very limited range of number expressions to refer to numerical concepts (Gordon, 2004, Pica et al., 2004). In bilinguals, the influence of language in numerical representation has been explored considering the distinction between approximate and exact arithmetic. Some studies have used exact and approximate number tasks to investigate numerical representation in both languages (Bernardo, 2001; Spelke and Tsivkin, 2001). These studies showed that bilinguals activate one preferred language for arithmetic facts retrieval but the preferred language not always matched the bilinguals´ L1. Instead, and consistent with assumptions derived from Encoding-Complex model (Campbell and Clark, 1988; Campbell et al., 1999), they activated the language used for learning and practicing arithmetic tasks. However, recent proposals have twisted the focus to the role that language plays in the evolution of the most basic magnitude knowledge (Delazer, 2003; Nieder and Dehaene, 2009; Butterworth, 2010; Piazza, 2010; Salillas and Carreiras, 2014; Salillas et al., 2015). To investigate this issue in bilinguals, recent studies have tested equally proficient bilinguals performing simple numerical comparison tasks (Salillas and Carreiras, 2014; Salillas, Barraza and Carreiras, 2015). The results indicated that bilinguals’ quantity code, may have been shaped by one particular language that not necessary agreed with the most proficient language. The so-called "Language of Learning Math (LL^{math})" is currently posited as the preferred verbal code for numerical representation in bilinguals.

To further investigate the nature of language influence in the essential numerical knowledge, the present study addresses the question of how spatial numerical representation (MNL) is affected by LL^{math} as result of early learning. Thus, this study proposes that a mapping process between the LL^{math} and number magnitude occurs during the development of the spatial number representation. This association is preferentially long-term stored, so that a language preference (LL^{math} vs. Other Language (OL)) would be expected in bilingual adults during the activation the MNL. To study these predictions, we reasoned that a way of detecting a possible impact of LL^{math} in the MNL could be by means of a Working Memory (WM) task wherein such language and numerical-spatial coding has to be managed conjointly. Therefore, we conducted a WM experiment wherein both, numerical and spatial information are processed.

Working memory entails a number of operations each one related to a transient cognitive stage (Friedman and Johnson, 2000; Ruchkin et al., 1992, 1997a, 1997b; Smith, Jonides and Koeppe, 1996). In this way, *encoding* and *maintenance* are both processes needed to keep information active while *retrieval* involves calling back the stored information in response to a cue. Previous WM research investigated the neural dynamics underlying working memory activity. Most of these studies used variations of *matching-to-sample task* with a delay response combined with ERPs methods. In this type of paradigm, the interval between the retained stimulus and the presentation of the test stimulus (i.e. delay period) elicits sustained neural activity identified as

slow wave that commonly index retention processes (Bosch et al., 2001; Drew, McCollough and Vogel, 2006; Klaver et al., 1999; McEvoy, Smith and Gevins, 1998; McCollough, Machizawa and Vogel, 2007; Ruchkin et al., 1990; 1992, 1995; 1997). It has been shown that the amplitude and topographic distribution of slow waves potentials correlate with the type and amount of information maintained in working memory. The usual polarity of the slow wave is negative (but sees Gevins et al., 1996; García-Larrea and Cezzane-Bert, 1998) and the time course is variable depending on the extension of the delay. Some studies showed negative slow wave (nSW) onset around 400 ms post-stimulus and lasting about 1400ms post-stimulus (Berti et at., 2000; McEvoy et al., 1998; Ruchkin et al., 1992; 1994). Moreover, scalp topography can differ between visual and auditory verbal material (Lang et al, 1992), possibly reflecting the kind of WM component they call upon (i.e. visuo-spatial sketchpad vs. phonological loop). For instance, left-anterior negativities have been reported during the delay period in verbal WM task (Ruchkin et al., 1990; 1992). Instead, during retention of visuospatial information, negative slow wave activity is largest in right-side scalp (Ruchkin et al., 1992; 1997). Thus, ERP slow waves are relevant brain signatures to study the type and amount of activated representations under different conditions.

Other WM studies reported an **N400-like** related with retrieval from long-term memory (Chao, Nielsen-Bohlman and Knight, 1995; Friedman and Trott, 2000; Friendman and Jonhson, 2000; Kutas and Federmeier, 2000; Nielsen-Bolchman and Knight, 1999; Rugg et al., 2002). In some specific cases, changes in the N400 amplitude have been related with activation of long-term memory representations (Federmeier and Laszlo, 2009; Kutas and Hillyard, 1980; Kutas and Federmeier, 2011). Specifically, the N400 activity would be generated by matching comparisons of semantic encodings of the stimuli with long-term representations. In the context of arithmetic tasks, N400-like effects have been reported in arithmetic facts incongruities (Galfano et al., 2004; Jost, Hennighausen and Rösler, 2004; Martinez-Lincoln et al., 2015; Niedeggen and Rösler, 1999; Niedeggen, Rösler and Jost 1999), with a noticeable functional similarity to the linguistic N400 (Kutas and Hillyard, 1980). Thus, instead of semantic representations, the N400-like in numerical tasks would reflect automatic activation of long-term arithmetic facts networks (Niedeggen and Rösler, 1999).

ERPs N1-P2 effects have been also observed in numerical cognition research (Libertus et al., 2007; Liu et al., 2011; Paulsen and Neville, 2008; Salillas and Carreriras, 2014). Previous studies investigating spatial-numerical association in the context of attention-orientation paradigm (Dehaene, 1996; Gut et al., 2012; Ranzini et al., 2009; Salillas et al., 2008) have shown the involvement of early ERP responses (P1, N1, P2p components). Shift of attention induced by number cues have been shown at the level of P2p component, mostly appearing in latencies between 200ms and 280ms approximately after the onset of the number (Ranzini et al., 2009). In the context of numerical comparison task, the N1-P2p activity is supposed to index the access to number semantics (Cao et al., al, 2010; Hyde and Spelke, 2009; 2012; Libertus et al., 2007; Liu et al., 2011; Salillas and Carreiras, 2014). The reported data showed that numerical semantic effects were associated with patterns of N1-P2p transition. For instance, the distance effect modulated by language reported by Salillas and Carreiras (2014) appeared at the N1-P2 latency band showing high sensitivity of this ERP component to the linguistic variables of the numerical information. In fact, it has been claimed that the P2p might be an index of the approximate magnitude representation system (Hyde and Spelke, 2012), and that these early effects are an indication of the automatic access to magnitude representation (see Dehaene, 1996; Temple and Posner, 1998). On the other hand, variations in the amplitude of the N1 and P2 components are linked to high cognitive functions such as working memory or spatial attention (King and Kutas, 1995; Münte et al., 2000). For instance, it has been reported early N1-P2 components evoked during encoding of objects or visuo-spatial information, sometimes preceding the P3 component (Mecklinger and Pfeifer, 1996; Peters et al., 2005)

In the present study, an EEG experiment was conducted to address the relation between early math learning and the MNL in balanced bilinguals. We employed a design that allowed isolating the electrophysiological signature of sustained activity during memory encoding, MNL retrieval and retention of numerical-spatial information. Electrophysiological measures were combined with a delayed matching-to sample paradigm. The commonest version of this task, requires participants to first encode a set of items (memorizing sequence) and after a delay, ask them to make a correctness-judgment response to a probe item (e.g. Sternberg task, Sternberg, 1966). Participants were instructed to memorize the spatial location of a set of numbers presented visually either in the LL^{math} or in OL, and respond accordingly to a test number. The presented number-words could be congruent with the spatial arrangement of the MNL (small numbers-left side/ large numbers-right side) or incongruent. In order to test our general hypothesis (i.e. impact of early learning factor), we investigated in first place the possible interaction between Language and Congruency.

Main classical ERPs such as a *N1-P2*, *N400-like* or the *nSW* are likely to be elicited (Gevins et al., 1997; Ineke van der Ham et al., 2010; Shucard et al., 2009). Based on previous studies investigating the numerical-spatial connection (Dehaene, 1996; Gut et al., 2012; Ranzini et al., 2009; Salillas et al., 2008) and studies of visuospatial WM (Berti et at., 2000; McEvoy et al., 1998; Ruchkin et al., 1992, 1994, 1997), critical comparisons were made within the time course of three WM processing steps: *early encoding* activity at the level of the N1-P2; *retrieval of MNL* representation at the level of N400 latency band; and *retention* consistent with the delay period activity (nSW). In second place, the pattern of ERPs distribution indexing congruency processing was inspected separately in each language condition (LL^{math} / OL). This allowed us testing the prediction of different neural pathways associated to the automatic activation of MNL representation in each language condition. We focused on lateralized scalp activity associated with manipulation of spatio-numerical information in WM to have a measure of possible underlying lateralized networks engaged as a function of the input processing material. Lateralized topographies have been already reported in previous numerical-spatial processing studies mainly suggesting the manifestation of possible hemispheric specialization processes (Gut et al, 2012; Ranzini et al., 2009). Furthermore, in WM studies, different scalp topographies have been reported depending on the type of information to-be-held (verbal/spatial), WM stage and memory load (Bosh et al., 2001; Löw et al., 1999; Mecklinger, Pfeifer, 1996; Ruchkin et al., 1992, 1997; Shucard et al., 2008). For instance, in Ruchkin et al. (1992) study, patterns of left-anterior slow waves were related with verbal rehearsal operations during a working memory task (see also similar results in Lang et al., 1992). In contrast, spatial WM have been shown to be more bilateral or slightly right-lateralized (Mecklinger, Pfeifer, 1996; Friedman and Johnson 2000 for a selective review). In our study we were interested in testing these topographic patterns under the influence of the early learning factor (LL^{math} vs OL). If early learning has an influence in long-term numerical spatial representation then, the pattern of neural activity associated to processing of congruency in the LL^{math} should differ from the evoked activity in the OL condition. Indeed, we hypothesized that the

LL^{math} would be the preferred verbal code in the automatic activation of spatial-numerical long-term representations. Therefore, this might be mediated by different processing mechanisms. This hypothesis has never been investigated before.

2. METHODS

2.1. PARTICIPANTS

Fourteen right-handed Spanish-Basque bilinguals (6 females, 8 males) aged between 19- 30 years-old (mean age=21) participated in this study. All had equal level of Spanish-Basque bilingualism, with an age of acquisition of both languages from 0 to 4 (mean age of exposure=2.5 years). None of them were experts in any math discipline or had any gifted ability for numbers. Seven participants reported learned math at school in Spanish and seven reported learning math at school in Basque.

Language assessment

All participants were evaluated in their language proficiency with Spanish-Basque adaptation of the Boston Naming Test (Kaplan et al., 1983; for other uses of the BNT as a measure of proficiency see Moreno and Kutas, 2005 or Salillas and Wicha, 2012). Scores of BNT are depicted in **table 1.1.** Participants named 60 pictures in Spanish and Basque thus, the maximum possible score was 60. Balanced proficiency was considered when the mean difference of total correct answers in Spanish minus the total correct answer in Basque was no greater than 10. All participants were equivalent in their language proficiency. For those participants whose LL^{math} was Spanish, the proficiency in Spanish was 50.8 (3.9) and in Basque was 43(3.7) ($t=8.883$, $p<.001$). For participants whose LL^{math} was Basque, the proficiency was 42.1 (5.4) and 48.5 (2.3) for Basque and Spanish respectively ($t=5.139$, $p<.002$). Thus, BNT scores were slightly superior in Spanish than in Basque in both linguistic profiles but relative proficiency was equivalent (LL^{math} minus OL: *t=.338, p=.741)* Furthermore, participants self-reported the percentage of use of Spanish and Basque in daily life (see table 1.1.). Importantly, all participants were collapsed for analysis regardless of whether LL^{math} or the OL was Spanish or Basque. Thus, a unique within-subjects variable resulted for the LL^{math} and for the OL implying a contrast between identical items.

BNT proficiency and % of use

BNT Scores	**Spanish**	**Basque**	**Difference (LL^{math}-OL)**
LL^{math}:Spanish	50.8 (3.9)	43.1(3.7)	7.6 (2.3)
LL^{math}:Basque	48.5(2.6)	42.2(5.4)	-6.3 (3.3)
% of use	**Spanish**	**Basque**	
LL^{math}: Spanish	70%	31%	
OL : Basque	69%	30%	

Table 1.1. BNT scores and percentage of use reports for relative proficiency.

2.3. Procedure

Stimuli and Design

Experiment design is depicted in **figure 1.1.** Selected stimuli were eight number-words ranged from 1 to 9 (excluding the midpoint number five) and four square-shapes horizontally arranged over the center of a slightly grey color background. Trials were designed combining eight items taken in groups of four. We selected only those combinations with an equally amount of small and large numbers to be presented in right/left side (e.g. {1,2,7,8}, {2,3,7,9}, etc). Experimental trials were varied in the verbal format (Spanish or Basque), but they were never mixed within each trial. Each number word was presented the same number of times in Spanish and Basque. Trials in Spanish and trials in Basque were randomly presented. A total of 768 trials were used of which, half were Spanish trials (384) and half were Basque (384). Among the Spanish trials, 192 were congruent and 192 were incongruent. So forth was featured for the Basque trials. This experiment structure was applied identically for all participants, independently of their language profile ($LL^{math}_{Spanish\_}$ OL_{basque} or $LL^{math}_{basque\_}$ $OL_{Spanish}$) . All participants were collapsed for analysis regardless of whether LL^{math} or the OL was Spanish or Basque, providing exactly the same items for the LL^{math}-OL contrast. There were two types of trials according to the congruency of the numbers with the Mental Number Line: 1) *congruent trial* always showed small numbers inside the left-side boxes and large numbers inside the right-side boxes 2) the reverse arrangement was designed for the called *incongruent trials*. Both, congruent and incongruent trials had two versions each: one with a correct target and the same one with an incorrect target. All trials were arranged identically across both formats (Spanish, Basque). Consequently, the experimental design was based in two factors (2x2) with 4 conditions as follows: Congruency (2- Congruent/Incongruent) x Language (2 – LL^{math} / OL).

Experiment procedures

The experiment was conducted in an electrically isolated and sound attenuated room. Participants were seated at a viewing distance of approximately 40 cm from the screen. They were instructed to judge the correctness of a match-to-sample task (see figure1). They were also asked to maintain a relax pose avoiding sudden blinks and posture movements during the experiment recording. Stimuli were delivered with Presentation (14.7) software appearing on the center of a monitor with a 1024x768 resolution (View sonic® G90fB 90 Hz). Six practice trials were presented before the experimental block.

Experimental paradigm: delayed match-to-sample task

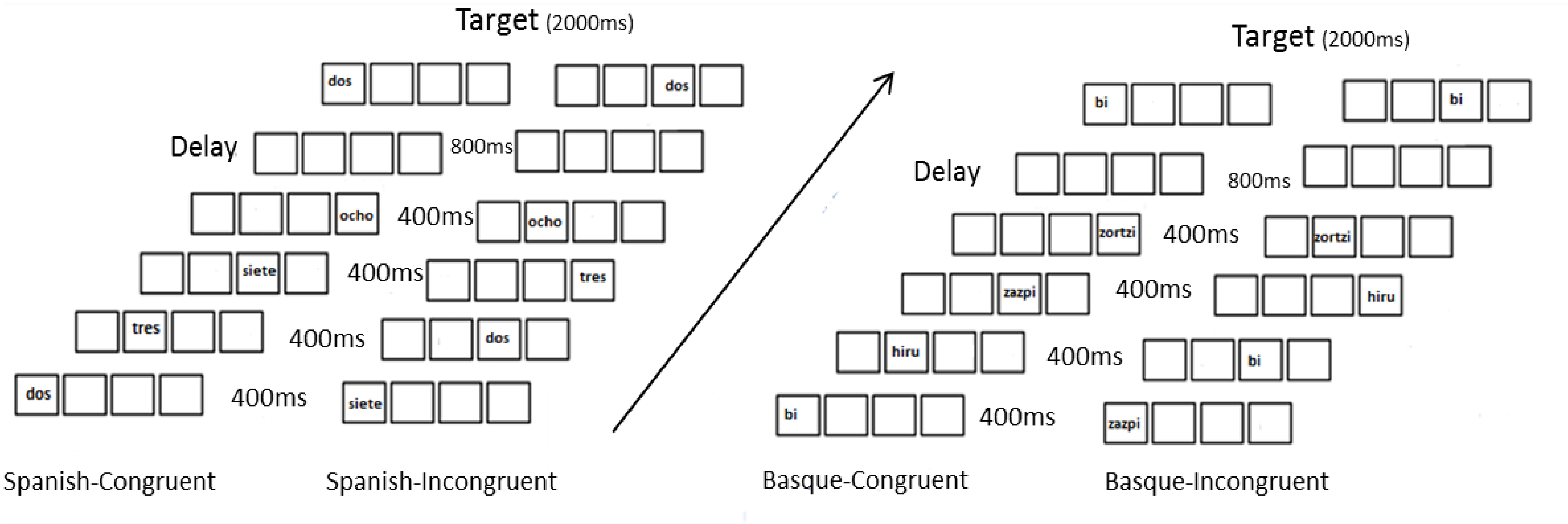

Figure 1.1. Participants judged the correctness of a match-to-sample task. Number words were presented randomly only once inside one of the boxes. In Spanish trials, only Spanish number-words were presented and the same was applied for Basque trials. A congruent trial consisted in small and large numbers presented in left and right- side boxes respectively. The reverse pattern was applied in incongruent trials. Following a delay period, a target number was presented remaining inside one of the figures for 2000ms maximum.

A trial sequence began with a 1500ms fixation cross followed by four squares figures horizontally displayed in the center of the screen. The first number (S1) was flashed inside one of the boxes remaining for 400ms before disappearing. With an ISI of 400ms the second number was presented (S2) in a different box, and so forth for the last two number-words (S3) (S4). Following the last number presentation, a blank delay period elapsed for 800ms. Then, a target number (T5) was presented inside one of the four boxes, remaining during 2000ms or until response. The time between the target presentation and the button press was measured. After the fixation mark, a trigger to the EEG was sent concurrent with the appearance of each stimulus (S1, S2, S3, S4,T5).

The task consisted of memorizing each number in its location. Participants were instructed to press the appropriate response button (correct/incorrect) as soon as the test number appears inside one of the four grid slots. To avoid speed differences for right and left hand responses, there were two active buttons of a Logitech ® precision gamepad, available to press only with the right-hand fingers. The response button was counterbalanced across a fix number of trials. Within trials, the language for each number-word was randomly displayed across trials to avoid participant´s strategies or the systematic prediction of the linguistic nature of next trial (see figure 1). Answers triggered after the specified 2000ms interval were considered missed responses.

In order to ensure that participants were correctly doing the task, at the end of each experimental session, they were asked to describe in a questionnaire how they proceeded to memorize the numbers (e.g. translation, verbal rehearsal), which strategies they used (if so) and other subjective questions of interest about their participation in the experiment. Those participants that were not doing the task properly or applying strategies systematically were discarded. A total of eight participants, out of the initial twenty-two participants, were discarded for this reason.

2.4. EEG RECORDING AND ANALYSIS

Electroencephalographic (EEG) activity was recorded from 32 channels (tin electrodes) mounted in an elastic Easy-cap using the International 10/20 System (Jasper, 1958; see figure 2). The left and right mastoids were used as online reference. Eye activity (movements and blinks) were monitored by means of four free electrodes, two located at the outer canthi (horizontal EOG) and two at the inferior orbital ridges (vertical EOG; see figure 2). Impedances were maintained below 5kΩ for all electrodes. Events and timing codes were delivered to the data acquisition computer throughout Brain Vision Recorder software concurrently with the onset of the EEG activity. Continuous EEG was filtered during the acquisition with a band-pass filter of 0.01-100Hz. All scalp electrodes were referenced off-line to the average activity of left and right mastoids. Signal was amplified with Brain Amp amplifiers and digitized at a sample rate of 1000Hz. To reduce high and low frequency content before data analysis, the signal was filtered with a digital 30Hz low pass and a 0.1Hz high pass filters.

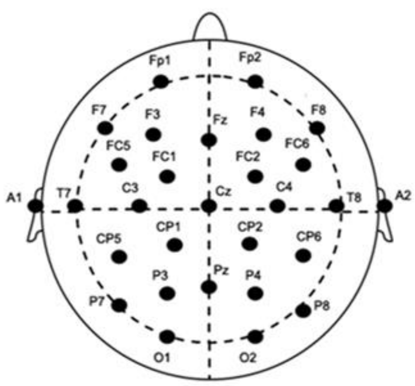

Figure 1.2. The illustration shows the montage for 27 electrodes in a geodesic array including left/right ear reference according to the 10/20 system of electrode placement.

The final EEG data was segmented into epochs of 1000ms with a -200 ms baseline and re-referenced to the averaged mastoids. Each epoch included 400ms corresponding to last number-word (S4) onset and the initial 600ms of the delay period. For each participant, ERP averages were performed off-line by averaging the EEG epochs as a function of experimental conditions (Language and Congruency) and time-locked to the onset of the fourth number-word. Segments containing artifacts exceeding ± 100 µV were removed to ensure roughly an equal loss of data across all conditions. Baseline correction was performed using the averaged activity in the 200ms pre-stimulus. The N100, P200, N400-like and negative slow wave (nSW) ERP components were identified. Four time windows centered on these brain potentials were chosen. N100 was defined as the maximum negativity within an early time window 0-200ms whereas transition to P200 was defined as the maximum positivity within the following 200-300ms time interval. The N400-like was identified as the following negativity within a later 300-500ms time window. The nSW component was consistent with the early and middle portion of delay period activity ranging from 500 to1000ms. The selected time windows were chosen to account for the congruency differences in LL^{math} and OL conditions during encoding, retrieval and retention WM activity. This allowed us to isolate the ERP effects associated to each WM stage. A similar approach has been reported in previous WM studies wherein main ERPs activity was functionally dissociated according to the different WM stages (see Bosch et al., 2001; Ruchkin et al 1996, 1997; Pinal, Zurron and Diaz, 2014; Shucard et al., 2009).

Analysis

Behavioral data was examined across conditions. Error rates were evaluated in the context of signal detection theory (McNicol, 1972; McMillan and Creman, 2005). The discrimination sensitivity index (d'prime) captures the ability of the participant to select the correct stimuli while avoiding the incorrect ones. A larger d-prime means a better ability to differentiate correct targets. Here, evaluates the ability to detect correctly the numerical-spatial match of the target. Values for d' were estimated for each subject. A one sample t-test against zero was conducted to determine whether accuracy (d') was acceptable (above chance). Additionally, reaction times (RT) for *Hits* were analyzed using repeated measures ANOVAs.

The main objective of the ERP analyses was to evaluate the effects of Congruency on the N1-P2 transition, N400 and nSW. Grand average waveforms for the Congruent and Incongruent conditions were computed. To examine the effects of congruency on each ERP component, statistical analysis was conducted in three time windows of interest within the intervals of encoding, retrieval and retention activity: 240-290ms, 350-480ms, 600-900ms. The initial analysis included a general three-way ANOVA (Electrodes (27), Language (LL^{math}/OL) and Congruency (Congruent/Incongruent)) run in each selected time window. Due to our major interest in characterizing the ERPs pattern of congruency processing as a function of early learning, follow-up analyses of variance were performed separately for LL^{math} and OL conditions in windows of interest. Interactions by electrode in these planned comparisons, allowed us to further compare ERP main effects of congruency and scalp-topography patterns in each language condition. Thus, repeated-measures ANOVAs were computed for each language condition including Electrodes (27) and Congruency (Congruent/Incongruent) as main factors. In case of significant interaction, subsequent ANO-

VAs were carried out to follow these interactions in four regions of interest (ROIs): Anterior-Left (FP1, F3, F7, FC1, FC5, T7), Anterior-Right (FP2, F4, F8, FC2, FC6, T8), Posterior-Left (P3, C3, O1, P7, CP1, CP5) and Posterior-Right (P4, C4, O2, P8, CP2, CP6). The p-values were Greenhouse-Geisser corrected when the assumption of sphericity was violated ($\varepsilon<0.75$). The described topographical division was chosen in order to explore the distribution of main ERPs effects. We focused on lateralized scalp activity associated with manipulation of spatial-numerical information in WM. This allowed us to better characterized underlying lateralized networks associated to each language.

3. Results

3.1. Behavioral results

Mean percentage of error rates (ER) are depicted in **table 1.2.** The overall percentage of accuracy was around or above 85%. The proportion of error rates per language and congruency condition is depicted in table 3 *(d'=.95;* t_{13} *=11.926; p = .001).* The Language x Congruency ANOVA on mean error rates showed no significant difference between congruent and incongruent conditions ($F\ (1, 13) = .189,\ p< .67$). Mean reaction times (RTs) for correct-trials responses are depicted in **table 1.3**. An overall ANOVA was conducted again with Language and Congruency as main factors. In general, congruent trials were responded faster than incongruent trials. Although these differences were not significant ($F\ (1, 13) = .990;\ p< .33$), mean reaction times were faster when number locations were congruent with the MNL in the LL^{math} condition (-17ms). However, given that RTs were delayed responses these results are only informative and not conclusive for the hypothesis of this study.

Mean Error Rate (ER)

General ER: 15 (5.1); d’ 0.95 (0.3)		
	LL^{math}	**OL**
Congruent	14 % (5.5) d’ 1.0 (0.3)	16% (5.7) d’ 0.9 (0.2)
Incongruent	20 %(7.1) d’ 0.9 (0.3)	14% (5.8) d’ 0.9 (0.3)

Table 1. 2. Percentage of errors and index of discriminability calculated per condition.

RTs per condition

	LL^{math}	**OL**
Congruent	*999ms (97)*	*1028ms (100)*
Incongruent	*1016ms (104)*	*1029ms (111)*
Total Mean	*1009ms (99)*	*1028ms (104)*
Diff (C-I)	*-17ms (n.s)*	*-1ms (n.s)*

Table 1.3. Mean RTs and differences between congruent and incongruent conditions.

3.2. ERPs RESULTS

Processing of congruency

Grand average ERPs waveforms lead for LL^{math} and OL are depicted in **Figure 1.3.** The displayed epochs show 400ms of last number-word presentation and 600ms of delay period. Amplitude differences between congruent and incongruent condition were elicited in main components of interest (N1-P2, N400-like and nSW) during encoding, retrieval and retention. Encoding activity reflects here the mapping of number-words presented in memorizing sequence with the spatial-numerical representation. After this number matching occurs, the MNL representation is retrieved and retained in WM. In the LL^{math} condition, amplitude differences were elicited at the

P200 latency larger in parietal topographies. The N400-like component followed with larger amplitude differences in frontal sites. A sustained nSW activity continued at the level of the delay period (500-1000ms) consistent with retention. For the OL, the P200 effect was more pronounced in anterior-posterior left topographies while no other amplitude differences were observed in rest of ERP components.

Global analysis results

Main effects of congruency and interactions are depicted in **table 1.4.** The table shows the results of congruency processing effects in selected time windows based on the latencies of each component of interest (N1-P2, N400-like and nSW). The performed Electrode (27) x Language (2) x Congruency (2) ANOVAs showed a main effect of Congruency *[F(1,13)=4.942 p<.04]* and a significant interaction effect between Electrode and Congruency *[F(26,338)=4.511 p<.009]* during encoding time interval (250-290ms). In the following time window (350-480ms), the effects did not reach the statistical significance and only the Electrode x Congruency interaction marginally approached the significance *(p=.06).* The ANOVA performed in the retention time window (600-900ms), showed a significant triple interaction effect *[F (26,338)=3.222 p<.02]* . No other effects were found significant at this time window. These results indicate that congruency effect followed a particular scalp distribution for each language condition.

ANOVAs: Electrode(27) x Language (2) x Congruency(2)	240-290ms	350-480ms	600-900ms
Congruency	***p=.04****	*p=.38*	*p=.17*
Language x Congruency	*p=.24*	*p=.14*	*p=.29*
Electrode x Congruency	***p=.009*****	***p=.06***	*p=.46*
Electrode x Language x Congruency	*p=.41*	*p=.28*	***p=.02****

Table 1.4. The p-values for main effects and interactions displayed in critical time windows of congruency processing.

Individual analysis

Most crucially for the purpose of this experiment, is to determine whether congruency effect has associated different neural pathways (bilateral, left-right lateralized) in each Language condition. Separated grand average ERPs for LL^{math} and OL with data pooled in four selected ROIs are depicted in **Figure 1.3**.

- *Congruency effect: N100-P200, N400-like and nSW*

LL^{math}: Results are depicted in table 5. Early processing of congruency elicited **N1-P2** components. The general ANOVA performed within the early time window (N1: 65-100ms), yielded no significant differences *[p<.10]*. The overall ANOVA performed in the following P2 time window (240-290ms), showed a significant interaction effect of Electrode and Congruency *[F(26,338)=3.065 p<.04]* due to a significant effect of Congruency *[F(1,13)=6.321; p<.02]* in the Posterior-Right ROI. In the **N400-like** time window (350-480ms.), the two-factor ANOVA showed a significant interaction between Electrode and Congruency *F(26,338)=3.829; p<.009]*, due to an effect of congruency in the Anterior-Right ROI *[F(1,13)=5.924; p<.03]*, that was also marginally significant in the Anterior-Left site *[F(1,13)=4.039; p<.06]*. During the time window (600-900ms) of the **negative slow wave** (nSW), the ANOVA revealed a significant interaction of Electrode and Congruency *[F(26,338)=2.921; p<.04]*. Subsequent ANOVAs in each ROIs revealed a significant main effect of congruency in Anterior-Right electrodes *[F(1,13)=5.719; p<.03]*.

OL: The same analyses were performed in OL condition. The ANOVA showed an main effect of Congruency within the P2 time window (240-290ms) [*F(26,338)=6.283; p<.02]*. The interaction between Electrode and Congruency was not significant. No significant differences were found in the N400-like and nSW latencies (see table 1.5).

Congruency effects

LL^{math}	WM stage	Time window	Overall ANOVA	Topographic ANOVA	ROI
	Encoding	*240-290ms*	***ExC [F(26,338)=3.065; p<.04]**** *C [F(1,13)=.792; p<.39]*	***C [F(1,13)=6.321; p<.02]****	*Posterior-Right*
	Retrieval	*350-480ms*	***ExC [F(26,338)=3.829; p<.009]***** *C [F(1,13)=1.949; p<.18]*	***C [F(1,13)=5.924 p<.03]**** *C [F(1,13)=4.039; p<.06]*	*Anterior-Right* *Anterior-Left*
	Retention	*600-900ms*	***ExC [F(26,338)=2.921; p<.04]**** *C [F(1,13)=2.734; p<.12]*	***C [F(1,13)=5.719; p<.03]****	*Anterior-Right*
OL	**WM stage**	**Time window**	**Overall ANOVA**	**Topographic ANOVA**	**ROI**
	Encoding	*240-290ms*	*ExC [F(26,338)=.1.940; p<.13]* ***C [F(1,13)=6.283; p<.02]****		
	Retrieval	*350-480ms.*	*ExC [F(26,338)=.218; p<.86]* *C [F(1,13)=.001; p<.98]*		
	Retention	*600-900ms*	*ExC [F(26,338)=.628; p<.57]* *C [F(1,13)=.022; p<.88]*		

Table 1.5. F-values and p-values for main congruency effects and significant interactions displayed in windows of interest.

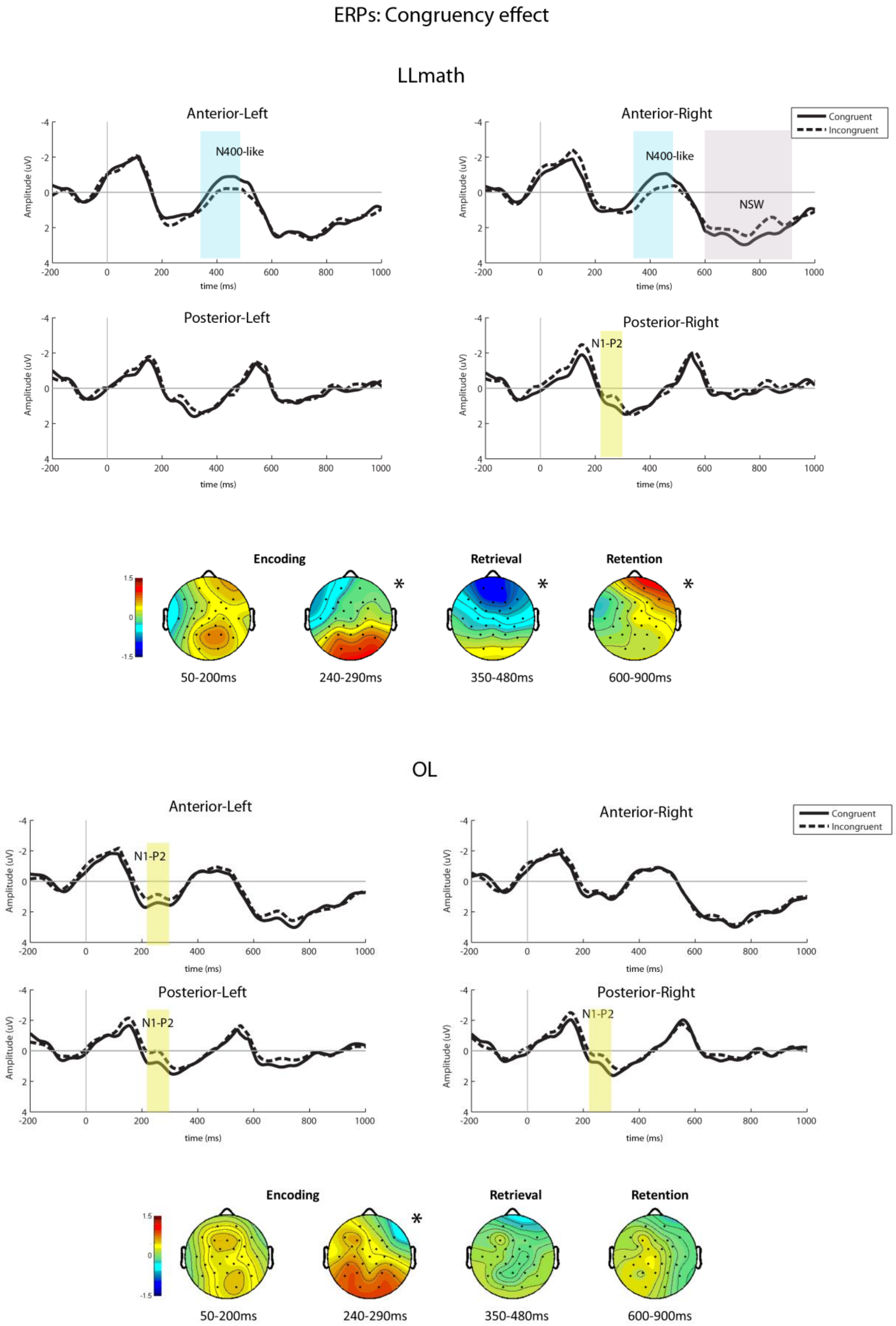

Figure 1.3. Grand average ERPs for LL^{math} (on the top) and OL (on the bottom), at four selected ROIs. The voltage maps show the scalp distribution corresponding to critical ERP effects found in time-windows of interest.

Regression analysis results

In order to discard any possible proficiency influence in the congruency effects, we performed a regression analyses. **Table 1.6** depicts for each language, the R^2 values obtained for P200, N400-like and nSW effects. Both, proficiency and percentage of use were used as regressor factors of main ERPs effects. The results confirmed that significant effects were not explained by differences in LL^{math} and OL relative proficiency or by the percentage of use of each language.

Regression

ERP congruency effects	LL^{math}		OL	
	BNT	**% of use**	**BNT**	**% of use**
240-290ms	*R^2=-.008; p<.36*	*R^2=- .082; p<.89*	*R^2=-.054; p<.57*	*R^2=.072; p<.73*
350-480ms	*R^2=-.018; p<.39*	*R^2=-.027; p<.43*		
600-900ms	*R^2 = .078; p<.17*	*R^2=-.054; p<.57*		

Table 1.6. Summary of regression analysis for all significant ERP effects obtained in LL^{math} and OL conditions. The relative proficiency difference (BNT_LL^{math}-BNT_OL) and self-reported percentage of use (%LL^{math}-%OL) were used as regressors.

3. Discussion

In this experiment, the impact of early learning in long-term MNL representation was investigated from the perspective of executive WM function, implying the processing of numerical-spatial congruency in a match to-sample task. The congruency effects associated to the automatic activation of the MNL when numbers were manipulated in LL^{math} and OL were examined in encoding, retrieval and retention stages. The obtained ERP results indicated a strong influence of early learning mostly at the level of retrieval (N400-like) and retention intervals (nSW). The N1-P2p congruency effect appeared for both LL^{math} and OL, but with different scalp distributions (LL^{math}:

Posterior-Righ; OL: Anterior-Left, Posterior) reflecting distinct brain processing mechanisms. At the level of retrieval and retention activity, amplitude differences between congruent and incongruent ERPs appeared sustained over time in LL^{math} distributed over anterior locations whereas in the OL, amplitude differences were significantly reduced. Moreover, the topographic pattern associated to congruency effects in LL^{math} is consistent with previous studies showing slow-waves potentials in Anterior and Posterior Left/Right electrodes during maintenance of visuospatial information (Mecklinger and Pfeifer, 1996; Ruchkin et al., 1994; 1997). Here, the topographic profile in retrieval and retention (right-lateralized anterior topographies) might indicate that retention of the numerical-spatial congruency with LL^{math} involves different buffering systems needed to manage visuospatial and numerical representations in working memory. Importantly, these dataset reflect different underlying brain activity when numerical information is handled with the LL^{math} supporting thus, the hypothesis of early learning impacts in long-term MNL representation. The ERP congruency effect reflected in the time course and topography suggests *qualitative differences* across languages, thus indicating a language influence in the MNL at the representational level. Therefore, the linguistic context of early learning seems to enhance retrieval of the MNL. Implications of these results for theories of math cognition and for the relationships between math and language will be put forward in the general discussion.

EXPERIMENT 2

1. INTRODUCTION

The goal of the second experiment was to further investigate how bilinguals' magnitude representation is influenced by the language of learning math when the cognitive demand increases. To that end, we have used a more sophisticated working memory (WM) paradigm. We investigated the impact of LL^{math} in long-term representations (MNL) through the management of different memory loads. Given that memory load strongly influences the numerical spatial associations (Herrera et al. 2008; Fias et al., 2011), a measure of the cognitive cost allows to more thoroughly evaluate the efficiency of brain networks associated with long-term representations. In the particular context of this study, retrieval of long-term MNL with LL^{math} as compared to the OL should be less affected by memory load, given the higher automaticity associated to long-term representations in LL^{math}. Thus, in Experiment 2 we use a similar design to that used in Experiment 1 to test early learning effects under low and high memory load conditions. It is important to remark here that our study does not aim to test working memory effects under high and low memory load. Instead, our study investigates whether an increase in the cognitive demand of the task (high memory load) is likely to affect both languages but not in the same manner. Long-term representations might have different levels of efficiency as a function of the early learning factor. Therefore, we examined how automatic retrieval of MNL is managed in both languages when the conditions of the task are more challenging and further, what pattern of ERP activity emerge as a result of processing congruency in low and high memory load situations.

As already mentioned in the description of Experiment 1, electrophysiological **WM studies** provide evidence of ERP markers associated to encoding, retention and retrieval. As indicated, the most common finding is a **slow wave** mostly related to the retention activity (Ruchkin et al., 1990; 1992, 1995; 1997; Klaver et al., 1999; McCollough, Machizawa and Vogel, 2007, McEvoy, Smith and Gevins, 1998; Bosch et al., 2001; Drew, McCollough and Vogel, 2006). A distinct property of this slow potential is that its amplitude increases with task demand (Lang et al 1992), either in visuo-spatial or verbal tasks (Ruchkin et al., 1992; Berti, Geissler, Lachmann and Mecklinger, 1999, 2010; see also Ruchkin et al., 2003 for a review). We have also referred to other components such as **N400-like** that have been related in many studies with retrieval from long-term memory (Chao, Nielsen-Bohlman and Knight, 1995; Nielsen-Bolchman and Knight, 1999; Friedman and Trott, 2000; Friendman and Jonhson, 2000; Kutas and Federmeier, 2000; Rugg et al., 2002; Mecklinger, 2010). In addition, consistent with numerical cognition literature, N1 and P2 components are expected to be involved in visuospatial numerical processing. As noted, the P2 component (appearing between 200 and 280ms) has been shown to be linked to processing of numerical magnitude (Dehaene, 1996). More precisely, transitions of N1-P2p has been found in numerical comparison task approximately 200ms post stimulus (Temple and Posner, 1998; Libertus et al., 2007; Cao et al., 2010; Salillas and Carreiras, 2014). Thus here, these components are expected to index the processing of numerical-spatial congruency.

For the present study, delayed version of a match-to-sample task (Petrides et al., 1994) was used combined with EEG recordings. As in Experiment 1, fully balanced bilinguals were selected to perform the behavioral WM task simultaneously with brain activity recordings. Furthermore, as we aimed to investigate the role of early learning in numerical-spatial representation in more cognitive-demanding context, task difficulty was increased by adding a high memory load condition. This allowed us to examine the efficiency of LL^{math} and OL during the time course of congruency processing, mostly in retention. Therefore, we focused on the ERP pattern associated to LL^{math} and the OL in both memory load conditions during the time course numerical-spatial congruency processing. The chosen design was modified according to variations of WM load and to track the processing of congruency in a relatively long delay interval. Thus, Spanish or Basque numbers-words arranged in sets of four or six items, were presented inside empty figures. Participants memorized the spatial location of each number-word and judge the correctness of a test-trial after a delay. Importantly and unlike Experiment 1, stimuli (e.g. empty boxes) were spatially arranged in a non-horizontal position and numbers were issued in left-right visual hemifields. The spatial-numerical coding is expected even when the spatial features of the task do not adopt the horizontal arrangement. In accordance to what has been observed in attentional paradigms experiments, small/large magnitudes presented congruent with left/right hemifields respectively activated the spatial-numerical association (Fischer et al, 2003; Fischer and Knops, 2014; Fischer and Shaki, 2015). In this respect, recent data has demonstrated that the numerical-spatial association is manifested at the conceptual level and therefore should not be contaminated by the external spatial features of the task (Fischer et al., 2016). Other studies, reported spationumerical association with lateralized stimuli and a non-lateralized response (e.g., Fischer, Castel, Dodd and Pratt, 2003; Ranzini et al., 2014). In this regard, has been recently demonstrated that just the perception of numerical stimuli is enough for numerical-spatial association to emerge, even when spatial features from stimuli and responses have been removed (Fischer and Campens, 2009; Fischer and Shaki, 2015; Ranzini et al., 2015). On this basis, in the present experiment the strictly linear position of numbers in the task would not be essential to activate the numerical-spatial association since this connection has been shown to be more a conceptual feature integrated in number semantics rather than a directional processing mapping (Fischer and Shaki, 2016). Thus, a non-linear spatial features of the task (e.g. left-right lateralized) it is assumed here to implicitly activate the internal spatial-numerical representation either way.

As in Experiment 1, main WM-related components (N1, P2, N400-like, nSW) are expected during the time course of numerical-spatial congruency processing. However, although non-horizontal distribution of numbers should not affect the activation of spatial-numerical representation, it might influence the time course of numerical-spatial coding and thus, the ERP pattern of activity associated to processing of congruency. Therefore, the pattern of ERP response in this experiment should not necessarily mimic that of Experiment 1 given that task features in the two experiments are not identical. Accordingly, we also hypothesized that different neural activity would be associated to both languages in low and high memory load conditions. However, if there is a substantial impact of early learning, greater differences between LL^{math} and OL should appear during processing of congruency in high memory load. This efficiency hypothesis is based on the assumption of higher cognitive cost associated to increases in WM load. By definition, WM efficiency is modulated by the amount of information that has to be hold but further, by the activation of long-term representations (Kutas and Ferdermeier, 2000). The degree of processing difficulty (or ease) would to some extent depend on the greater (or lesser) compatibility of long-term representations with previously presented stimuli or information (Cameron et al, 2004; Ruchkin et al., 2003). On this basis, we predict that LL^{math} automatically activates long-term numerical-spatial representation and consequently, greater efficiency is expected compare to the OL when task difficulty increases (e.g. high working memory load). In addition, left and right fronto-parietal topographies are expected, given the fact that visuospatial and verbal WM are involved. Anterior and Posterior scalp topographies have been observed during verbal and visuospatial WM operations (Gevins et al, 1996; Schack et al 2005) and under different memory loads conditions (McEnvoy et al., 1998; Löw et al., 1999; Shucard et al., 2009).Thus, our interest was to examine the lateralized scalp activity to better characterize the possible spatial and/or linguistic networks that mediate processing of spatio-numerical information in WM. Therefore, different scalp topographies should be elicited only if underlying neural activity differs between both languages (LL^{math} and OL) during the activation of MNL representation.

2. Methods

2.1. Participants

Fourteen healthy right-handed participants (11 females; mean age 22) were recruited as volunteers for this study. They were all balanced Spanish-Basque bilinguals with a range age of language acquisition between 0 and 3. Seven participants learned math during the early school years in Spanish and seven learned math in Basque. Participants were also asked for the percentage of use of each language in their daily life (48% for LL^{math}/ 52% for OL). At the end of each experimental session, all participants reported in a questionnaire how they proceeded to solve the task (e.g. translation), strategies they used (if so) and other subjective questions of interest about their participation in the experiment. In addition, participants were tested in their WM capacity with the standard Battery of cognitive abilities of Woodcock-Johson III, test 7 (Number Reverse) and 9 (Auditory WM) (Schrank, Wendling and Woodcock, 2008, 2010; Muñoz-Sandoval, Woodcock, McGrew, and Mather, 2005). The mean average of the standardized scores[1] was 106 (6.6), which indicate that participants have similar relative WM capacity (see table below).

Standard Score Range	Percentile Rank Range	WJ III Classification
131 and above	98 to 99.9	*Very Superior*
121 to 130	92 to 97	*Superior*
111 to 120	76 to 91	*High Average*
90 to 110	**25 to 75**	***Average***
80 to 89	9 to 24	*Low Average*
70 to 79	3 to 8	*Low*
69 and below	0.1 to 2	*Very Low*

Table 2.1. Standard scores according to Woodcock Johnson III battery of cognitive abilities. Participants´ mean scores was within the category *Average.*

Language assessment

In the same way as in Experiment 1, participants' linguistic proficiency was measured with the Spanish-Basque adaptation of the Boston Naming Test (Kaplan, Goodglass, and Weintraub, 1983; for other uses of the BNT as a measure of proficiency see e.g., Moreno and Kutas, 2005 or Salillas and Wicha, 2012). Mean scores of BNT and self-reported percentages of each language use are depicted in **table 2.2**. The maximum possible score was 60. Spanish and Basque language competence was equivalent for all participants. Proficiency of participant´s two languages was slightly superior in Spanish than in Basque for both profiles: LL^{math}*_Spanish:* $t=9.363$, $p<.001$; LL^{math}*_Basque:* $t= - 5.599$, $p<.001$. The participants´ relative proficiency (LL^{math} minus OL) was equivalent ($t=.544$, $p<.596$).

In order to have an additional measure of proficiency all participants self-reported the percentage of use of each language in their daily life (see table 2.2). Importantly, all participants were collapsed for the ERP analysis regardless of whether

[1] The Woodcock Johnson III battery of cognitive abilities applies this index to identify and classify the relative standings from very low to very high. It is based on a mean of 100 and a standard deviation of 15. The measurement applies standardized scores and percentile rank range indicating that 2 out of 3 times (or 68% of the time) the subject is expected to make on that task (131 and above = very superior; 121 - 130 = superior; 111 - 120 = high average; 90 - 110 = average; 80 - 89 = low average; 70 - 79 = low; 69 and below = very low).

LL^{math} or the OL was Spanish or Basque. Thus, a unique within-subjects variable resulted for the LL^{math} and so forth for the OL implying a contrast between identical items.

BNT proficiency and % of use

BNT Scores	**Spanish**	**Basque**	**Difference (LL^{math}-OL)**
LL^{math}:Spanish	51.1(4.7)	43.8(4.3)	7.3
LL^{math}:Basque	50.8(5)	45.5(5.5)	-5.3
% of use	**Spanish**	**Basque**	
LL^{math}: Spanish	62%	38%	
OL : Basque	67%	33%	

Table 2.2. BNT scores and percentage of use self-reports. The relative language proficiency was calculated by subtracting the scores in LL^{math} from scores in OL.

2.3. Procedure

Stimuli

A whole set of six Spanish number-words and six Basque number-words ranging from 1 to 9 (excluding midpoint 5) were considered as stimuli for this experiment. The number word six (“seis”-“sei”) was excluded due to the phonetic similarity between both languages. In order to keep the same amount of large vs small numbers, we excluded also the number word one (uno, bat), which is the smallest size numerosity of the numbers lower than 5. A fixation point (“+”) remained constant by default in the center of the screen. The selected number-words were displayed with equal probability inside one of the six squared figures in series of either four (LML=Low memory load) or six set of items (HML=High memory load). Unlike the horizontal layout used in Experiment 1, the six squared-shapes (black outside borders and grey background) were arranged around the cross-mark following a circular disposition (see figure 1). The main reason was to avoid excessive artifacts due to eye movements since the number of stimuli to-be-presented increased. There was no reason to infer a lack of activation of the MNL representation since small and large magnitudes were placed in left/right positions connecting with the conceptual representation of the MNL. However, the differences in the stimuli arrangement can influence the ERP response at some point and therefore the brain pattern in Experiment 2 may not be identical as Experiment 1.

DESIGN

The experiment design is depicted in **figure 2.1**. The procedure was identical to that of Experiment 1, with the following exceptions pertaining to stimuli arrangement, timing and memory load variations. As in Experiment 1, participants judge the correctness of a test-number presented after the memorizing sequence. Memory load was randomly varied across trials and so forth was the language (Spanish-Basque). The delay period was extended (1100ms) in order to have a better tracking of the retention activity. A total of 576 trials were presented: 288 trials per memory load condition, among which, 144 pertained to the Spanish number-words set of stimuli *(dos(2), tres(2)...)* and 144 pertained to the Basque number- words stimuli set *(bi(2), hiru(3)...).* Additionally, half of the Spanish number-words (72) pertained to congruent condition and half pertained to incongruent; the same was featured for the Basque set of words. Stimuli location within trials was combined randomly but always small and large numbers were presented lateralized at the same side (right/ left). Thus, we never mixed low and high number magnitude on the same hemifield. With these restrictions, different trials were obtained as result of combining six stimuli taken in groups of four elements (Low WM load) and six stimuli taken in groups of six elements (High WM load). Based on these constrains, eight types of trials obtained: *Spanish-congruent-Low ML, Spanish-congruent-High ML, Spanish-incongruent-Low*

Experimental paradigm: low/high memory load version in a delayed match-to-sample task

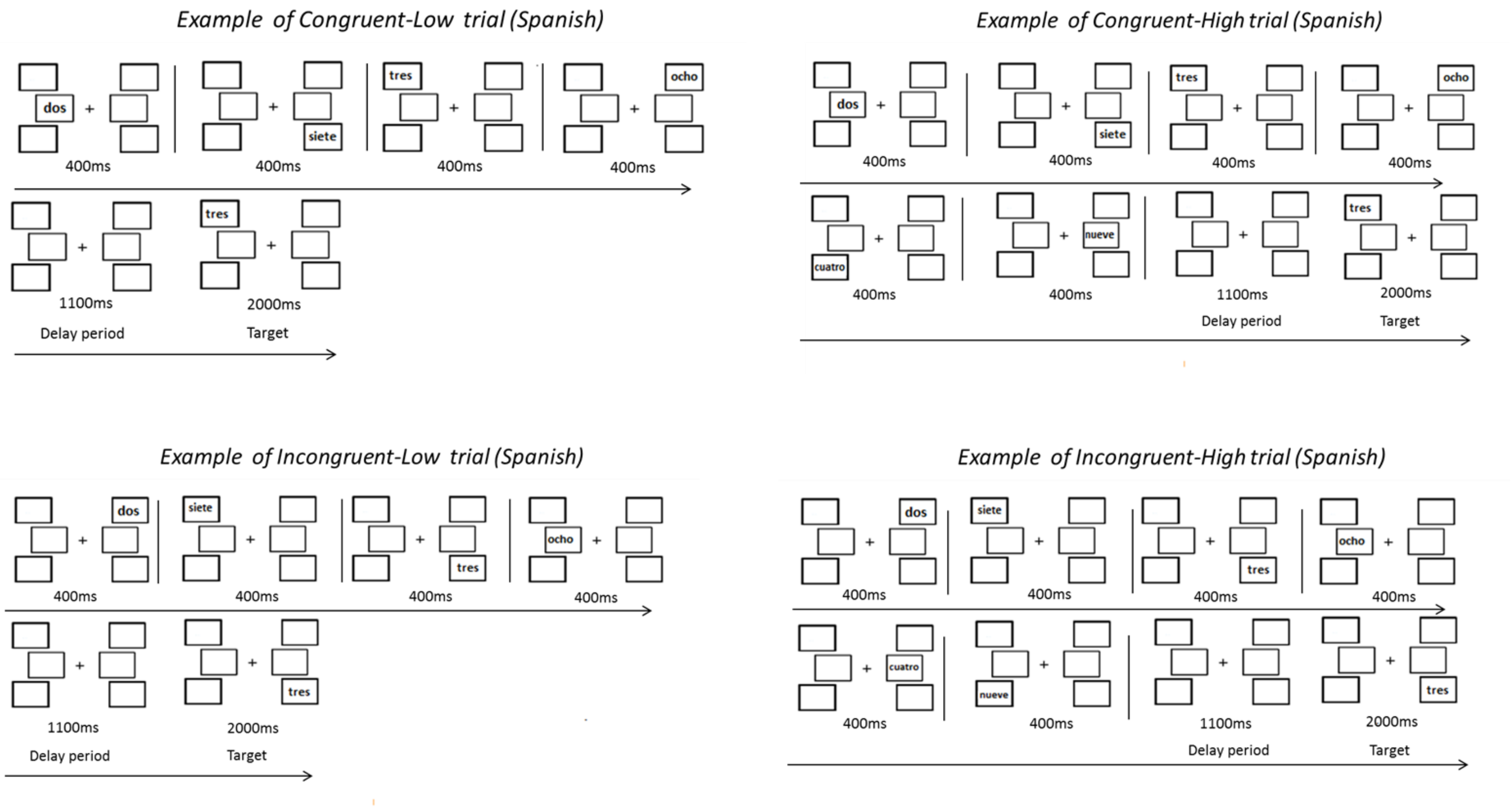

Figure 2.1. Example of congruent and incongruent trials in high/low memory load conditions for the Spanish version of the experiment. Number words appeared sequentially inside one of the boxes, lasting 400ms. The number of stimuli in the memorizing sequence could be four (low memory load) or six (high memory load). After a delay period, a target number-word was presented remaining inside the box for 2000ms maximum. Participants were instructed to answer (button-press) as fast and accurate as possible before the offset of the target. In the Basque version, trials were exactly the same as the Spanish version.

ML, Spanish-incongruent-High ML, Basque-congruent-Low ML, Basque-congruent-High ML, Basque-incongruent-Low ML and Basque-incongruent-High ML. All trials were intermixed and randomized so the participant was unable to predict or anticipate the length of the ongoing trial. The different combinations of numbers and location within one of the six boxes were equiprobable and presented in a random sequence. Exactly the same stimuli were included in the two language conditions (LL^{math} and OL). The total duration of the experiment was about 90 min including resting pauses every 12 min.

The experimental conditions involved three factors: 1) *Memory load*, including two levels, high memory load (High_ML, six numbers) and low memory load (Low_ML, four numbers) 2) *Congruency*, included congruent (mapping the MNL representation)and incongruent condition (opposite to the MNL layout) 3) Language factor (LL^{math}/OL). As purpose of this experiment was to study effects of congruency in LL^{math} and OL when memory load increases, we considered the same experimental design as Experiment 1 (Language x Congruency) for low and high memory load conditions.

2.4. EEG RECORDINGS AND ANALYSIS

The EEG activity was recorded and processed identically to Experiment 1. Recordings were **segmented** in epochs of 1200ms. Activity was time-locked to the last number-word onset (400ms) plus 800ms of delay interval. Epoch's length for high and low memory conditions was the same, since the 0-ms point corresponded to the presentation of the last word. The analyzed segments were averaged relative to a 200ms pre-stimulus interval. Procedures for behavioral data were similar as Experiment 1 (sensitivity measure d-prime, Error Rates and RTs). Errors were also compared by memory load condition. A repeated measures Language x Congruency ANOVA was conducted separately in each memory load condition to examine error rates (ER) and reaction times (RTs) of correct responses.

For the ERP analysis, only correct hit trials were considered. Similar as in Experiment 1, mean amplitudes differences within N1-P2 latencies (ranging from 0 to 300ms), N400-like (ranging from 300 to 500ms) and negative slow wave (nSW) (ranging from 500 to 1000ms) were identified. Based on these latencies, five time windows of interest were selected for analysis: 50-200ms (early encoding), 200-300ms (encoding), 400-500ms (retrieval of MNL). Given the long-lasting nSW activity (800ms), amplitude was analyzed in two time windows defined as onset (550-600) and offset (800-1000ms for low memory load; 750-800 for high memory load). The selected time windows were consistent with the synchronized activity associated to encoding, retrieval of MNL and retention. For the nSW, time windows were chosen based on similar approaches adopted in WM studies, wherein the reported slow waves are analyzed in separate time steps to have a better measure of memory load influence (Ruchkin et al., 1997).

One main objective of the ERP analyses was to investigate the congruency effects in high and low memory load conditions. Main effects of memory load or interactions of memory load with other factors were out of the scope of this experiment. For that reason, the initial analysis of variance included Electrode (27) x Language (LL^{math}/OL) x Congruency (C/I) as independent factors. Based on significant interactions (Electrode x Congruency, Language x Congruency and Electrode x Language x Congruency), a second analysis of data examined effects of congruency individually for LL^{math} and for the OL in each level of memory load condition. Individual ANOVAs included Electrode (27) and Congruency (2) as factors. In case of significant interactions, further ANOVAs were carried out by region of interest. The main purpose here was to examine in detail the distribution pattern of congruency effects in order to better characterize the impact of early learning in different memory load contexts. As in Experiment 1, we focused on lateralized scalp activity associated with manipulation of spatio-numerical information in WM. Scalp electrodes were pooled for statistical analysis in four regions of interest identically as Experiment 1 (Anterior-Left, Anterior-Right, Posterior-Left, Posterior-Right). ANOVAs were carried out considering electrodes of ROIs (6 channels each) and Congruency (2) as independent factors.

In order to discard a possible influence of relative dominance differences or daily frequency of use of each language, regression analysis was applied to ERP congruency effects. The regression analysis included BNT scores (scores in LL^{math} minus scores in OL) and self-reported percentage of daily use of each language (LL^{math} minus OL), as regressor factors.

3. Results

3.1. Behavioral results

Mean percentage of errors rates per condition were examined. Accuracy was around 78% *(d'=.64;* t_{13} *=10.547; p = .001).* The proportion of error rates per condition is depicted in **table 2.3.** Differences between errors in Congruent and Incongruent conditions and between LL^{math} and OL were examined separately in each level of Memory load condition. The performed Language x Congruency ANOVAs in low and high memory load condition indicate equivalent percentage of errors in congruent and incongruent conditions *[Low: F(1,13)= 1.398, p<.25; High: F(1,13)= .003,* *p<.95]*.Interactions (Language x Congruency) were not significant either *[F(1,13)= .011, p<.91; F(1,13)= .870, p<.36]*.

Mean Error Rate (ER)

	Low Memory Load		High Memory Load	
	LL^math	**OL**	**LL^math**	**OL**
Congruent	18 % (7.2) d' 0.8 (0.3)	20% (7.1) d' 0.7 (0.3)	25% (6.2) d' 0.6 (0.1)	28% (12.2) d' 0.5 (0.3)
Incongruent	19%(7.3) d' 0.7 (0.2)	21% (8.3) d' 0.3 (0.1)	27% (7.7) d' 0.5 (0.2)	27%(8.3) d' 0.3 (0.1)

Table 2.3. Mean percentage of error rate and d-prime (d') calculated per condition.

The mean RT for correct responses was around *890ms.*A summary of RTs data is depicted in **table 2.4.** In general, congruent trials were responded faster than incongruent trials in LL^{math} (-15ms) whereas in the OL condition, incongruent trials were response slightly faster than congruent (8ms). The performed Language x Congruency ANOVAs in low memory load indicated that these RTs differences were not statistically significant *[F(1,13)= 1.111, p<.31; F(1,13)= .012, p<.91]* and the same stands for high memory load condition *[F(1,13)= .182, p<.67; F(1,13)= 1.137, p<.30*). Nonetheless, we should keep in mind that these RTs outcomes are delayed measures and non-conclusive for the results of these study.

Mean Reaction Time (RTs)

	LL^math	**OL**	**LL^math_Low**	**OL_Low**	**LL^math_High**	**OL_High**
Congruent	*883ms (92)*	*890ms (122)*	*865ms (90)*	*856ms (126)*	*902ms (105)*	*924ms (139)*
Incongruent	*898ms (89)*	*882ms (93)*	*880ms (99)*	*868ms(81)*	*916ms(93)*	*896ms (114)*
Total Mean	*891ms (96)*	*886ms (117)*	*872ms (88)*	*862ms (98)*	*909ms(91)*	*910ms(115)*
Diff (C-I)	*-15ms (n.s)*	*8ms (n.s)*	*-15ms(n.s)*	*-12ms (n.s)*	*-13ms (n.s)*	*27ms(n.s)*

Table 2.4. Summary of mean RTs results depicted per condition and overall differences between congruent and incongruent conditions. These differences were not significant.

Participants' answers to a questionnaire after the experiment session indicated that all participants adopted verbal strategies during the memorization sequence (i.e. verbal rehearsal or silence repetition of each number-word); some of them reported having used spontaneously spatial strategies like mental imagery or clustering but as they noticed less accuracy in their retention, they end up returning to the verbal re-hearsal. Those participants who systematically adopted alternative strategies or were not doing the task as they were instructed were not included. Six participants out of the total of twenty were discarded for this reason.

3.2. ERPs RESULTS

PROCESSING OF CONGRUENCY

Grand average ERPs waveforms lead for LL^{math} and OL in low and high memory loads are depicted in **Figure 2.2**. Plots show the contrast of mean amplitudes of congruent vs incongruent conditions in four ROIs. Topographic maps show the mean voltage distribution in the selected time windows. Visual inspection indicates large amplitude differences indexing the spatial congruency processing of number words in the LL^{math}. In the following lines, the results of general and individual ERP analysis are described. As noted, the main objective of the initial ERP analyses was to examine the effects of Congruency and interactions by Electrode and Language on critical components (N1-P2, N400-like and nSW). A follow-up analysis examined more closely those effects in critical regions of interest.

GLOBAL ANALYSIS RESULTS

Results of main effects of congruency and interactions for low memory load condition are depicted in **table 2.5.** For **low memory load condition**, the performed ANOVA indicated a significant effect of Congruency *[$F(1,13)=8.917$, $p<.01$]* and a significant interaction between Electrode and Congruency *[F(26,338)=2.999, p<.03]* starting in an early time window of encoding activity (50-200ms). In the following time window (200-300ms), there was a significant interaction effect of Language x Congruency *[F (1,13)=4.988, p<.04]*. At the N400-like time window (400-500ms), there was a main effect of congruency *[F (1,13)=8.590, p<.01]* and a significant interaction between Electrode and Congruency *[F (26,338)=6.150, p<.001].* During the time course of retention activity (nSW), an Electrode x Congruency interaction effect was found in onset (550-600ms) and offset (800-1000ms) time windows *[F (26,338)=4.189, p<.007; F (26,338)=4.643, p<.002].* The Language x Congruency interaction effect only resulted marginally significant *[F (1,13)=3.540, p<.08]* at this latency band.

Low Memory Load

ANOVAs: Electrode (27) x Language(2) x Congruency(2)	**Time windows**				
	50-200ms	**200-300ms**	**400-500ms**	**550-600ms**	**800-1000ms**
Congruency	***p=.01****	***p=.01****	***p=.01****	*p=.11*	*p=.11*
Language x Congruency	*p=.19*	***p=.04****	*p=.94*	*p=.25*	*p=.08*
Electrode x Congruency	***p=.03****	***p=.001*****	***p=001*****	***p=.007*****	***p=002*****
Electrode x Language x Congruency	*p=.63*	*p=.15*	*p=.51*	*p=.47*	*p=.13*

Table 2.5. The p-values for main effects and interactions displayed in critical time windows in low memory load condition.

General results in **high memory load condition** are summarized in **table 2.6**. The conducted ANOVA in the early time window of encoding (50-200ms) showed a triple interaction effect of Electrode x Language x Congruency *[F (26,338) =2.766, p<.04].* There was a significant interaction effect of Electrode x Congruency *[F (26,338) = 4.459, p<.009]* in the following time interval (200-300ms) consistent with encoding. Effects in the N400-like component did not reach the statistical significance and only a marginally significant interaction was shown between Electrode and Congruency (see table 2.6). The subsequent ANOVAs performed in the retention time intervals showed a triple interaction effect *[F (26,338)=2.928, p<.02]* in the onset (550-600ms) and a main significant effect of congruency *[F (1,13)=9.825, p<.008]* at the level of nSW offset (750-800ms). We observed that during the time course of the nSW component, the polarity in the congruent condition inverted. This can be related to memory-increasing demands. As already mentioned, slow waves changes has been shown in previous studies to be sensitive to WM load (Mecklinger, Kramer, Strayer, 1992; Gevins et al., 1996; McEvoy, Smith and Gevins, 1998; Ruchkin et al., 2007). No other effects were found significant.

High Memory Load

ANOVAs: Electrode (27) x Language(2) x Congruency(2)	**Time windows**				
	50-200ms	**200-300ms**	**400-500ms**	**550-600ms**	**750-800ms**
Congruency	*p=.48*	*p=.60*	*p=.80*	*p=.91*	***p=.008****
Language x Congruency	*p=.81*	*p=.35*	*p=.64*	*p=.91*	*p=.37*
Electrode x Congruency	*p=.07*	***p=.009*****	*p=.09*	*p=.21*	*p=.66*
Electrode x Language x Congruency	***p=.04****	*p=.52*	*p=.47*	***p=.02****	*p=.41*

Table 2.6. The p-values for main effects and interactions displayed in critical time windows in high memory load condition.

Individual Analysis Results

One major interest of this experiment was to test whether the LL^{math} and OL have each, particular networks mediating the processing of numerical-spatial association when memory load increases. Thus, it was crucial to explore the congruency effects observed in previous analysis by examining individual topographies (ROIs) and ERP components. The advantage of performing separate analysis is to have a more differentiated measurement of the initial ERP effects associated to the LL^{math} and to the OL, mostly in the high memory load condition. In following lines, results of individual analyses are described for each level of memory load and language conditions.

- *Low memory load: N100-P200, N400-like and nSW*

LL^{math}: Results of individual ANOVAs are depicted in **table 2.7**. Early ERP components (N1/P2) were elicited during the encoding of numerical-spatial congruency. Amplitude differences between congruent and incongruent conditions were larger and started earlier in the LL^{math}. At the **N1** latency band (50-200ms), the Electrode (27) x Congruency (2) ANOVA revealed a main significant effect of congruency *[F(1,13)=11.802; p<.004]* broadly distributed over Anterior and Posterior electrodes. The main congruency effect remained significant during transition to the **P2** component (200-300ms) *[F(1,13)= 21.081; p<.001]*. The Electrode x Congruency interaction effect also resulted highly significant at this latency band *[F(28,338)=7.811; p<.001]*. Inspection of the interaction by ROIs showed a main effect of congruency, distributed over Left/Right Frontal and Centroparietal sites. In the next time window (400-500ms), amplitude differences were observed at the level of the **N400-like**. The performed ANOVA showed a main effect of Congruency *[F(1,13)=5.256; p<.03]* broadly distributed over Frontal and Centroparietal electrodes. The interaction only resulted marginally significant at this latency band (*p<.06, see table 2.3)*. A subsequent **slow negative wave (nSW)** ERP was elicited during the retention of congruency. Mean amplitude differences started in an early stage (550-600ms) of the delay interval. The results of the general ANOVA showed a main effect of Congruency *[F(1,13)=5.144; p<.04]* while Electrode x Congruency interaction only resulted marginally significant *[F(26,338)=2.483; p<.06]*. Large amplitude differences remained during last part of the slow wave (800-1000ms). There was a main significant effect of Congruency [*F(1,13)=5.860; p<.03]* and no other effects reach the statistical significance (see table 2.7).

OL: The Electrode (27) x Congruency (2) ANOVA calculated for the early time interval (N100) revealed no significant effects of Congruency *[p<.21]* or interaction between Electrode and Congruency *[p<.11]*. Although the interaction between Language and Congruency was not revealed in the general ERP analysis (see table 2.5), it seems that early effects of congruency are not strong enough to approach the minimal significance in the OL compared to effects in LL^{math}. Larger amplitude differences between congruent and incongruent were elicited in the P2 (200-300ms) mostly centered in left-side channels (see figure 2.2). Results confirmed a significant Electrode x Congruency interaction *[F (26,338)=4.077; p<.01]*. The performed ANOVAs in selected ROIs showed a main significant effect of congruency in Anterior-Left *[F(1,13)=12.486; p<.004]* while no significant effects were found in other ROIs. The ANOVA conducted in next time window (N400-like), showed a main effect of Congruency *[F(1,13)=5.590; p<.03]* and a significant interaction between Electrode and Congruency *[F(26,338)=4.389; p<.006]*. Congruency effects were significant in Anterior-Left and Posterior-Left ROIs as revealed by respective regional ANOVAs *[F(1,13)=13.313; p<.003; F(1,13)=14.759; p<.002]*. Effects of congruency and interaction in the initial part of retention (nSW onset) did not reach the statistical significance (see table 2.7). Amplitude differences of the nSW increased in next time window (800-1000ms). The overall ANOVA showed a significant Electrode x Congruency interaction effect *[F(26,338)=5.116; p<.005]*. The ANOVA by region of interest confirmed a main congruency effect left-lateralized in Anterior sites *[F(1,13)=15.054; p<.002*]. No other effects were found significant.

- *High memory load: N100-P200, N400-like and nSW*

LL^{math}: A summary of results is depicted in **table 2.8.** Mean amplitude differences between congruent and incongruent started in the range latency of the N100. The Electrode (27) x Congruency ANOVA revealed a significant interaction effect between Electrode and Congruency *[F(26,338)=3.922; p<.009]*. The performed regional ANOVAs confirmed a significant effect of Congruency only in Anterior-Right ROI *[F(1,13)=4.759; p<.05]*. Congruency effects continued in the transition from the N100 to the P200 component with an opposite polarity. The ANOVA showed a significant interaction effect of Electrode and Congruency *[F(26,338)=3.300; p<.02]*. Inspection of this interaction confirmed a main significant effect of congruency at Posterior-Left electrode sites *[F(1,13)=7.667; p<.02]*.

At the level of the ***N400-like***, the polarity trend and distribution switched back to Right-side electrodes. There was a significant interaction of Electrode and Congruency *[F(26,338)=3.125; p<.03]*. The performed ANOVAs by ROIs confirmed a main effect of congruency only in Anterior-Right ROI *[F(1,13)=4.287; p<.05]*. Similar as in low memory load condition, large nSW amplitude differences were observed during the delay interval (500-800ms). The ANOVA performed at the onset nSW interval (550-600ms) revealed a significant Electrode x Congruency effect *[F(26,338)=3.266; p<.02]*. Analysis by ROIs, showed a main significant effect of Congruency in Anterior-Right *[F(1,13)=5.428; p<.03]* and in Posterior-Left ROIs *[F(1,13)=6.300*; *p<.03]*. The slow wave reversed the polarity in last part of the nSW (750-800ms). The overall ANOVA indicated a main significant effect of Congruency *[F(1,13)=.6.641; p<.02]*.

ERP congruency effects: Low Memory Load

LL^{math}	WM stage	Time window	Local ANOVAs	Topographic ANOVAs	ROI
	Early-Encoding	50-200ms	ExC [F(26,338)=1.671; p<.18] C [F(1,13)=17.231; p<.001]**		
	Encoding	200-300ms	ExC [F(26,338)=7.811; p<.001]** C [F(1,13)=21.081; p<.001]**	C [F(1,13)=27.809; p<.001]** C [F(1,13)=13.099; p<.003]** C [F(1,13)=43.675; p<.001]**	Anterior-Left Posterior-Right Posterior-Left
	Retrieval	400-500ms	ExC [F(26,338)=2.508; p<.06] C [F(1,13)=5.256; p<.03]*		
	Retention onset	550-600ms	ExC [F(26,338)=2.483; p<.06] C [F(1,13)=5.144; p<.04]*		
	Retention offset	800-1000ms	ExC [F(26,338)=1.205; p<.32] C [F(1,13)=5.860; p<.03]*		
OL	**WM stage**	**Time window**	**Local ANOVAs**	**Topographic ANOVAs**	**ROI**
	Early encoding	50-200ms	ExC [F(26,338)=2.252; p<.09] C [F(1,13)=664; p<.43]		
	Encoding	200-300ms	ExC [F(26,338)=4.077; p<.01]* C [F(1,13)=1.148; p<.30]	C [F(1,13)=12.486; p<.004]**	Anterior-Left
	Retrieval	400-500ms.	ExC [F(26,338)=4.389; p<.006]** C [F(1,13)=5.590; p<.03]*	C [F(1,13)=13.313; p<.003]** C [F(1,13)=14.759; p<.002]**	Anterior-Left Posterior-Left
	Retention onset	550-600ms	ExC [F(26,338)=2.4591;p<.08] C [F(1,13)=.614; p<.44]		
	Retention offset	800-1000ms	ExC [F(26,338)=5.116; p<.005]* C [F(1,13)=0.13; p<.90]	C [F(1,13)=15.054; p<.002]**	Anterior-Left

Table 2.7. F values and p-values for main and interaction effects of congruency in five time windows of interest. The congruency effects were significant in four ROIs.

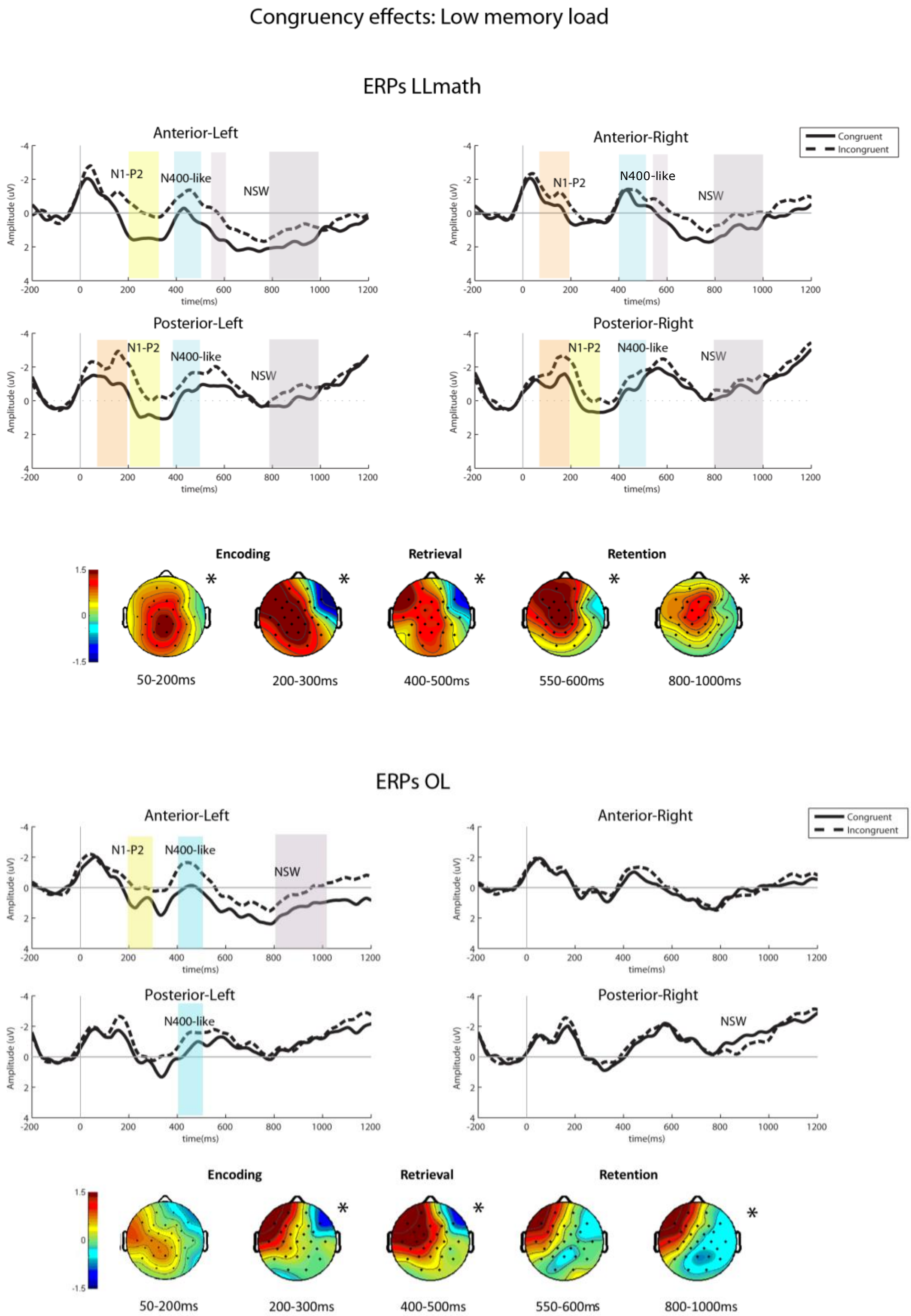

Figure 2.2. Grand averages ERPs and voltage maps elicited by congruency processing in critical time intervals. Plots on top show congruent vs incongruent comparisons for LL^{math}, plots on the bottom display the same comparisons in the OL.

The referred inverts in polarity are difficult to interpret. In general, literature refers to them as brain markers of changes in neural generators possibly reflecting an additional cognitive process (e.g. greater conscious awareness of mental processes) that is different from the primary one (for a more detailed discussion of the factors that affect the polarity of an ERP, see Luck 2005 , chap. 1 and Luck and Kappenman, 2012). In studies of WM, has been shown that polarity inverts as well as amplitude deflections varied as a function of proportional increases in the memory load level or perceptual difficulty of the task (Pauli et al, 1994; Ruchkin et al, 1988, 1990, 1991,2003; Reinhart et al., 2012). Here, the reversed polarity can be attributed to the influence of WM memory load, mostly during retention activity (nSW).

OL: Even though amplitudes differences in early N1-P2 were slightly present during the first 200ms, these differences did not reach statistical significance (table 2.8). No other significant interaction or main effects were found in later ERP potentials (N400-like /nSW).

Congruency effects: High Memory Load

LL^{math}	WM stage	Time window	Local ANOVAs	Topographic ANOVAs	ROI
	Early-Encoding	*50-200ms*	***ExC [F(26,338)=3.922; p<.009]**** *C [F(1,13)=.199; p<.66]*	***C [F(1,13)=4.759; p<.04]****	*Anterior-Right*
	Encoding	*200-300ms*	***ExC [F(26,338)=3.300; p<.02]**** *C [F(1,13)=.882; p<.36]*	***C [F(1,13)=7.667; p<.02]****	*Posterior-Left*
	Retrieval	*400-500ms*	***ExC [F(26,338)=3.125; p<.03]**** *C [F(1,13)=.235; p<.63]*	***C [F(1,13)=4.287; p<.05]****	*Anterior-Right*
	Retention onset	*550-600ms*	***ExC [F(26,338)=3.372; p<.01]**** *C [F(1,13)=.693; p<.42]*	***C [F(1,13)=5.428; p<.03]**** ***C [F(1,13)=6.300; p<.03]****	*Anterior-Right* *Posterior-Left*
	Retention offset	*750-800ms*	*ExC [F(26,338)=1.073; p<.37]* ***C [F(1,13)=.6.641; p<.02]****		
OL	**WM stage**	**Time window**	**Local ANOVAs**	**Topographic ANOVAs**	**ROI**
	Early encod-ing	*50-200ms*	*ExC [F(26,338)=1.477; p<.22]* *C [F(1,13)=.374; p<.55]*		
	Encoding	*200-300ms*	*ExC [F(26,338)=1.631; p<.20]* *C [F(1,13)=.248; p<.62]*		
	Retrieval	*400-500ms.*	*ExC [F(26,338)=.698; p<.55]* *C [F(1,13)=.012; p<.91]*		
	Retention onset	*550-600ms*	*ExC [F(26,338)=.631; p<.59]* *C [F(1,13)=.001; p<.99]*		
	Retention offset	*750-800ms*	*ExC [F(26,338)=.357; p<.75]* *C [F(1,13)=.881; p<.36]*		

Table 2.8. F-values and p-values for main and interaction effects of congruency, in five time windows. The congruency effects were significant in three ROIs only for LL^{math}.

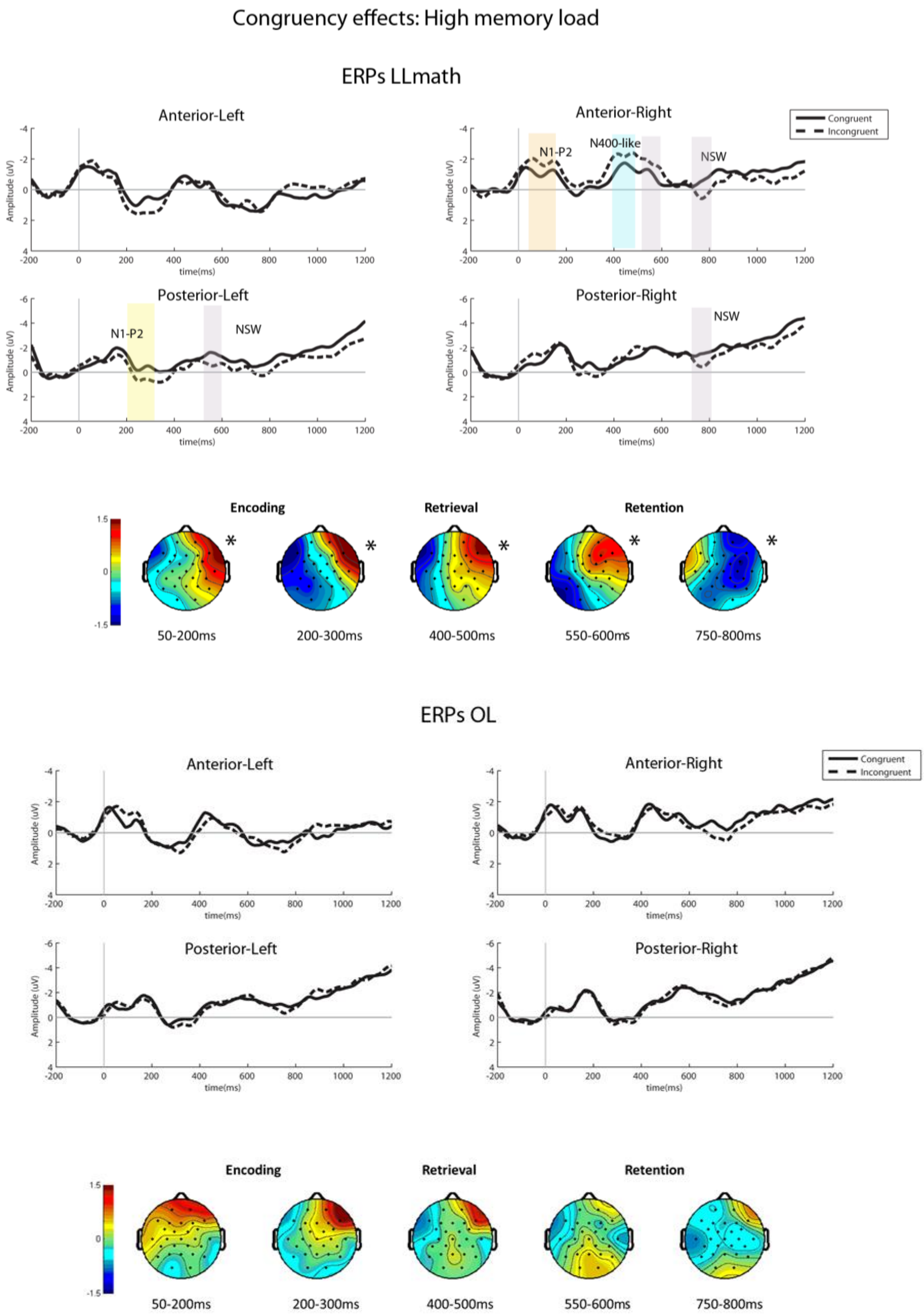

Figure 2.3. Grand averages ERPs and topographic profiles elicited during congruency processing in critical time intervals. Waveforms on top, show congruent vs incongruent comparisons for LL^{math}, waveforms on the bottom show the same comparisons in the OL.

Regression analysis results

As in Experiment 1, in order to discard any possible proficiency influence in the congruency effects, a regression analyses was carried out. Results of regression analyses are depicted in **tables 2.9** and **2.10**. The regression included BNT scores (scores in LL^{math} minus scores in OL) and self-reported percentage of frequency use of each language (frequency of use of LL^{math} minus frequency of use of OL) as regressor factors. The correlations obtained in each time window, confirmed that significant ERP effects were not explained by differences in LL^{math} and OL relative proficiency or by the percentage of use of each language. Only the congruency effect found for the OL in low memory load condition correlated ($p < .04$) with percentage of use during retention activity. However, given the trend of the dataset, this is an isolated effect that lacks of implications whatsoever in the general results.

Regression Low ML

ERP congruency effects	**LL^{math}**		**OL**	
	BNT	**% of use**	**BNT**	**% of use**
50-200ms	*R^2=.016; p<.29*	*R^2= .133; p<.10*		
200-300ms	*R^2=-.172; p<.08*	*R^2=.037; p<.24*	*R^2=-.051; p<.55*	*R^2=.040; p<.23*
400-500ms	*R^2=-.083; p<.95*	*R^2=.201; p<.07*	*R^2=-.078; p<.81*	*R^2=- .082; p<.91*
550-600ms	*R^2=.165; p<.09*	*R^2=-.063; p<.64*		
800-1000ms	*R^2= -.083; p<.94*	*R^2=-.078; p<.81*	*R^2=- .079; p<.82*	*R^2=.252;* ***p<.04****

Table 2.9. Results of regression analyses conducted for all significant ERP effects obtained for LL^{math} and OL in low memory load condition. Scores of BNT (LL^{math}-OL) and self-reported percentage of language use (% LL^{math}-%OL) were introduced as regressor factors of the ERP effects.

Regression High ML

ERP congruency effects	LL^{math} BNT	LL^{math} % of use	OL BNT	OL % of use
50-200ms	R^2=-.077; p<.79	R^2 = -.082; p<.16		
200-300ms	R^2=-.075; p<.76	R^2=.095; p<.15		
400-500ms	R^2=-.070; p<.71	R^2=.021; p<.40		
550-600ms	R^2=-.042 p<.50	R^2=-.077; p<.80		
800-1000ms	R^2 = -.044; p<.23	R^2=-.032; p<.45		

Table 2.10. Results of regression analyses for ERP effects obtained in high memory load condition.

4. Discussion

In this study, we examined the impact of early learning on the numerical-spatial magnitude representation in two memory load conditions. The obtained ERP pattern of results indicated an important influence of the LL^{math} in the MNL retrieval. Thus, the main suggestion is that balanced bilinguals would automatically activate the spatial component of magnitude representation in the LL^{math} .

Our results corroborate this hypothesis in both working memory load conditions. Under a low memory load, spatial-numerical representation was processed earlier when numbers were managed in LL^{math} compared to the OL time course. Such delayed effects were also extended to retention suggesting slower processes when spatial-numerical information is rehearsed in the OL. Critically, congruency effects in high memory load were only noticeable in LL^{math} while for the OL were barely present. This could be interpreted as an enhancement in the activation of long-term MNL likely associated to an early learning influence or to a failure of activation in a weak and non-automatic OL representation under higher memory load conditions. Importantly, the noticeable reduction of N400-like effects in high memory load compared to effects in low memory load (or even with N400-like effects in Experiment 1) can be associated to a greater processing cognitive cost. Consistently, similar reduction of N400 effect associated to congruency processing under high memory WM load has been also reported literature. Particularly, in some studies were suggest that effects of high working memory on the semantic N400 response tend to reduce the congruency effect, attenuating amplitude differences of the positive-going components, as was the case of congruent condition amplitudes (D´Arcy, Service, Connolly and Hawco, 2005; Gunter et al, 1995). Thus, it seems likely that WM demands altered at some point the processes related with congruency processing.

Moreover, topographical differences found at both levels of the WM load reinforce the early learning impact in the MNL hypothesis. For the LL^{math}, results showed a general bilateral distribution of ERP effects in anterior and posterior electrodes with a significant focus toward right-side during the time course of retention (high memory load condition). For the OL, the distribution of ERP effects in the low condition was centered over left scalp topographies. Processing of congruency in OL is more affected by memory load than LL^{math} which might reflect a greater dependency of spatial-numerical association to external variations of the task.

Taken together, results confirm very different brain correlates associated to LL^{math} and OL involved in access to the MNL that might indicate differences at the representational level. Thus, in line with Salillas and Carreiras (2014), these results suggest possible differences in basic magnitude representation as a function of the early learning math context. Theoretical implications of these results will be further discussed in the general discussion of this thesis.

EXPERIMENT 3

1. INTRODUCTION

The present study aims to explore the effects of language in the spatial numerical representation as result of early learning, by investigating the connection of the LL^{math} and the OL with the MNL in the *auditory modality*. As already pointed, the role of language in the core magnitude knowledge is critical in the context of bilingualism (Salillas and Carreiras, 2014; Salillas, Barraza and Carreiras, 2015). In light of these recent findings, current research tends to be more focused on what sort of relation the LL^{math} has with basic magnitude representation. Therefore, it should be contemplated the different ways in which numerical-spatial information can be processes or managed, including the perceptual modality. There is large amount of empirical evidence showing that auditory modality can activate the internal visuospatial representation of MNL. It has been suggested that spatial magnitude representation is amodal and therefore is not restricted only to visual modality (Cattaneo et al., 2010; Nuerk, Wood and Willmes, 2005; Salillas, Graná, El-Yagoubi and Semenza, 2009; Zorzi, Priftis, and Umilta, 2002). For instance, the SNARC effect (Dehaene, Bossini and Giraux, 1993) which is usually observed when numbers are presented visually, has also been reported with numbers presented aurally suggesting that the link between numerical magnitude and space occurs in other modalities as well (Castronovo and Seron, 2007; Wood, Nuerk and Willmes, 2006). This modality independence has been observed also in blind individuals. In this regard, there is evidence showing the *SNARC effect* and the *distance effect* in blind individuals when numbers were presented in the auditory modality (Salillas et al., 2009; Castronovo and Seron, 2007; Szücs and Csépe, 2005). However, it should be noticed that although the spatial numerical association in non-visual modalities has been demonstrated, is more stable within the visual modality in the Arabic notation. Thus, the main suggestion derived from these studies is that although automatic activation of magnitude representation is initially amodal, the association to space has greater automaticity in the visual modality (see also Dehaene et al., 1993; Nuerk et al 2005).

On the other hand, associations of large and small numbers to left and right hemifields can be induced after presenting sounds through right and left ear. Previous studies have reported an effect of auditory pitch on right-left responses. That is, high and low pitches presented in right and left ear induce the labeled SMARC effect (spatial– musical association of response codes). In Rusconi et al. (2006) study, a tone of higher or lower frequency was presented through headphones and participants had to judge whether the pitch of a following test tone was higher or lower than the referent pitch. Similar as the SNARC effect, these subjects responded faster with right hand when higher pitches were congruent with the right ear-side and the reverse occurred when lower pitches were presented in left ear. These findings suggest that high and low magnitudes can automatically activate spatial congruency responses (right-left) in the auditory modality mainly because the MNL representation is strong enough to influence the horizontal response over the perceptual modality of the task (see also Lidji, Kolinsky, Lochy and Morais, 2007).

It is well-known that visual and auditory modalities have associated each different processing network. The effects of perceptual modality in WM have already been pointed in behavioral research wherein different streams for visual and auditory material have been suggested (Allport et al., 1972; Kroll et al., 1970; Penney, 1989). Additionally, imaging studies (fMRI/ERPs) have provided solid evidence of modality-specific brain activity attributable to the sensorial modality (Crottaz-Herbette, Anagnoson and Menon, 2004; Lang et al, 1992; Khalafalla et al., 1999;; Protzner et al., 2009). The most common finding observed in WM ERPs studies is a slow wave which differs in topography depending on the type of information to-be-held and the modality (Barrett and Rugg 1989, 1990; Ruchkin et al., 1997; 2003). The usual polarity of the slow wave during the maintenance stage is negative, but positive slow waves after stimulus offset (600-900ms) have been reported following earlier components (e.g. N2, P3) mostly indexing retrieval of information from WM (see Gevins et al., 1996; Garcia-Larrea and Cezanne-Bert, 1998). Furthermore, as has been already mentioned, negative slow wave (nSW) amplitudes are sensitive to WM load manipulations involving differential patterns of neuronal activation during the time course of encoding and retention (Lang et al. 1992; Ruchkin et al. 1992). In general, the ERP activity recorded during the encoding and retention seems to be sensitive to both, modality and memory load (Crottaz-Herbette, Anagnoson and Menon, 2004; Ruchkin et al, 1997; Ruchkin et al, 2003; Smith, Jonides and Koeppe, 1996; Shah and Miyake, 1996). In the present study, we used an auditory working memory paradigm to detect differences in numerical-spatial processing as a function of the language of early learning math. At the same time and, as in our Experiment 2, the use of different memory loads will allow us to examine the impact of LL^{math} in the efficiency of WM processes.

The presented Experiments 1 and 2 provide ERP evidence of a possible influence of LL^{math} in the MNL representation when numerical-spatial information is managed in the visual modality. As mentioned above, spatial-numerical associations (e.g. SNARC effect) have been reported across modalities. Thus, assuming that the link between number and space is amodal, it is reasonable to predict that numbers presented in the aurally might activate the MNL as in the visual modality. For this reason, the main goal this experiment is to investigate the ERP patterns elicited by both languages (LL^{math} vs OL) in the auditory modality and thus, characterize neural networks associated with early learning. So far, the relation between LL^{math} and the MNL has never been tested in the auditory modality. Therefore, we focused on whether the association of LL^{math} with the MNL also extrapolates to the auditory modality in the cognitive context of working memory. Most of our understanding of processing differences between visual and auditory working memory is based on neuroimaging studies (fMRI/ERP) showing important quantitative and qualitative brain differences in the way internal representations of the stimuli are handled (Crottaz-Herbette et al., 2004; Petrides et al, 1993; Ruchkin et al 1997). Part of these differences has been attributed to the additional translation process into a phonological format needed in the visual modality. In contrast, auditory stimuli do not undergo such transformation as information automatically enters into the phonological store through articulatory rehearsal (Baddeley, 1986, 1997, 2000; Shallice and Vallar, 1990). In Crottaz-Herbette et al. study (2004), authors scanned brain activation differences during performance of auditory and visual verbal WM tasks. A particular region of the parietal cortex was activated during both visual and auditory tasks, but greater activity was found in the visual modality. This led authors to suggest that although the phonological storage is accessed by both auditory and visual stimuli, greater neuronal processing resources might be involved in the visual modality. Using EEG recordings, Ruchkin et al. (1997), showed that retention in WM of visually presented stimuli resulted in an earlier and more sustained slow wave compared to retention in the auditory modality. These empirical reports are consistent with the hypothesis that auditory stimuli have a more direct access to phonological representations (Baddeley, 1986; Penney, 1989). On these bases, we hypothesized that influence of modality during processing of congruency should be reflected in encoding and retention WM processes. We predict greater modality differences during encoding activity due to the additional coding step that takes place necessarily in the visual modality. Besides, we expect similar ERP activity in both modalities during retention since maintenance activity is subjected to phonological rehearsal.

A sample of balanced bilinguals engaged in a working memory task in which both, language and space, were simultaneously activated. An auditory version of a match-to-sample task (Petrides et al., 1994) was used to investigate the ERP activity associated to processing of congruency as a function of early learning (LL^{math} vs OL). We hypothesized that automatic activation of spatial-numerical representation will involve different brain responses depending on the language of learning math. As in Experiment 2, we tested this hypothesis under high and low memory load conditions. A way to assure the activation of the horizontal representation of numbers in the auditory modality is by means of presenting large and small magnitudes in left and right ear. Therefore, selected stimuli consisted of a range of six number-sounds belonging to each language. Participants listened to a set of numbers-words presented either through the right or through the left earphone. They were requested to memorize the side of each listened number word and judge the correctness of a probe number after a delay. Presentation of four numbers accounted for low memory load and presentation of six numbers accounted for high memory load. The management of both, numerical and spatial information in WM, entails that participants implicitly activate MNL long-term memory representations while they encode and rehearse the memorized sequence. We hypothesized that a spatial congruency effect would appear during the encoding and retention of the number words as a function of the early learning math factor. Main components associated with WM processing are expected during processing of congruency in both memory loads conditions. Auditory WM related ERPs (e.g. N1, slow wave) are expected consistent with the time course of encoding and retention of congruency. Slow wave potentials have been observed also in the auditory modality mostly indexing retention-rehearsal operations (Lang et al., 1992 Ruchkin et al., 1997). In our study, we predict that if early learning modulates long-term spatial-numerical representation, ERPs belonging to LL^{math} should differ from ERPs belonging to the OL. In addition, if bilinguals´ LL^{math} is the preferred verbal format for spatial numerical representation, then we expect the OL to be more affected by memory load during retention. Overall, the goal of this study was to better characterize the pattern of ERP activity associated to LL^{math} and OL when the MNL representation is activated through a non-visual input.

2. Methods

The participants' profile and experimental design was similar to those presented in Experiments 1 and 2 but stimuli were issued in the acoustic modality. A detailed illustration of the paradigm and procedures is included at the end of this section (**Figure 3.1).**

2.1. Participants

We selected 14 adult participants (7 females, mean age = 23) who volunteered for this experiment. All were healthy, right-handed bilingual speakers of Spanish and Basque. The average age of language acquisition was 0 for Spanish and 1 for Basque. The language in which they learned math was Spanish for half of the participants, and Basque for the other half. This information was obtained before the EEG recording, asking them three questions: "In which language did you learn math"? ; "In which language do you usually count?"; In which language do you perform arithmetic facts?". Additionally, all participants were tested in their WM capacity with the standard Battery of cognitive abilities of Woodcock-Johnson III, test 7 (Number Reverse) and 9 (Auditory WM) (Schrank, Wendling and Woodcock, 2008, 2010). The mean average of the standardized scores was 101 (9) indicating that participants have roughly similar relative WM capability.

Language assessment

Participants were selected after language assessment. As in previous experiments of this study, the Spanish-Basque adaptation of the Boston Naming Test was used to assess bilinguals´ linguistic competence (BNT; Kaplan, Goodglass and Weintraub, 1983). According to the BNT scores, all selected participants were equally proficient in Spanish and Basque (see **table 3.1).** Scores were slightly superior for Spanish in both bilinguals´ profiles (i.e. bilinguals who learned math in Spanish and bilinguals who learned math in Basque). These differences were significant in participants that had Spanish as LL^{math} *($t=4.258$; $p< .005$)* but not in participants whose LL^{math} was Basque *($t=- 2.027$; $p<.089$).* Participants were equivalent in relative language proficiency *($t=1.372$; $p<.193$).* The reported percentages of use of each language in their daily life are depicted in table 3.1.

BNT proficiency and % of use

BNT Scores	**Spanish**	**Basque**	**Difference (LL^{math}-OL)**
LL^{math}:Spanish	54.7 (3.9)	48.2(6.4)	6.5 (3.9)
LL^{math}:Basque	50 (5)	47.7(4.7)	-2.3 (2.9)
% of use	**Spanish**	**Basque**	
LL^{math}: Spanish	75%	57%	
OL : Basque	25%	43%	

Table 3.1. BNT scores and self-reported percentage of use. The relative language proficiency was calculated by subtracting the scores in LL^{math} from scores in OL.

Identically as in Experiments 1 and 2, all participants were collapsed for analysis. Thus, language condition was considered as unique within-subjects variable regardless of whether LL^{math}/OL was Spanish or Basque.

2.4. Procedure

Stimuli

A similar type of match-to-sample task as in Experiment 2 was featured but in the acoustic modality. Single digit number-words for high and low magnitudes, were used as stimuli. The combination of stimuli in experimental trials followed the same procedure as in Experiment 2. Numbers-words 4, 5 and 6 (“seis/sei”, “five/bost”, “cuatro/lau”) were excluded for the same reason as Experiment 2. A pitch sound was included as a cue to indicate the presentation of the number test. The total duration of the experiment session including breaks was 1h 30min.

Design

The same design as Experiment 2 was considered to test our hypothesis in the auditory modality (see **figure 3.1**). There were four types of trials depending on combinations of congruency and memory load conditions. A congruent trial consisted in small numbers triggered through the left ear-side and large numbers through the right ear-side. The incongruent version presented the reversed arrangement. High-load accounted for the presentation of six number-words whereas low-load accounted for the presentation of four items. The arrangement of number-words was randomized and intermixed across trials. Half of the number-sounds were presented through the left earphone and half through the right. The percentage of occurrence of each number and its location (right/left) was balanced across trials so all numbers were equiprobable in left and right sides. A total of 576 trials were presented, 288 were Spanish trials and 288 were Basque trials whereby 144 pertained to high memory load trials (72

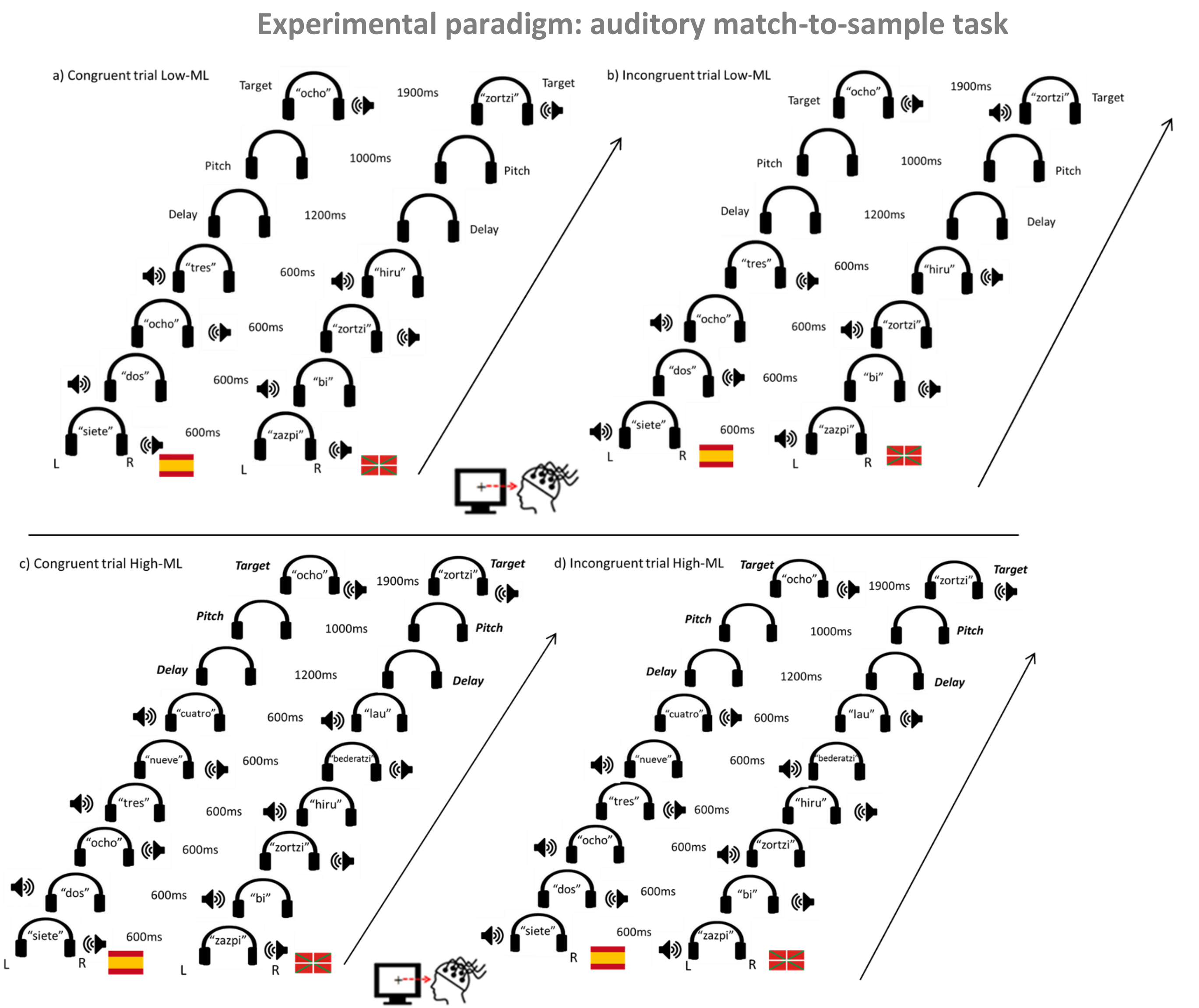

Figure 3.1. Experiment trial examples per condition. Number-words were presented randomly through left or right-side earphone a) shows a Spanish/Basque version of a congruent trial in low memory load condition b) illustrates a Spanish/Basque incongruent trial in low memory load condition c) shows a Spanish/Basque congruent trial in high memory load condition and d) shows a high memory load version of a incongruent trial.

congruent and 72 incongruent) and 144 pertained low memory load trials. As the number of participants who learned math in Spanish and Basque was the same, stimuli and experiment structure was identical for all participants. Thus, all conditions were collapsed for analysis regardless of the early learning math background.

Participants were tested individually inside an electro-acoustically shielded room. They were instructed to avoid body movements and fixate their eyes looking at the cross-mark in the center of the screen. The task began with a default fixation mark. Number sounds were issued through isolated headphones. The experiment session consisted in a memorizing sequence wherein numbers could be listened (500ms) either through right or left earphone. To prevent the sense of overlapping, a longer inter-stimulus interval (ISI) was used (600ms). Thus, the delay period was extended up to 1200ms. After a delay interval, an unpredictable test-number was presented in right or left earphone. Participants had to quickly memorize numbers and respond after a pitch sound (1000ms). They were instructed to judge the correctness of the sound-side accordingly and answer pressing the appropriate button of the gamepad device. The time interval given to respond was limited up to 2000ms. Answers beyond that restriction were considered missing trials. In order to prevent loss of attention and tiredness, feedback was given to participants. The next trial started after the response feedback disappeared from the screen (500ms).

2.5. EEG RECORDINGS AND ANALYSIS

The continuous EEG was recorded and processed identically to Experiment 2. Grand averaged ERPs were obtained for each condition and pooled across all subjects. Timing was adjusted based on duration of the sound-files (500ms). A 200ms pre-stimulus interval was used for baseline correction. Thus, averaged segments ranged from -200ms to 1500ms relative to last number-word onset (500ms) plus a portion of 1000ms of delay interval preceding the test number.

ANALYSIS

Behavioral data was analyzed similarly as Experiment 1 and 2. For each participant, accuracy and mean RTs were examined. Percentage of errors rates (ER) was calculated in each experimental condition. Values for d-prime (discrimination index) were estimated and evaluated using one-sample t-test against zero. Mean reaction times were computed only for correct responses. An analysis of variance was carried out for ER and RTs including Language and Congruency as factors.

ERPs epochs were computed for correct-hit trials. A long-lasting nSW potential was identified. Time-windows selection was similar to Experiment 1 and 2 but particular adjustments were made due to the greater duration of the experiment (i.e. stimuli and delay period). Similar isolated analysis at the level of encoding and retention has been reported in **previous WM** studies (Berti and Roeber, 2013) some of them based on delayed matching-to-sample task (Klein et al., 1997; Löw et al, 1999). After visual inspection, slow wave latencies were divided in critical intervals spanning the encoding and the retention activity (early encoding: from 0 to 200ms; late encoding: 200-300; retrieval of MNL: from 400 to 600ms; retention: from 600 to 1500ms). Subsequently, specific time windows were defined based on this division. Statistical analysis was performed separately for each time window and for each level of the memory load in all electrodes. Thus, for each memory load level, a general Electrode (27) x Language (2) x Congruency (2) repeat measure ANOVA was calculated in the following time windows of interest: 150-200ms, 200-300ms, 400-600ms, 700-850ms, 1000-1100ms and 1100-1200ms. Significant interactions of congruency with language and electrodes were further examined separately in LL^{math} and OL.

Individual ANOVAs conducted in each time window included Electrode (27) x Congruency (2) as factors. Significant interactions by electrode were inspected in ROIs as in experiments 1 and 2 (ROIs: Anterior-Left (6), Anterior-Right (6), Posterior-Left (6), Posterior-Right (6)). Regional ANOVAs included selected electrodes in each ROI (6) and Congruency (2) as independent factors. Based on significant ERP effects, a regression analysis was included to test whether nSW effects were influenced by the relative language proficiency or by the percentage of use. Thus, BNT scores and percentage of language were used as correlated regressors.

3. Results

3.1. Behavioral results

The distribution of errors for congruency and memory load conditions is depicted in **table 3.2.** General accuracy was above 80% *(d'=0.9;* t_{13} *=8.792; p = .001).* Considering each verbal format separately (LL^{math}/OL) the error rates (ER) was almost identical (LL^{math}= 15.9% (8), OL=15.8% (8)). The performed Language x Congruency ANOVAs in low and high memory load conditions showed equivalent ER between congruent and incongruent conditions *(Low: Congruency (F(1,13)=.034; p<.85); High: Congruency (F(1,13)=.641; p<.43).* Interactions by language were not found significant either *(Low: Language x Congruency (F(1,13)=.992; p<.33); High: Language x Congruency (F(1,13)=3.425; p<.08).*

Mean Error Rate (ER)

General ER: 15 (8); d' 0.9 (0.4)				
	Low Memory Load		**High Memory Load**	
	LL^{math}	**OL**	**LL^{math}**	**OL**
Congruent	14% (8.3) d' 1.1 (0.4)	16% (8.1) d' 0.7 (0.3)	19% (9.8) d' 0.8 (0.4)	15% (10.5) d' 1.1 (0.5)
Incongruent	15% (10.5) d' 1.3 (0.8)	14% (9.7) d' 0.3 (1.1)	14% (9.7) d' 1.1 (0.4)	17% (13.1) d' 1.0 (0.5)

Table 3.2. Mean percentage of error rates and d-prime calculated per each experimental condition.

A summary of mean RT´s are depicted in **table 3.3**. On average, congruent trials were responded faster than incongruent trials in LL^{math} *(-15ms)* and in the OL *(-20ms)*. The performed Language x Congruency ANOVA in low memory load condition indicated that these differences were not statistically significant *(Congruency: $F(1,13)=1.120$; $p<.30$; Language x Congruency: $F(1,13)=.069$; $p<.79$)*. In high memory load, the performed ANOVA revealed a significant main effect of Congruency *($F(1,13)=12.021$; $p<.004$)* while the Language x Congruency interaction was not significant *($F(1,13)=.661$; $p<.43$)*. Due to the delayed nature of RTs outcomes, we considered these effects an approximate estimation of the behavioral trend and not conclusive for the purposes of this study.

Mean RTs

	LL^{math}	OL	LL^{math}_Low	OL_Low	LL^{math}_High	OL_High
Congruent	*793ms (92)*	*799ms (122)*	*780ms (90)*	*786ms (91)*	*807ms (112)*	*808ms (103)*
Incongruent	*808ms (89)*	*819ms (93)*	*794ms (99)*	*792ms(112)*	*823ms (93)*	*840ms(121)*
Total Mean	*801ms (94)*	*808ms (98)*	*787ms (96)*	*789ms (94)*	*815ms (99)*	*826ms (109)*
Diff (C-I)	*-15ms (n.s)*	*-20ms (n.s)*	*-14ms(n.s)*	*-6ms (n.s)*	*-16ms (n.s)*	*-32ms(n.s)*

Table 3.3. Mean RTs and differences between congruent and incongruent displayed for each experimental condition.

3.2. ERPs RESULTS

PROCESSING OF CONGRUENCY

Averaged ERPs for LL^{math} and OL in low and high memory load conditions are depicted in figures 2 and 3. The displayed epochs show a long lasting slow wave ERP with data pooled in four ROIs. Visual inspection reveals larger amplitude differences for LL^{math} than for the OL condition. Such amplitude differences started earlier in high memory load condition (150ms). For LL^{math}, effects of congruency were sustained during low memory load activity and were heavily pronounced in high memory load whereas in the OL, the nSW amplitude differences were more transient and barely noticeable in both memory load conditions.

Global analysis results

Results of general ANOVAs in all time windows of interest in low condition is summarized in **table 3.4**. For low memory load, no significant interactions or effects of congruency were found during encoding activity. The performed Electrode (27) x Language (2) x Congruency (2) ANOVA showed a significant main effect of congruency *[F(1,13)=4.778, p<.04]* in retrieval time window (400-600ms). The ANOVA performed in the nSW onset interval (1000-1100ms) showed a significant interaction between Language and Congruency *[F(1,13)=9.448, p<.009]*. In the last

Low memory load

Anova: Electrode x Language x Congruency	Time windows				
	150-200ms	200-300ms	400-600ms	1000-1100ms	1100-1200ms
Congruency	*p=.77*	*p=.97*	***p=.04****	***p=.01****	*p=.07*
Language x Congruency	*p=.95*	*p=.30*	*p=.79*	***p=.009****	*p=.26*
Electrode x Congruency	*p=.70*	*p=.71*	*p=.35*	*p=.22*	***p=.05****
Electrode x Language x Congruency	*p=.51*	*p=.26*	*p=.17*	*p=.56*	*p=.64*

Table 3.4. P-values (*p<.05) for main effects of congruency and interactions in time windows of interest

part of the nSW (1100-1200ms), there was a significant Electrode x Congruency interaction *[F (26,338) = 2.894, p<.05]*.

Table 3.4 contains the results for high memory load condition. The conducted ANOVAs showed a significant Language x Congruency interaction effect in both, early encoding (150-200ms) *[F(1,13)=5.205, p<.04]* and encoding intervals (200-300ms) *[F(1,13)= 7.130, p<.01]*. At the level of retrieval, there was a significant triple Electrode x Language x Congruency interaction *[F (26,338)=3.543, p<.01]*. At the level of nSW offset (1100-1200ms), there was a significant triple interaction effect *[F(26,338)=3.408, p<.01]*.

High memory load

Anova: Electrode x Language x Congruency	Time windows				
	150-200ms	200-300ms	400-600ms	700-850ms	1100-1200ms
Congruency	*p=.21*	*p=.51*	*p=.55*	*p=.40*	*p=.795*
Language x Congruency	***p=.04****	***p=.02****	*p=.20*	*p=.49*	*p=.275*
Electrode x Congruency	*p=.69*	*p=.27*	*p=.19*	*p=.26*	*p=.521*
Electrode x Language x Congruency	*p=.25*	*p=.24*	***p=.01****	*p=.19*	***p=.01****

Table 3.5. P-values (*p<.05) for main effects of congruency and critical interactions carried out in windows of interest.

Individual analysis results

As in Experiment 2, a major interest of this experiment was to examine the particular networks mediating the processing of numerical-spatial in each language condition across both memory loads. In this experiment in particular, it was crucial to perform a topographical inspection individually, given the fact that processing of information in the auditory modality is mediated by different brain networks and this might elicit different brain responses during the processing of congruency. In following lines, results of individual analyses are described individually for each level of memory load and language condition.

- ***Low memory load***

LL^{math}: Table 3.6 shows the results of ANOVAs carried out in selected time windows of interest. Only significant or marginally significant effects reported in former analysis were inspected. In the 400-600ms time window, there was a significant congruency effect *[F(1,13)=4.462; p<.05*] while the interaction did not reach the statistical significance. The analyses of congruency effects in the retention interval yielded a main significant effect of congruency in selected onset and offset time windows (1000-1100ms: *[F(1,13)=19.387; p<.001*]; 1100-1200ms *[F(1,13)=13.241; p<.003*]. No other effects were found significant.

ERPs congruency effect: Low Memory Load

LL^{math}	**WM stage**	**Time window**	**Local ANOVAs**
	Retrieval	*400-600ms*	*ExC [F(26,338)=1.072; p<.35]* ***C [F(1,13)=4.462; p<.05]****
	Retention onset	*1000-1100ms*	*ExC [F(26,338)=1.502; p<.23]* ***C [F(1,13)=19.387; p<.001]*****
	Retention offset	*1100-1200ms*	*ExC [F(26,338)=1.702; p<.16]* ***C [F(1,13)=13.241; p<.003]*****
OL	**WM stage**	**Time window**	**Local ANOVAs**
	Retrieval	*400-600ms*	*ExC [F(26,338)=1.845; p<.15]* *C [F(1,13)=2.769; p<.12]*
	Retention onset	*1000-1100ms*	*ExC [F(26,338)=.632; p<.56]* *C [F(1,13)=.441; p<.51]*
	Retention offset	*1100-1200ms*	*ExC [F(26,338)=1.484; p<.23]* *C [F(1,13)=.144; p<.71]*

Table 3.6. F values and p-values for main and interaction effects of congruency in five time windows. There was a general significant effect of congruency in all WM stages only in LL^{math} condition.

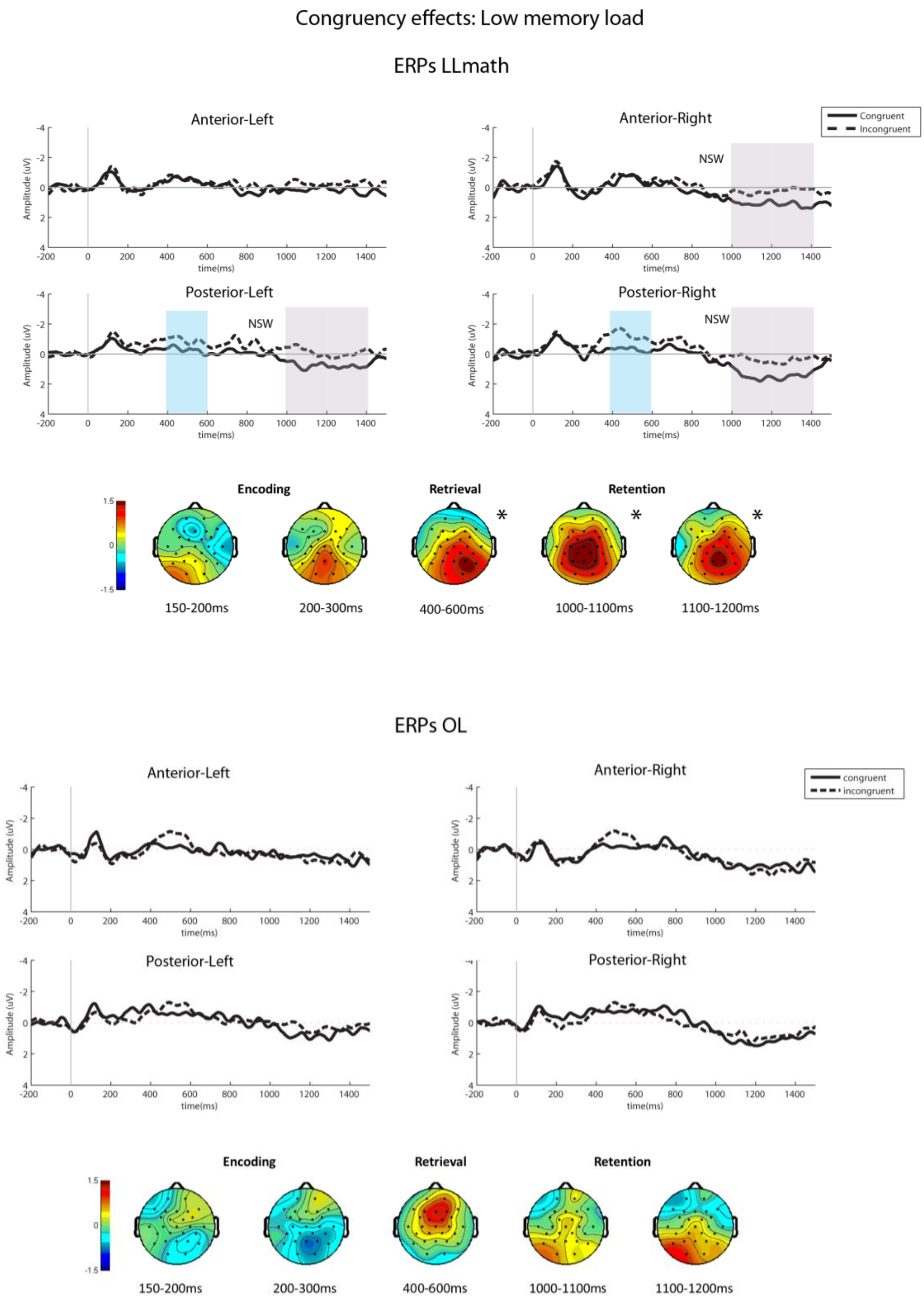

Figure 3.2. Grand averages ERPs and topographic profiles of congruency condition in critical time intervals. The waveforms on top show congruent vs incongruent comparisons for LL^{math}. Waveforms on bottom show the same comparisons in the OL.

OL: The nSW amplitude was affected in less extent by processing of congruency. The individual ANOVAs performed the respective time windows confirmed that effects of congruency and interactions were not statistically reliable (see p-values table 3.6).

- ***High memory load***

LL^{math}: Results of individual and regional ANOVAS are depicted in **table 3.7.** As in low memory load condition, effects of congruency were indexed by an nSW component. The Electrode x Congruency ANOVA revealed a main significant effect of congruency in two consecutive time windows of interest mirroring encoding activity: 150-200ms *[F(1,13)=7.464; p<.01];* 200-300ms *[F(1,13)=12.6971; p<.003]*. The interaction effects were not significant at this latency band. At the level of the delay period, the nSW amplitude differences increased consistent with retention. Individual ANOVAs performed in selected onset (700-850ms) and offset (1100-1200ms) time windows, confirmed significant interactions between Electrode and Congruency *[F(26, 338)=2.789; p<.03]; [F(26, 338)=3.198; p<.02]*. Inspection of these interactions in ROIs (Electrode (6) x Congruency (2)), confirmed a main significant effect of congruency in Posterior-Right sites *[F(1,13)=5.199; p<.04]; [F(1,13)=8.614; p<.01]* mainly reflecting a right-side lateralization of congruency effect during rehearsal activity similar as Experiment 2 (see table 3.7).

OL: Similar to low memory load, nSW differences between congruent and incongruent were attenuated and appeared transiently in the time course of WM activity. Interaction effects (Electrode x Congruency) were significant in 400-600ms time window *[F (26,338)=3.210; p<.02]*. The follow up analyses in respective ROIs only revealed a marginally significant effect of congruency in Posterior-Right ROI *[F (1,13)=4.037;*

p<.06]. No other effects approached the statistical significance in the rest of ROIs (see **table 3.7**).

Congruency effect: High Memory Load

LL^{math}	WM stage	Time window	Local ANOVAs	Topographic ANOVAs	ROI
	Early-encoding	*150-200ms*	*ExC [F(26,338)=1.242; p<.19]* ***C [F(1,13)=7.464; p<.01]****		
	Encoding	*200-300ms.*	*ExC [F(26,338)=.936; p<.43]* ***C [F(1,13)=4.772; p<.04]****		
	Retrieval	*400-600ms*	*ExC [F(26,338)=1.933; p<.12]* *C [F(1,13)=1.164; p<.30]*		
	Retention onset	*700-850ms*	***ExC [F(26,338)=2.786; p<.03]**** *C [F(1,13)=1.227; p<.28]*	***C [F(1,13)=5.199; p<.04]****	*Posterior-Right*
	Retention offset	*1100-1200ms*	***ExC [F(26,338)=3.198; p<.02]**** *C [F(1,13)=1.; p<.27]*	***C [F(1,13)=8.614; p<.01]****	*Posterior-Right*
OL	**WM stage**	**Time window**	**Local ANOVAs**	**Topographic ANOVAs**	**ROI**
	Early Encoding	*150-200ms*	*ExC [F(26,338)=.794; p<.49]* *C [F(1,13)=.016; p<.90]*	.	
	Encoding	*200-300ms.*	*ExC [F(26,338)=1.678; p<.17]* *C [F(1,13)=.468; p<.51]*		
	Retrieval	*400-600ms*	***ExC [F(26,338)=3.210; p<.01]**** *C [F(1,13)=.150; p<.71]*	*C [F(1,13)= .668; p<.42]* *C [F(1,13)=2.463; p<.17]* *C [F(1,13)=4.086; p<.06]* *C [F(1,13)=1.398; p<.25]*	*Anterior-Right* *Anterior-Left* *Posterior-Right* *Posterior-Left*
	Retention onset	*700-850ms*	*ExC [F(26,338)=.187; p<.94]* *C [F(1,13)=.003; p<.95]*		
	Retention offset	*1100-1200ms*	*ExC [F(26,338)=.856; p<.47]* *C [F(1,13)=.382; p<.54]*		

Table 3.7. F-values and p-values of main and interaction congruency effects found in five time windows consistent with WM activity. The interaction effects were significant in Posterior-Right ROI in the LL^{math} condition whereas in OL, congruency effects did not reach the statistical significance in selected ROIs.

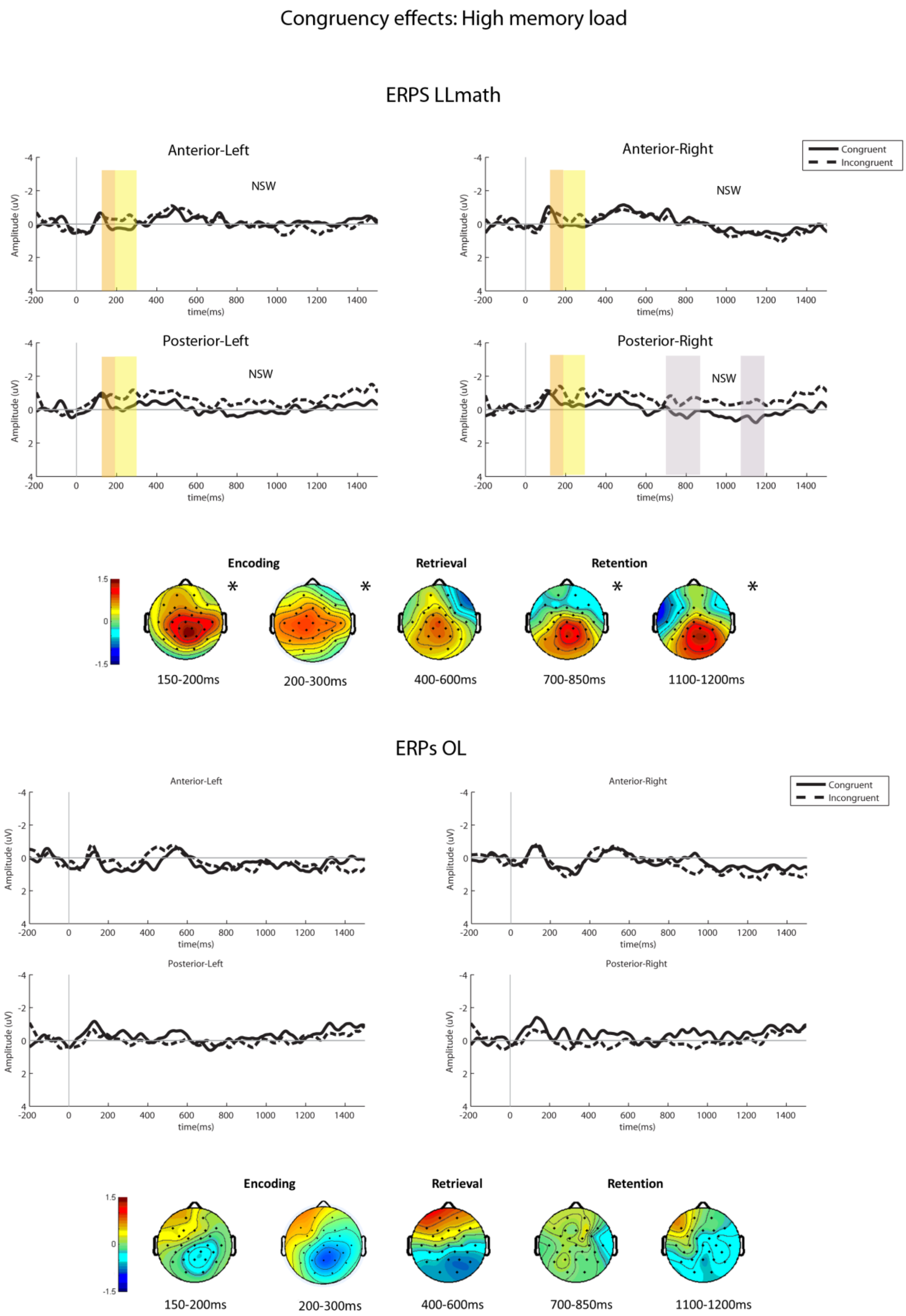

Figure 3.3. Grand averages ERPs and topographic profiles elicited during congruency processing in critical time intervals. Waveforms on top show congruent vs incongruent comparisons for LL^{math}. The waveforms on the bottom show the same comparisons in the OL.

Regression analysis results

The R-squared values and p-values yielded by the linear regression analysis are depicted in **tables 3.8 and 3.9 below**. There was no significant relationship between ERP congruency effects and differences in relative language proficiency (BNT). Similarly, effects did not depend on frequency of language use. Thus, these data exclude the possibility that congruency effects found in LL^{math} are explained by differences in relative language proficiency or the frequency of language use.

Regression: Low ML (LL^{math})

ERP congruency effects	BNT	% of use
400-600ms	*R^2=-.083; p<.96*	*R^2=-.080; p<.85*
1000-1100ms	*R^2=.001; p<.33*	*R^2=.202; p<.06*
1100-1200ms	*R^2= -.068; p<.69*	*R^2=-.049; p<.54*

Table 3.8. Adjusted R2 values and p-values in low ML (p-level of 0.05). ERP effects in respective time windows, were not significantly related neither with relative language proficiency (LL^{math} minus OL) nor with frequency of language use.

Regression: High ML (LL^{math})

ERP congruency effects	BNT	% of use
150-200ms	*R^2=-083; p<.99*	*R^2= -.060; p<.61*
200-300ms	*R^2=.169; p<.08*	*R^2=-.017; p<.39*
400-600ms	*R^2=.144; p<.10*	*R^2=-.051; p<.55*
700-850ms	*R^2=.083; p<.16*	*R^2=-.006; p<.35*
1100-1200ms	*R^2= .015; p<.29*	*R^2=-.069; p<.70*

Table 3.9. Adjusted R2 values and p-values in high ML .There is no statistical significant relationship between ERP effects with each regressor factor.

4. Discussion

The present study aimed to investigate the time course and distribution of congruency processing effects in the auditory modality. We explore the pattern of ERP activity associated with each language condition in respective low and high memory loads. Our results are consistent with a different management of numerical-spatial associations depending on the early learning factor. Consistent with our two previous experiments, these results confirm that early learning might have consequences in the retrieval of long-term MNL representation and emphasizes that the possible connection of the LL^{math} with the MNL occurs across modalities and cognitive processing demands. For the LL^{math}, evidence of congruency processing started at the level of retrieval time interval (400-600ms). During the retention, effects increased broadly distributed over frontal and centro-parietal locations. In high memory load, effects of congruency started at the level of encoding (150-200ms) and continued during retention, more centered over right-side centro-parietal electrodes. Consistent with literature, this might be an indication of spatial processing networks engagement (Dehaene et al., 2003). Thus, the pattern ERP activity related to congruency effects was similar in both, low and high memory load conditions starting earlier in high memory load. These encoding differences can be attributed to more direct phonological rehearsal activity occurring in low compared to high memory load since encoding in the auditory modality is more automatic. However, in high memory load, it seems that encoding is less direct.

Instead, the OL has associated a transient pattern of activity reflecting weak congruency effects. Effects of congruency were no statistically reliable neither in low nor in high memory load. This might indicate that connection of OL with the MNL is not that obvious as reflected by the lack of clear differences. Thus, our results show that during processing of numerical-spatial congruency, the neural activity differ qualitatively and quantitatively over time in the LL^{math} compared to the OL. In general, these results provides evidence of a clear distinction in the management of numerical-spatial representations and further confirm that processing of congruency clearly entails different brain correlates likely due to important influence of language of learning math. Furthermore, the automatic activation of MNL representation also extrapolates to auditory modality when numbers are manipulated in the LL^{math} which is consistent with the amodal numerical-spatial association assumption. Theoretical implications of these results will be put forward in the general discussion of this thesis together with Experiments 1 and 2.

General Discussion

Summary

The aim of the present thesis was to explore language and math links through the window of bilingualism. Our research was based on a neurocognitive approach using ERP methods with a main focus on the linguistic impact that the LL^{math} has on bilinguals' numerical-spatial representation. The effects of managing two languages in bilingual numerical cognition have been addressed considering the relationship that each verbal format has with the spatial component of magnitude representation. To understand how bilinguals activate the MNL as a function of the verbal input, we investigated the influence of the LL^{math} versus the OL at different stages of a WM task (encoding, retrieval of MNL and maintenance of numerical information). The results of three ERP experiments suggest that numerical-spatial information, when is manipulated in LL^{math}, has associated different brain dynamics compared to the ERP brain pattern associated to the OL input. Our results have important implications in particular aspects of the Math Cognition and Bilingualism framework. In following lines, a summary of results of the three experiments is presented and discussed.

Experiment 1 showed ERPs effects associated with processing of numerical-spatial congruency at different time intervals depending on whether they were processing in LL^{math} or OL. First, the P2 effect elicited during encoding reflects the automatic activation of the MNL representation. Second, the N400-like effect is consistent with retrieval of long-term MNL representation. Finally, the sustained nSW effect mirrors the retention activity, highly influenced by the activation of the MNL representation. Thus, the presented results show different brain responses depending on whether the numerical input was LL^{math} or OL. In general, congruency effects were greater and more sustained in the LL^{math}. After the P2 effect elicited in both languages, significant effects were found only in LL^{math} during the time course of retrieval (N400-like) and retention (nSW) stages. This indicates a direct and stronger connection of the LL^{math} with long-term MNL representation due to the early learning. The OL activates the spatial-numerical association during encoding as well but has a weak connection with the MNL as reflected by the lack of significant effects during retrieval and retention. Differences were also reflected in respective topographic profiles. Distribution of ERP effects followed a right-side trend in the LL^{math} during encoding and retention intervals being more bilateral during retrieval. In the OL, effects were bilaterally distributed in posterior sites with a slightly trend towards anterior-left sites. Thus, consistent with our hypothesis, these results suggest different brain responses as a function of early learning factor.

In **Experiment 2**, the effects of congruency between a given spatio-numerical input and the MNL were explored under two memory load conditions. We aimed to further investigate the ERPs induced during processing of congruency by comparing the effects of low versus high WM load. The input in LL^{math} elicited different ERP patterns during the MNL retrieval compared with the numerical input in OL. For both languages, processing of congruency was modulated in the low memory load condition by the N1-P2p complex starting earlier in LL^{math}. Congruency effects continued in a later negativity (N400-like) but importantly, the size and the distribution of these effects varied depending on the numerical language input, with more bilateral distribution over anterior and posterior channels for LL^{math} numerical input and focused on left-side topographies in OL. At the level of retention, congruency effects were obtained for both languages but with different time courses and topographies. Under high WM load condition, the congruency effect remained only for the LL^{math} at the encoding-retrieval stages (N1/P2/N400) and during the retention (nSW). Compared with the LL^{math}, congruency effects in the OL were not strong enough when cognitive demands of the task increased. As mentioned, the congruency effect reflects the level of automaticity in the retrieval of the spatial-numerical representation (MNL). Unlike the OL, the LL^{math} seems to have a stronger connection with the MNL long-term representation, which means a direct and rapid access but also greater processing efficiency. The early math learning context has enabled this link between the spatial-numerical relationships with the LL^{math} thus establishing the bases of long-term representations. This means that the MNL activation (SNARC) would emerge earlier when the verbal input agrees with the LL^{math} and importantly, suggests different cognitive processing compared with the OL.

Experiment 3 explored the same hypothesis as in Experiment 2, but in the auditory modality. When number-words were presented in their phonological form, the processing in WM involved different brain responses (nSW) compared with the brain activity observed in the visual modality (N1, P2, N400-like, nSW).This could be a consequence of the “modality effect” contemplated in Baddeley’s multicomponent framework, described as a rehearsal operation that facilitates access to the phonological store (Baddeley and Hitch, 1974; Baddeley and Logie, 1999). Beyond the possible effect of the auditory modality, we examined differences in numerical–spatial congruency processing across both verbal formats and two memory loads. Consistent with Experiments 1 and 2, the brain signatures elicited when the congruency was processed with LL^{math} were significantly different (in amplitude and topography dimensions) compared with the brain response elicited by the OL. The congruency effect was modulated by a long-lasting negative slow wave (nSW). According to the results, nSW amplitude differences were only significant in LL^{math} during the time course of encoding, retrieval and retention intervals. Unlike Experiment 2, the OL did not elicit congruency effects in any of the memory load conditions during the maintenance of congruence in WM. This could be interpreted as clear evidence of neural differences in the cognitive processing of the numerical-spatial congruency. Another important aspect of these dataset is that the time course of congruency effects at the level of encoding and retrieval varied from low memory load to high memory load condition. Congruency effects started earlier in high memory load (150-200ms) but were delayed in low memory load condition (400-600ms). This can be attributed to less encoding activity needed in low memory load due to greater ease management of numbers. That is, once numbers have been listened they are automatically encoded into a phonological format. Instead, when memory load increases, the access to the phonological rehearsal seems to be slowed. Processing of numerical-spatial congruency in the high memory load condition might involve an extra cognitive cost and thus, greater activity is reflected during encoding. This processing stage differences can be interpreted as an index of automaticity in the retrieval of the MNL. Similar as in Experiment 2, the topographical distribution of the nSW effects was bilateral in general, with a switch towards right-side during retention in high memory load condition

Taken together, these results support the predictions formulated in this thesis. On the one hand, we have demonstrated that the LL^{math} and OL have associated very different brain pattern of ERPs during the retrieval of MNL representation. Based on the significant congruency effects obtained in critical processing steps, we have shown that these differences are modulated by the early learning math factor. Such effects of congruency persist consistently in LL^{math} across different memory loads (low/high) and modalities (visual /auditory). On the other hand, the ERP topographic profiles associated with the LL^{math} and OL suggest unequivocal differences in neural activity likely driven by separate processing streams or networks. Finally, we have provided evidence that the connection of LL^{math} with the MNL is amodal and thus, less dependent on the visual code. Contrary, the activation and retrieval of the MNL in the OL is weak and more dependent on the visual encoding. The combination of results of the three experiments leads us to conclude that early learning impacts magnitude representation reflecting different processing mechanism between LL^{math} and OL. As part of this influence, the LL^{math} connects automatically with the MNL supporting the view of a linguistic trace in numerical-spatial long-term representations. Thus, we found these results in line with Salillas and Carreiras (2014) early learning impact in the core magnitude representation. In the next section, the implications of these results in the Numerical Cognition framework will be further discussed.

Activation of the MNL: ERP correlates in the context of WM

In the present study, the processing of spatial-numerical congruency has been explored during the performance of a delayed match-to-sample task. An important aspect of the experiment design concerns the simultaneous presentation of numerical and spatial information in different stages of working memory (WM). This allowed us to study the cognitive processes that rule the SNARC effect in a non-response selection stage. Furthermore, the manipulation of numerical information in WM encompasses several stages that in our study have been isolated in processing time intervals based on similar procedures adopted in previous ERP studies. This allowed us to better track the congruency effects during the time courses of encoding, retrieval of the MNL and retention activity. I will discuss the ERP results according to the reference framework of WM and Numerical Cognition studies.

Making sense of N1-P2 and N400-like congruency effects

The reported ERP components during encoding, MNL retrieval and retention are consistent with previous WM studies showing different neural activity during the time course of each processing stage (Löw et al., 1999; McEnvoy et al., 1998; McCollought et al., 2007; Shucard et al., 2009; Ruchkin et al, 1992; 1997). In a typical WM task, the to-be-retained information enters the phonological store after visual or verbal encoding and binds the long-term memory representations through the subsidiary system (central executive; Baddeley, 1986; Baddeley, 2000). Thus, these continuous processing stages characterized the ERP effects found in our study. Firstly, early ERP effects (N1-P2p) found in Experiments 1 and 2, are associated with the encoding of numerical-spatial information while the N400-like mirrors the retrieval of long-term MNL representation. The high sensitivity of P2 during encoding of words or digits in complex memory tasks has been demonstrated in previous studies (LeFebvre et al., 2005; Evans and Federmeier, 2007). Secondly, in Experiment 3 encoding is more automatic since is directly mediated by the verbal rehearsal. Therefore, in absence of visual stimuli, these N1-P2p components are rather unlikely. Instead, in Experiment 3 we observed the nSW component during congruency processing in all stages likely influenced by the phonological input. Overall, these results agree with Baddeley WM framework and allow us to interpret neural activity associated to congruency processing in separate processing steps.

We also find our results consistent with Numerical Cognition literature. In the context of numerical comparison task, early N1-P2 components have been reported mapping numerical comparison processes (Libertus et al, 2007; Salillas and Carreiras, 2014). Precisely, the N1-P2 amplitude has been shown to be sensitive to linguistic components of magnitude representation and is supposed to index the access to number semantics (Cao et al., al, 2010; Libertus et al., 2007; Liu et al., 2011; Salillas and Carreiras, 2014). Consistently, in our study, the early involvement of N1-P2p congruency effect might reflect the influence of language (LL^{math}) in the activation of MNL representation. Furthermore, the presence of the P2p component has been observed in numerical estimation and comparison tasks consistent with the access to number semantics in an early stage of visual identification (Dehaene, 1996; Hyde and Spelke, 2009; Libertus et al, 2007; Pinel et al, 2001). In our study, this occurs when number-words are matched with right/left spatial locations inducing the retrieval of long-term representations of magnitude in a post-perceptual stage of the congruency processing. Following the P2p early effects, the N400-like effects were consistent with activity in later stages of congruency processing (Experiment 1 and 2). This succession of components has been already observed in a previous study comparing Arabic and Chinese numerical notation effects in access to number semantics (Liu et at., 2011). The main suggestion was that the late N400 component might reflect a subsequent underlying processing during the access of analogical magnitude representations. The sensitivity of the N400 to long-term memory representations in response to previously presented information is contemplated in classical N400 literature (Kutas and Hillyard 1989; Cameron et al, 2005; Kutas and Federmeier, 2011). Indeed, the N400 effect has been observed during processing of incongruous mental calculation problems (Niedeggen et al., 1999) and importantly, during the retrieval of arithmetic facts (Niedeggen and Rösler, 1999; Galfano et al., 2003, 2004). As with the arithmetic facts, the MNL is long –term stored and its automatic retrieval will depend on the interconnected numerical-spatial representation networks with each verbal code. Consistent with this view, the N400 differences (in amplitude and topography) that we observed in Experiments 1 and 2 between LL^{math} and OL are related to a distinct activation and retrieval of the internal numerical-spatial representation. In Experiment 1, the N400-like effect might reflect the cognitive manipulation of spatial congruency, a process that initially only occurs when the MNL is retrieved with the LL^{math}. Further, the results of Experiment 2 showed the N400-like effect in both languages but with different scalp topographies. This likely suggests the involvement of different brain networks depending on whether the MNL is retrieved with LL^{math} or the OL and therefore, different brain mechanisms. One possible interpretation is that, due to the early learning, the mapping of the linguistic input to the MNL is modulated by a distinct degree of association of each language to this long-term representation, which seems to directly support the hypothesis of a linguistic impact of early learning in magnitude representation. We acknowledge that processing of numerical-spatial material with the OL would also trigger, at a certain delayed time point, the long-term MNL representation, and indeed, magnitude information tends to activate its spatial features sooner or later, independent of the format (Nuerk et al., 2005b). However, our results show that the connection of the OL with the MNL is more dependent of external features of the task than LL^{math} and therefore, less connected with the conceptual aspect of numerical spatial representation (see Fischer and Shaki, 2016). Moreover, in Experiment 2 the arrangement of stimuli was not the same as in Experiment 1. While for LL^{math} the N400-like effects remained in both experiments regardless of external stimuli arrangement, this was not the case for the OL. Indeed, notice that when the modality changed (Experiment 3) and numbers were perceived aurally, the pattern of brain activity found in the LL^{math} and OL differed dramatically. In line with this view, the results of our study converge in two important considerations to explain the access of each language to the MNL: 1) the degree of association that each verbal format (LL^{math} and OL) has with this long-term spatial numerical representation. 2) The extent to which these representations have been shaped by the specific linguistic early learning context.

In summary, the brain activity reflecting the congruency effect during encoding and retrieval appears to be conditioned by the long-term representation of the MNL. We suggest that even though both languages can process the spatial congruency at some point, a higher level of automaticity and earlier retrieval is expected when the numerical information is presented in LL^{math} mainly because of a strong connection with long-term representations. Thereby, a fast retrieval of the MNL would be influenced by the early learning context, in line with the view of a linguistic memory trace at the representational level. An important part of the results of three experiments were found during delay period consistent with retention activity (nSW). In the following section, the impact of early learning during retention of MNL will be discussed.

Negative slow wave: retention of the MNL

The relationship between early learning factor and the MNL also was observed during the delay period mirroring the retention of information in WM. The congruency effects found in our three experiments were modulated by a long lasting nSW potential. The influence of long-term memory activation resulting from the preceding mnemonic processing is reflected in the delay period activity recorded during the retention of the numerical-spatial information that was either heard or visualized. This assumption is primarily based on studies of single neuron recording suggesting that the delay period activity sustains the representation of information held in memory throughout the retention interval (Miller and Desimone, 1994; McCollought et al., 2007). In addition, empirical evidence suggests that the delay period activity underpins the activation of long-term memory representations associated with the input stimuli (Cameron et al., 2005; McCollought et al., 2007; Ruchkin et al., 1992). In the great majority of ERP studies, this memory retention activity has been related to a large and broadly distributed slow wave components as already mentioned (McCollought et al., 2007; Ruchkin et al., 1990, 1992, 1997a, 1997b). In line with these empirical reports, the ERP activity found in our study during the delay period is consistent with the retention of congruency in WM.

Thus, the current results demonstrate strong differences during retention across languages and memory loads, likely modulated by the early learning factor. The maintenance of numerical visuospatial or audio-spatial information in WM with the LL^{math} produced differences in timing and topography compared to the retention activity with the OL which supports the hypothesis of a linguistic impact of early learning on numerical-spatial representation of magnitude. Moreover, the nSW congruency effect appeared systematically across both memory loads when retention was performed with the LL^{math} (Experiments 2 and 3) while for the OL congruency effects were more transient. Indeed, congruency effect in Experiment 2 was only elicited under low memory load condition while in Experiment 3, no significant effects occurred. Thus, these differences in the ERP response further support a key role for the LL^{math} and suggest that different cognitive processes are engaged during the retention of congruency as a function of the early learning. It could be reasoned that while activation of MNL representation when numbers are manipulated in the LL^{math} is less dependent on external variations of the task (modality, task difficulty, stimuli arrangement) the OL is influenced by external spatial task demands (e.g. Proctor and Cho, 2006). We find this explanation in line with Fischer and Shaki´s (2016) recent claim of a conceptual link in numerical-spatial associations. In their study, authors investigated whether this association exists at the conceptual level and not only based on the influence of the spatial features of the task. They used a go no-go task involving a spatial instruction relevant for objects ("respond if the duck points to left or right") and a non-spatial rule for numbers ("respond if the digit is less than 5"). Objects and magnitudes were presented together in different combinations (e.g. congruent vs incongruent). The results showed that numbers were indeed associated with space at the conceptual level, even though the spatial component of the task was irrelevant for magnitude comparison. In our study, we find the connection of the LL^{math} with numerical-spatial association to occur at this conceptual level which basically entails the internal representation of MNL. Once the conceptual numerical-spatial association is activated in the LL^{math} at the representational level, it is not surprising that a working memory mechanism such as rehearsal, operates differently in the OL wherein the access to the numerical-spatial association it is unlikely to occur at the representational level. Therefore, we discard that the reported relationship between LL^{math} and the MNL is merely the result of the external spatial influence of the task (as suggested in Fias et al., 2011) instead of a stable reflection of the impact of LL^{math} at the representational level.

Moreover, it could be argued that the effects of congruency during the retention of the retrieved numerical-spatial information are due to a more conscious process and thus, are subject to certain cognitive strategies. The short-term retention of spatial and numerical information might be transcoded through phonological rehearsal, allowing the use of verbal strategies to enhance retention before the answer to the target is required (see the Baddeley and Hitch multicomponent model, 1974; Baddeley, 2000). One of these verbal strategies could be related to spontaneous translation. When numbers were presented in the OL, participants were more tempted to translate to the LL^{math} perhaps, motivated by the processing easiness in a "familiar" code

(Campbell and Epp, 2004). Even though this strategy was not used consistently across all trials it denotes a particular difference in the cognitive management of numerical words. The key question here would be why bilinguals need to translate numbers presented in the OL. If both languages were associated identically with the MNL there would be no need to translate. Similarly, the differences in the pattern of ERP response would be minor. It is worth to remind here that all participants were equivalent in language dominance for Spanish and Basque and only differed in their LL^{math}. Indeed, the ERP results were not correlated with the relative proficiency of the LL^{math} and OL. Therefore, it is plausible to think that the brain pattern for the congruency effect during the retention period reflects the early linguistic trace in bilingual MNL representation.

In summary, the present study supports the hypothesis that there is an early learning influence on spatial-numerical processing of congruence. Furthermore, the ERP activity during WM retention in the LL^{math} is apparently modulated by the pervasive conceptual association between numbers and space rooted in long-term representations of the MNL. Consequently, although the activation of the MNL when number words are presented in OL also occurs at some point, the described ERP patterns (timing and topography) suggest that different cognitive processes and thus, different neural generators are recruited during the retention of congruency across the two languages.

THE INFLUENCE OF MODALITY IN THE MNL RETRIEVAL: THE ROLE OF EARLY LEARNING.

Evidence of modality effects during WM processing have been reported in several neuroimaging studies (Crottaz-Herbette, Anagnoson and Menon, 2003; Lang et al., 1992; Penney, 1989; Schumacher et al., 1996; Ruchkin et al., 1997a). The majority of them show different neural processes underlying visual and auditory WM. In the present study, we took advantage of these perceptual differences at the neural level to characterize the influence of early learning in numerical-spatial representation in the respective input modalities. Indeed, although magnitude representation system is independent of modality, our understanding of numbers includes the different formats and modalities in which magnitude can be access or represented (see Campbell, 2005). The current models of Math Cognition offer an account of perceptual modality effects in numerical representation. Dehaene and Cohen's (1995) triple code model claims that numerical processing is based on three codes, two of which are modality based (visual-Arabic and verbal-auditory). However, according with the Dehaene´s model, the spatial association of numbers is independent of any format and modality. Indeed, the SNARC effect is not affected by variations in either format or modality (e.g. Dehaene et al., 1993; Fias, 2001; Nuerk et al., 2004; Reynvoet et al., 2002). Thus, in agreement with this idea, the perceptual modality of presentation should not affect access to this representation of magnitude per se. Our results corroborate that the congruency effect emerges independently of whether numbers were listened to or read. However, they suggest that perceptual modality interacts with the cognitive management of the MNL depending on the early learning factor. In the present thesis it was of major interest to inquire in the modality aspects that might influence the activation of the spatial component of magnitude representation when numerical information is handled in LL^{math} and OL.

In general, results of this thesis support differences in the management of magnitude as a function of early learning in both modalities. The ERP components found in Experiments 1 and 2 (N1-P2p, N400-like, nSW) were dramatically different to ERP pattern in Experiment 3 (nSW) suggesting that processing of congruency in visual and auditory modalities engages separate networks. It can be inferred that perceptual modality affects the access to the MNL only when numerical information is managed in the OL but not when is managed in the LL^{math}. Our Experiment 3 demonstrates that congruency effects were still preserved in the LL^{math} in absence of a visuo-spatial coding while effects in OL declined significantly. This provides a very strong evidence of *qualitative differences* between both languages at the representational level due to the early learning impact. Moreover, supports the prediction that different WM processes acquired more relevance in visual modality than in the auditory modality affecting the spatio-numerical processing differentially in each language. In next lines I will discuss these aspects based on the pattern of ERPs found in each modality.

The perceptual modality of number-words presented in the LL^{math} and OL affected the time course and topography of encoding, retrieval and retention of numerical-spatial information. One of the main modality differences found in our study involved the early components (N1-P2), which were only clearly observed when number-words were presented visually. This seems reasonable given the presupposed high sensitivity of the N1-P2 evoked response to visual stimuli (Luck and Hillyard, 1994; Wascher et al., 2009). These differences could be explained based on a re-coding process (from visual to phonological form) that is applied to the visual stimuli. Note that the ERP pattern of activity at the encoding and retrieval stage differs critically between the auditory modality and the visual modality. Furthermore, the N400-like effect that appears systematically when number words are presented visually in the LL^{math} is not elicited when the modality changes to auditory. Instead, a long-lasting sustained nSW emerged from the early encoding to the retention within the delay period. Probably, the retrieval of the MNL in the auditory modality is mediated by a faster process and implies less neural resources consistent with the phonological advantage contemplated in Baddeley´s (2000) framework.

In our study, modality differences might indicate a certain functional influence on the basic cognitive mechanism involved in the processing of congruency, which interacts with the early learning factor. That is, the ERP results in Experiment 2 showed that processing of congruency in the visual modality dramatically affects the early access to the MNL with the OL but not with the LL^{math} (the congruency effect started almost 200ms earlier in the LL^{math}). This suggests that brain mechanism underlying automatic activation of spatial-numerical association operate earlier in LL^{math} while in the OL these processes are delayed. Thus, the delay might indicate that in the OL the visual-spatial coding that precedes the activation and retrieval of the MNL is not that automatic. In turn, when the input was presented in the auditory modality (i.e. with no visual-spatial coding), it radically increased the differences between languages in the processing of congruency (Experiment 3). It can be inferred that the OL is more dependent of visual modality to access the MNL representation. This also connects once more, with Fischer and Saki (2016) conceptual locus of numerical-spatial associations mentioned in previous section.

Based on these results, the following conclusions can be inferred about the influence of modality on congruency processing across LL^{math} and OL: 1) Visual modality clearly has a strong influence on the early processing of congruency at the encoding (N1-P2) and later retrieval stages (N400-like) for both languages. However, the LL^{math} activates the MNL representation earlier, connecting with a more conceptual locus of numerical-spatial association that is independent of modality; 2) the influence of modality is less evident in the retention (nSW) likely due to the involvement of similar phonological rehearsal processes in both visual and auditory modalities. Conversely, the retention of congruency is heavily affected by the modality when numbers are presented in the OL. Possibly, this imbalance between languages in the auditory modality can be also accounted by the learning context, which is primarily given in the auditory modality; 3) The ERP differences in timing and topography found in visual and auditory experiments is consistent with the activation of distinct modality processing streams reported in previous literature (Crottaz-Herbette et al., 2004; Ruchkin et al., 1997).

Overall, our studies suggest that the role of perceptual modality during the processing of congruency is likely to affect the routes of access to long-term representations, being more direct in the phonological modality. However, although both languages can access the MNL representation, the LL^{math} entails faster and stronger MNL activation. This, subsequently, allows the subject to better maintain/rehearse information in WM. Our study provides further evidence supporting the concept of different neural activity for LL^{math} and OL during number-spatial encoding, retrieval and retention processes.

LL^{MATH} VS OL: ARE THERE DISTINCT NETWORKS ASSOCIATED WITH THE MNL?

One important aim of this thesis was to examine similarities and differences in scalp topographies associated to congruency effects found in both languages. Topographic profile analyses were used thus, to determine whether amplitude differences obtained in the LL^{math} and OL respectively, reflected similar or different neural activity generators. Thus, based on previous studies showing hemisphere scalp differences in executive attention processing (Gut et al., 2012; Ranzini et al., 2009; Salillas et al., 2008), bilateral, right-side and left-side lateralized patterns were inspected in anterior and posterior regions of interest (ROIs). The results indicated that brain activity pattern during the processing of congruency in encoding, retrieval and retention was different between LL^{math} and OL. In the following lines, I will discuss these topographic differences found in critical ROIs between languages.

Towards a distinction between LL^{math} and OL numerical-spatial networks

The topography profiles found in the three experiments suggest different types of cognitive processes underlying the processing of congruency from each language (LL^{math}/ OL). Analogous to the amplitude differences found in the respective ERP components, the topography distribution in LL^{math} followed a bilateral and right-side tendency compared to more left scalp distribution found in the OL. This topography differences are more evident during retention of **visuo-spatial** numerical information. The distinct topography has been related to different underlying cognitive networks in other studies (Löw et al., 1999). In our study, it can be associated with visuospatial and phonological rehearsal processes which seem to be modulated by different representational networks. On this basis, given the impact that the LL^{math} has on the magnitude code (Salillas and Carreiras, 2014; Salillas, Barraza and Carreiras, 2015) and its integration with the spatial component, we infer that the topographic differences observed between the two formats might be mediated by separated spatial and linguistic networks. At the representational level, the LL^{math} appears more integrated with the spatial component of magnitude representation, and this is reflected by the bilateral and right voltage distribution found in our Experiments 1 and 2 during the delay activity. This assumption is consistent with some ERP studies showing right scalp activation during the rehearsal of spatial information (Postle et al., 2004; Ruchkin et al, 1997; van der Ham et al., 2010). Additionally, frontal and parietal scalp topographies have been also related with spatial WM retention activity during the delay period

(Awh et al., 1996; Ruchkin et al, 1997a, 1997b; van der Hamet al. 2010). In our study, a frontal distribution of congruency effects (nSW) was observed during the delay period for both languages (Experiment 2). However, while the frontal activation found for the LL^{math} was concentrated more in the right hemisphere the OL exhibited a left-side pattern. This left-side pattern (experiment 1 and 2-low) suggests a greater reliance on linguistic processing perhaps due to the activation of verbal circuits which are heavily required in transcoding or perhaps translation processes. Together with the higher processing cost and the weak congruency effects in retention it could be suggested a weaker connection of the OL to the spatial components of magnitude. In other words, while LL^{math} would have been integrated with the spatial components of numerical representations, OL would be more dependent on a superficial linguistic aspect of the stimuli, further apart from a conceptual spatial processing account.

In the **auditory WM** domain, specific patterns of brain activity have been shown to be substantially more bilateral when verbal and spatial information is presented aurally (Ruchkin et al, 1997a). This is consistent with the results in our Experiment 3, clearly showing sustained brain activity during retention with bilateral posterior scalp distribution. This bilateral activity emerged earlier in time in posterior sites for the LL^{math} , mapping the mnemonic operations needed to maintain the spatial and verbal features of numbers in WM. Comparisons with a related ERP study provide useful information when considered in conjunction with our study. Ruchkin et al (1997a) showed that auditory stimuli elicited a less lateralized scalp distribution compared to the visual modality (see also Ruchkin et al., 2003). Bilateral activity has been also observed in numerical tasks independently of the particular input modality, consistent with the neuroanatomical view of the Triple Code Model (Dehaene, 2003; see also Pinel et al., 2001; Piazza, Mechelli, Butterworth, and Price, 2002). Specifically, the bilateral activation of the HIPS was found to be implicated in the magnitude representation of numbers (Pinel et al., 2001; Dehaene, 1997; 2003). It is possible that in our study, part of this bilateral negativity (at the neural level) reflects the core magnitude representation involvement during unconscious quantity processing. However, although we found our study consistent with this trend, the particular focus on right-side topographies that ultimately remained during retention in high memory load (Experiment 3), may be related with a greater spatial rehearsal. Hence, a possible interpretation is that when memory load increases, higher spatial rehearsal is needed to retain right/left locations which is also consistent with results of Experiments 1 and 2 (high-load). Similar spatial rehearsal processes have been associated in neuroimaging studies with the involvement of a frontal and parietal right-hemisphere dominant network (Awh and Jonides, 2001; McCarthy et al., 1996; Smith et al., 1997).

A broader explanation of such differences in the topography distribution (asymmetric vs symmetric) across visual and auditory modalities can be found in the auditory code advantage (Baddeley, 1986, 1997, 2000; Penney, 1989). Thus, the combined early learning impact (LL^{math} vs OL) with an auditory facilitation, may involve very different brain patterns during the retention of spationumerical information. This is in line with qualitative rather than quantitative differences attached to the linguistic role that LL^{math} and the OL have in the MNL representation. Therefore, we consider these differences to be supportive of the claim of different brain networks, implying qualitative processing differences in both modalities as a function of the early learning math factor.

In summary, we propose that WM operations interact to some extent with long-term representations of the MNL. If a memory trace is linked with the LL^{math} then it is reasonable to expect differences in the automaticity of retrieval and rehearsal processes. The topography variations found in our three experiments might indicate that different networks mediate when numbers are processed with the LL^{math} compared with the OL, each involving different numerical-spatial and/or linguistic processing mechanisms.

HIGH AND LOW MEMORY LOAD: IMBALANCE BETWEEN LL^{MATH} AND OL

A second goal of this study was to compare the congruency effect across two memory loads (low and high) as function of the input language. Working memory tasks require mental effort to hold information before decaying. Working Memory models, focused on explaining the implications of the memory load in WM performance, explain the load effect as a cognitive cost (Baddeley and Hitch, 1974; Cowan, 1988; Ericsson and Kintsch, 1995; Just and Carpenter, 1992). We know that variations in the memory load correlate with changes in certain brain regions. For instance, functional imaging studies that used variations of memory load in n-back tasks (Braver et al., 1997; Cohen et al., 1997) found associated increases in activity in prefrontal regions. Moreover, it has been shown that the ERP activity related to the retention of verbal information, either heard or read, is affected by memory load manipulations in different WM tasks (Gevins et al., 1997; Gundel and Wilson, 1992; Ruchkin et al. 1997a). Our results are consistent with this functional sensitivity of brain activity to WM load.

In Experiments 2 and 3, we tested the effects of congruency in high and low memory load conditions during encoding, retrieval and retention. The results showed that the time course and distribution of congruency effects differed between LL^{math} and OL across memory loads. When the memory demands of the task increased, the expected cognitive cost affected in greater extent the numerical-spatial processing in the OL (Experiment 2) and simply, the congruency effects vanished. Conversely, when the numerical input was LL^{math}, congruency effects remained consistently regardless of memory load increments (Experiment 2 y 3). This suggests two important considerations. On the one hand, the activation of long-term MNL representation facilitates the management during retention after matching previously presented material in the LL^{math}. The consistent apparent lack of congruency effects for the OL in both experiments when memory load increases indicates that long-term representations of MNL are less active and therefore, incurs in a greater cost. The previous assumption is consistent with Cameron et al (2004) conceptualization of a facilitator effect of long-term representations mostly during retention. On the other hand, the fact that congruency effects found in LL^{math} were independent of memory load supports the hypothesis of a strong connection with the MNL at the representational level. Thus, differences observed between LL^{math} and OL in high and low memory loads can be explained based on early learning modulations experiences. Unlike the LL^{math}, the OL produces weak MNL activation since it lacks the early learning experience. That is, spatial-numerical processing in the OL depends on more superficial cognitive resources (e.g. transcoding/translation) affecting the efficiency in WM. This is in line with Campbell's (1994; 2004) encoding-complex assumption of more efficient encoding-retrieval processes when numerical information is managed in a familiar code compared to encoding-retrieval with an unfamiliar code. In summary, results are consistent with more efficient cognitive management of magnitude in the LL^{math}. Activations of long-term MNL when numbers are processed in the LL^{math} enable a better WM maintenance across memory loads. Due to the early learning factor, the LL^{math} is less sensitive to the external demands of the task since connects automatically with this numerical-spatial representation. The weak level of activation of MNL in the OL is appreciated by the lack of congruency effects in high memory load condition which reflect a greater cost. Variations of ERP scalp topography as a function of memory load simply reflect separate cognitive processes or neural generators for LL^{math} and OL likely influenced by the early learning impact.

THE ROLE OF LANGUAGE IN THE MNL REPRESENTATION

The results discussed in this thesis suggest that balanced bilinguals have different brain mechanism to process the numerical-spatial representation depending on early learning. In light of empirical evidence regarding the role that early learning plays in exact arithmetic (Salillas and Wicha, 2012; Spelke and Tsivkin, 2001) our study provides additional evidence to a possible impact also in memory networks for numerical-spatial association. Consistent with the available evidence of a link between the LL^{math} and magnitude (Salillas and Carreiras, 2014), our proposal raises the possibility of a linguistic impact on the MNL at the representational level.

None of the current **models of math cognition** provide a complete explanation of a possible linguistic impact on the MNL. Moreover, none of them contemplate a possible impact in balanced bilinguals. So far, it is unknown how bilinguals represent magnitude beyond the context of exact arithmetic. Congruent with the Triple Code Model (Dehaene and Cohen, 1995), our results agree with the MNL hypothesis contemplated in the model as a representation that evolves from the analogue magnitude representation. In addition, we provide evidence supporting the role of language beyond the context of numerical fact retrieval. That is, in the absence of mental arithmetic operations, the MNL can be accessed by the verbal code (Dehaene, 1992). However, in the case of bilinguals we have shown that a more direct access, and possible integration, is expected with the LL^{math} compared with the OL. Therefore, when the spatial features of numbers are manipulated in WM with the LL^{math} , long-term associations are retrieved automatically due to the so-called early learning impact. This is consistent with Salillas and Carreriras's (2014) hypothesis of a linguistic influence in magnitude representation mainly based on the early learning factor. We reasoned that the development of MNL took place in a certain linguistic context during early math acquisition, originating a linguistic print at the representational level. Thus, we propose that such an association can determine the nature of long-term representations, likely affecting the cognitive manipulation of numbers presented verbally.

In line with Campbell´s (2004) interactive model, more learning experiences with one verbal format strengthen the associations with the core magnitude representation system. In the case of bilinguals the model explains that specific associative pathways for each language account for the encoding-retrieval processes optimizing magnitude processing in each code. However, the critical issue shown in our results does not reside just in the mere experience of repeatedly using one or another verbal code in different contexts. Rather, is focused on the idea of a linguistic interaction with the numerical-spatial development that co-occurs with the acquisition of numerical verbal symbols. Indeed, most of the participants reported switching to the LL^{math} for counting and simple arithmetic even when they more frequently used the OL in a specific context (e.g. friends, school, work, etc.)

In summary, results of this study suggest an important role of language in the access to the MNL. The main rationale is that the MNL evolves from the core numerical system, which is the most basic level of magnitude representation (Deahene, 1993). A bilingual's numerical-spatial representation enjoys a fast and automatic retrieval when the number words agree with the LL^{math}, mainly because there is a memory trace stored in long-term memory that provides the access efficiently (see figure 1). The differences between patterns of ERP activity for LL^{math} and OL support that the spatial features of numbers (MNL) are clearly affected by the early learning factor. However, these differences are not sufficient to reject a partial retrieval of the MNL from OL input at some point, since congruency effects where found also for this format. However, latencies, topographies and functional properties differed for the OL. Thus it could be argued that although the two languages have access to the MNL, the representations are not the same, thus affecting its cognitive impact, first during the encoding, and ultimately during the retention processes. This would account for quantitative and qualitative differences due to early learning impact. Therefore, these findings support the view of a linguistic impact that operates at the representational level. Finally, this linguistic influence should be considered in the general definition of bilinguals' numerical representations since it affects basic processes of the core magnitude system, beyond exact arithmetic.

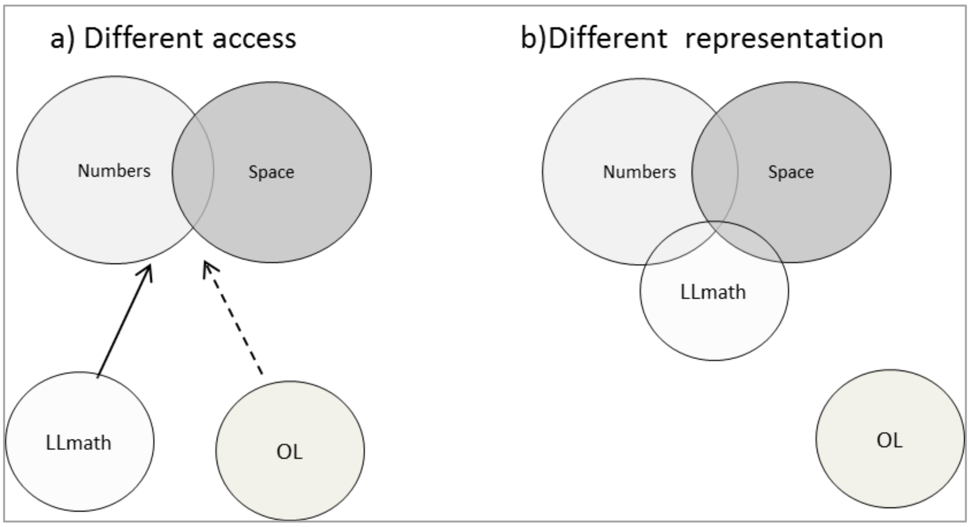

Figure 1. The conclusions of this study predict a different role of LL^{math} and OL in the activation of the MNL (a) Represents quantitative differences in the access to the long-term MNL representation: due to the early learning, LL^{math} has stronger connection than the OL and thus, the MNL activation is automatic. (b) Represents a qualitative difference at the representational level: LL^{math} is integrated in long-term MNL representation due to the early learning math experience while the OL lacks of such connection.

Final remarks and further directions

At this point, it is important to reconsider some of the research grounds of Numerical Cognition in bilinguals in which this thesis provides new evidence. Individuals speaking very different languages as in the case of Spanish and Basque bilinguals, with different numerical systems (10-based vs 20-based) to name quantities, provide a unique and certainly valuable context to extent our knowledge within a different neurocognitive perspective. In particular, it is necessary to precise the role that language plays in numerical cognition development from an integrative point of view that requires considering the interplay with other cognitive functions (see Looi and Cohen Kadosh, 2016) . Although current research keeps bringing further evidence of a language preference for arithmetic, they are limited in what refers to provide a full explanation of the origin and development of this connection. The study of the neural networks related with these early processes can help to disentangle these questions. Beyond the context of math performance, the neural bases underlying the imprint of language from a very basic level of magnitude development are rather unexplored yet. The research of this thesis was carried out in light of new evidence showing early linguistic prints in the basic magnitude knowledge system. Through the study of numerical representation in balanced bilinguals with very different linguistic structures, we have compared the neural correlates of basic numerical representation considering the spatial component associated to magnitude. Besides the interest that the issue of math and bilingualism generates in our society, with this study it has been possible to combine two research domains with important implications in both, Numerical Cognition and Bilingualism theories. The results of this thesis provide a more profound knowledge on the cognitive mechanism that mediates number representation in bilinguals and the implications that early math learning has in the MNL representation. We have demonstrated that the connection between number and language arise in bilinguals during the early learning and seems to affect the preexisting spatial component integrated in the basic level of magnitude representation. Overall, these findings add meaningful evidence to the question of numerical representation in bilinguals and promote a more comprehensive research approach that should be considered in future research advances on Math Cognition.

IMPLICATIONS

Our findings clearly have **consequences in models** of numerical processing, more precisely, on the role that the verbal format has in magnitude representation beyond the context of arithmetic facts. It has been proposed that analogue magnitude representation is independent from any numerical or verbal symbols (Dehaene and Cohen, 1995). However, given the available empirical evidence, we suggest that the language must influence the basic magnitude representation (Salillas and Carreiras, 2014). Such linguistic permeability has been observed through approximate magnitude comparisons and is consistent with recent proposals from Dehaene´s Triple Code model framework (Dehaene, 2009). The spatial aspect of numerical representation is also contemplated in Dehaene´ s model as language-independent. However, the linguistic role was not defined in relation with the abstract magnitude representation, only in relation to the retrieval of arithmetic facts (Dehaene et al., 1993; Hubbard et al., 2005). Our results would agree with the MNL hypothesis but furthermore, stress the possibility to consider the role of language beyond the exact arithmetic. That is, we refer to the **linguistic impact** on numerical-spatial representation view, which is not contemplated in any model. From our ERP results it could be inferred that language has an active role in the definition magnitude representation and thus, has implications in the development of bilinguals´ numerical system.

In one way, our study can also be taken as supporting evidence of Campbell ´s encoding-complex approach (Campbell and Clark, 1988; 1992; Clark and Campbell, 1991). The model assumes that there are different ways in which number processing can be discerned depending mostly on cultural or idiosyncratic experiences. These experiences would determine the strength of specific interactions between the different numerical codes and functions. Our results characterized the nature of the associations between verbal codes and basic magnitude representations in bilinguals. We propose the early learning factor rather than idiosyncratic experiences, to explain these associative pathways. The expected strength of these associations would be the result of the early learning trace, which would ultimately integrate the spatial component of magnitude representation in long -term memory. For this reason, we found our results susceptible to be adjusted accordingly in the Encoding-Complex framework.

Further directions

Future research on how bilinguals represent numbers from a neurocognitive account will have to consider not just the temporal brain mechanism that mediates for LL^{math} and the OL but also the main brain structures underlying such functional differences. The multi-modal approach combining EEG source analysis with fMRI or MEG seems to be an adequate following step. For instance, we propose EEG source analysis to address the specific brain structures that operate for both LL^{math} and OL. Knowing the specific location of the neuronal activity will inform us about the nature of bilinguals' numerical system and how is organized in the brain.

The comprehension of the whole machinery that works in bilinguals, based on intra-subject designs is considered advantageous to get rid from individual differences bias. Future directions should complete the main aspects of the numerical cognition theory taking advantage of bilingualism or multilingualism cultural experience. We believe that beyond the research of number processing effects across different tasks and population (i.e. SNARC, size effect, distance effect, etc.), the comprehension of numerical representation system at all levels should attempt to understand how it relates with other cognitive systems. Is therefore worthwhile to inquire into the question of how language is connected and affects numerical cognition. So far, it remains unclear which interrelations or interactions characterize the numerical cognition in bilinguals because this issue has rarely been studied considering both fields together. In this regard, some issues that need further investigation in people who use more than one language to refer the same magnitude concern to how they manage the numerical information in their different languages (e.g. multilingualism).

From a **neurocognitive perspective**, using non-invasive methods such as functional connectivity or brain stimulation techniques (transcranial magnetic stimulation) can unveil the different interacting brain networks that connect LL^{math} with basic aspect of magnitude representation such as the MNL. The contribution of prefrontal cortex and parietal lobes in the automatic activation of numerical-spatial representations is an open window that requires further detailed research. The exploration of this structural networks in typical and special population (i.e. bilinguals with developmental dyscalculia or synesthesia) considering the early learning processes will help to understand the brain mechanism that rule numerical abilities development. To our knowledge, the new trends in Math Cognition are focused in most of these issues combining conventional methods with neuroimaging advances. However, the missing part is the lack of connection with bilingualism research. A full comprehension of how numerical cognition is represented in human's brain should not leave aside the bilingualism experience.

The very basic aspects of human numerical system development and functioning should be re-evaluated in light of the new research evidences (Cohen Kadosh et al, 2007; 2009; Salillas and Carreiras, 2014: Salillas et al., 2015; Sella, Sader, Lolliot and Cohen Kadosh, 2016). In this regard, exploring the ontogenetic and cultural components of the relation between language and numerical cognition remains useful to understand the numerical competence acquisition and mathematical performance in children and adults bilinguals. Such investigation would require the contribution of other disciplines such as Psycholinguistics. Finally, the most practical effects of language upon numerical cognition reside in its pedagogical consequences as bilingualism has become a crucial factor in the educational context. On such issue, the link between math and language requires considerable research effort.

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