Facultad de Psicología y Logopedia

Departamento de psicobiología

Programa de doctorado en Neurociencias / PhD in Neuroscience (3142): RD99/2011

VNIVERSITAT DE VALÈNCIA

Toma de decisiones: el valor adaptativo de los sesgos y la influencia del estrés

Decision-making: The Adaptive Value of Biases and the Influence of Stress.

Tesis Doctoral / Doctoral thesis

Presentada por / Presented by: Francisco Jose Molins Correa

Dirigida por / Directed by: Dr. Miguel Ángel Serrano Rosa

Valencia, junio 2023

"*Reason is, and ought only to be the slave of the passions, and can never pretend to any other office than to serve and obey them.*"

David Hume

Agradecimientos / Acknowledgments

La literatura científica sugiere que las emociones no se procesan ni expresan con la misma intensidad cuando se utiliza un segundo idioma que cuando se utiliza el materno (Hsu et al., 2015). Por ello, y dado que no quisiera que estos agradecimientos queden fríos, aunque el idioma utilizado para el resto de la tesis sea el inglés, esta sección quedará en español. Bueno, por ello y porque me gustaría que haya al menos una parte que puedan entender mis padres.

Y es que, aunque no sé si es habitual comenzar por otro orden o seguir ciertos formalismos, yo quiero empezar agradeciéndoles justamente a ellos que hoy pueda estar escribiendo estas líneas. De niño me compraron un ordenador. Confiaban tanto en mí que me dejaron explotar mi curiosidad científica y, como no podía ser de otro modo, acabé borrando un fichero clave del sistema operativo y lo rompí. Nunca hubo reproches. Su confianza ni se inmutó. Finalmente, igual que lo rompí, conseguí arreglarlo. Papá, mamá: por ser mi ejemplo y apoyo, por permitirme equivocarme y aprender, por vuestra paciencia y amor incondicional, gracias. Habéis sembrado en mí todo lo necesario para sobrevivir a un doctorado.

Gracias también a mi hermana, quien bien podría explicar esta tesis tras la cantidad de horas que me ha escuchado hablar de ella. Me ha visto en mi versión más *peripatética*, con pensamientos intrusivos y formando parte de ese elevado porcentaje de doctorandos que sufren ansiedad, y ni por esas dejó tampoco de confiar en mí jamás. Recuerdo que poco después de matricularme en el programa de doctorado, hundido porque me habían denegado la ayuda predoc y rechazado mi primer artículo, salimos a dar un paseo por el monte. No sé bien qué nos llevó a este pensamiento mágico, pero *decidimos* que cada bicicleta que se nos cruzase en el camino sería un artículo que me publicarían durante la tesis. Parecía improbable entonces, pero hermana, nos han faltado bicis. Aunque aún no tengas claro qué vas a hacer cuando te gradúes, y aunque siempre te digo que huyas de la investigación, lo cierto es que me haría ilusión ver algún día un "Molins & Molins, 2025". Tiempo al tiempo. No obstante, de lo que no me cabe duda es de que serás una psicóloga como la copa de un pino.

Como también lo será otro de mis pilares fundamentales: Daniela. Llegó más tarde, pero llegó *para quedarse*. En plena recta final, cuando mis piernas flaqueaban, allí estaba.

Mi punto de avituallamiento. Un soplo de aire fresco. Un toque de humor. Un punto de inflexión que me hizo ver que hay vida más allá de la tesis, y a la vez dio más sentido a todo lo que he conseguido durante este periodo. Y ahora que me acompañas, conseguiremos mucho más. Por la ilusión, por el cariño, por verme como me ves, gracias. Y sí, gracias también a Oreo, que me ha visto escribir estas líneas y ha venido ronroneando para que lo incluya. Por llenarme el ordenador de pelos; por tirar trastos y despertarme de madrugada; en definitiva, por enseñarme paciencia, gracias.

Tampoco puedo dejar de agradecer a mis fieles escuderos, sin los cuales, quizás habría podido vencer a los molinos, pero nunca al temido revisor 3. Julián[1] y Sergio[1], gracias por poner, siempre que lo necesitaba, una cerveza en mi mano, un paseo en mis tardes y una palmada en mi espalda ([1]ambos autores han contribuido por igual a este trabajo). Sólo un reproche: sigo esperando que aparezcáis en una de mis clases vestidos de T-Rex (aunque lo diré bajito, por si acaso, porque sé que sois perfectamente capaces de hacerlo). Y no puedo olvidarme de Sergio y Víctor. Con sus "¡ole mi Paquito!", Sergio siempre insistió en que acabaría dando clases en la Universidad. Me provocó un efecto Pigmalión. No sé si *acabaré*, Sergio, pero al menos he empezado. Y Víctor, el tío con el corazón más grande que conozco y mi amuleto de la suerte: la aceptación de mi primer artículo llegó mientras nos tomábamos un café. Gracias.

Muchos otros nombres podrían incluirse aquí: Javier, Carla, Alba, Carlos, Dom, Jota… pero los agradecimientos se extenderían más que la propia tesis. Así que disculpadme si no os he nombrado expresamente. Todos y cada uno de vosotros ha puesto su granito de arena para que hoy pueda estar aquí. Pero bueno, ha llegado el momento de ponerse serio y *entrar* en la Universidad.

De nuevo, muchas personas me han apoyado, enseñado y acompañado durante este largo y, a veces ~~siempre,~~ tedioso camino que es la tesis. Yasmina, Samuel, Alexandra, Maca, Namra, Nur, Ana, Nerea, Lucía, Liza, Noemí, Raquel, Cristina, Laura, Uma… Que ese *siempre* esté tachado es gracias a ellas.

Pero especial mención merecen mis hermanos mayores de la ciencia. Tras darme la bienvenida al mundo de la investigación haciéndome escupir en muchos *salivettes*, Diana me puso en el camino y lo allanó. Quizás todo esto sería muy diferente si ella no me hubiera presentado al equipo del que hoy formo parte. Equipo en el que estaba también Adri. Al principio, confieso que me dio miedo. Luego vi que miedo debía tener si él no

estaba. Adri siempre ha mirado por mí como si mi CV fuese el suyo propio —algo que no abunda en este mundo—. Me ha enseñado los entresijos de un laboratorio, estadística Bayesiana y los mejores vinos de Montpellier. Diana, Adri, a los dos: millones de gracias.

Entonces llegó el día en que ambos se hicieron mayores y defendieron sus tesis. Un momento precioso, pero triste, pues el laboratorio se quedaba vacío sin ellos. No voy a negar que no disfruté al ordenarlo todo a mi gusto y heredar el trono de Adri, la verdad; pero ¿acaso alguien sobrevive a un doctorado sin compañeros de calidad? Afortunadamente, no tardaron en aparecer las personas que lo cambiarían todo para siempre.

Mónica y Nour. La fusión Colombia-Túnez. Llegaron y revolucionaron el gallinero. Con ellas llegaron también Matilda, Drácula, Frankenstein y Paquito Abdul. Llegaron los "bajo para abajo" y los "voy por agua". ¿Cuántos cafés de avellana habremos tomado? ¿cuántas horas de salseos? ¿cuántos debates sobre la tortilla de patatas perfecta? —que claramente es sin cuajar y con cebolla—. Ellas me tatuaron eso de que el apoyo social amortigua el estrés. Y qué *chévere*. Gracias por tantísimo a las dos.

Gracias también a Patri, la mejor profesora que la Universitat de València podría tener y una de las mejores personas que he conocido en mi vida. Ha estado ahí para todo, incondicionalmente. Ha creído en mí desde el minuto uno y se ha desvivido por ayudarme a cumplir un sueño. Sueño que pasaba necesariamente por poner un ingeniero en mi vida, y ella lo puso. Ese ingeniero, por supuesto, es Pepe, al que también le debo mucho. Por confiar en mis ideas, pero sobre todo por la predisposición. Ojo, porque este camino no ha hecho más que empezar.

Y no puedo cerrar este apartado sin darles las gracias a todos los estudiantes que han pasado por mis clases. Por su motivación y entrega. Habéis confirmado mi vocación. Habéis hecho que disfrute durante tres años seguidos y que haya valido la pena recorrer este largo camino. A esas casi 200 personas, gracias.

Creo que no me dejo a nadie, ¿no? Bueno, un momento, porque me da la sensación de que algo me falta… Familia, amigos, compañeros… Aunque en las tesis suele haber alguna figura más, alguien que… dirige. ¡Claro! ¡mi director! ¡¿cómo he podido olvidarme de mi director?!

Vale. En realidad esto tiene una explicación. Se me olvidaba *La figura* del director de doctorado, pero no olvidaba a Miguel Ángel Serrano. Por definición, director es la *persona que dirige algo en razón de su profesión o de su cargo*. Así pues, técnicamente, no he tenido director. Miguel Ángel nunca me ha impuesto directrices. Desde el minuto uno, que llegó mucho antes de matricularme en el programa de doctorado, él siempre se dejó el traje de superior en casa. Café en mano, Miguel Ángel me ha enseñado, por lo que ha sido mentor. Me ha guiado, por lo que ha sido tutor. Me ha escuchado y fomentado la curiosidad científica —y hasta artística—, por lo que ha sido catalizador. Me ha apoyado y se ha preocupado por mí, profesional y personalmente, ha confiado en mí: ha sido amigo. Por todo ello me cuesta verlo como director, aunque oficialmente lo sea. Gracias, Miguel Ángel, por ser el mejor *director* que todo doctorando quisiera tener. Y bueno, si alguien se pregunta por qué lo he dejado para el final, esto se debe a que he empezado agradeciendo a mis padres y, ahora, quería acabar agradeciendo a mi padre académico.

En definitiva, muchas personas han pasado por mi vida antes y durante la tesis, contribuyendo a que ésta llegue a buen puerto. Ha sido un camino largo, que empezó incluso antes de la matrícula. Y pese a la extensión, en realidad, no es más que el prólogo de todo lo que está por venir. La vida da mil vueltas, y este *mundillo* es muy complejo, pero estoy tranquilo porque sé que todas las personas a las que he mencionado en las líneas previas —y un gato—, seguirán acompañándome.

Foreword

Each cognitive ability contributes some functionality, but the convergence of all enables us to carry out the most complex executive function: decision-making. Our future depends on our decisions. The consequences of our choices give rise to the paths we traverse, which essentially define our lives. The process of decision-making has concerned us since classical philosophy: why do we decide what we decide? Is there a best decision? What is the path to reaching it? Reason or emotion? These questions have guided the field of decision-making study, with economics making the primary contributions over the past two centuries. Today, cognitive sciences and neuroscience take the baton and seek to update classical models and theories by providing evidence on human nature and how it shapes our decisions. This doctoral thesis is placed within this frame.

Section 1 contains the general introduction, beginning with a brief historical overview of the main contributions from economics and culminating in the development of Prospect Theory by Kahneman and Tversky. From there, the main criticisms of classical approaches and the emerging alternative lines of thought that guide cutting-edge studies on decision-making are detailed. Once the object of study of this thesis has been outlined within the provided framework, the main objectives are defined, accompanied by a comprehensive explanation of the studies employed to address them.

Section 2 presents these studies. Specifically, the scientific articles obtained after their completion have been included. Eight of them are in their original format, as they were published in international and influential journals. Study 9, however, is presented in its final version, which is under review at the time this thesis is deposited.

Section 3 consists of a general discussion on the results obtained in the nine studies, structured according to the objectives proposed in Section 1. This section also includes the common limitations across all our studies, as well as proposals to overcome them and avenues for future research. Finally, a general conclusion is drawn, integrating the knowledge contributed by this thesis and presented in bullet-point format.

Section 4 contains all the references cited throughout the doctoral thesis, following the format specified by the American Psychological Association (APA), in its seventh version.

Section 1: Introduction

1. Do we make good decisions?

When studying the cognitive capacities of the human being, it is customary to first establish a criterion that indicates its normative functioning. After empirically observing a representative percentage of the population, it is possible to employ statistical tools to describe the central tendency of the scores. This methodology not only provides information on typical performance, but also allows for the detection of significant deviations from the normative standards in specific contexts or when affected by pathologies (Evans, 2014). For example, human auditory capacity ranges from 20 to 20,000 hertz (Lasrado, 2019), and an audiometry test could detect hearing loss. On the other hand, our short-term memory capacity was estimated to be 7 ± 2 units of information (Miller, 1956; Saaty & Ozdemir, 2003), and a simple memory test could indicate that someone who remembers 20 words has above-average capacity.

By relying on empirical data, this normative criterion serves a dual purpose: it describes human nature and acts as a watchdog when something deviates from it, in any direction. Additionally, it prevents biased interpretations: in the absence of an objective benchmark, anyone could judge our capacity based on inadequate criteria. For example, even someone who retains 20 words in their immediate memory, a lot for a human, would appear to have serious cognitive limitations if compared to a computer. In Einstein's words, "...if you judge a fish by its ability to climb a tree, it will live its whole life believing it is stupid." Therefore, it is crucial to establish an appropriate criterion that allows for evaluations to be made in comparison to our true nature.

But what happens when we evaluate our capacity to make decisions? We are constantly deciding, consciously or unconsciously, between a few or infinite alternatives, with different degrees of importance —from trivial decisions to decisions where our life is at stake—, and with different degrees of certainty —from complete certainty of what the outcome of our choice will be, to decisions that will not have clear results in 20 years, maybe never—. What criterion determines which decision should be made? How can we know if someone is making good decisions or, on the contrary, is constantly failing and putting their economy, health, or future at risk? In trying to answer these questions, the study of decision-making under uncertainty has been mainly linked to economics. Thus, what is considered a good decision would be determined by the criterion of *economic rationality* (Bossaerts & Murawski, 2015).

2. *Homo economicus* and the economic rationality criterion

Adam Smith is considered the precursor of modern economics with his foundational work, *The Wealth of Nations* (1776). Smith could have been one of the first behavioral economists, as he included important psychological aspects such as individual motivations in his doctrine (Ashraf et al., 2005). However, as economics grew as a scientific discipline, it became infused with pragmatism and strong mathematization, which led it to abandon many of these psychological factors in order to isolate the aspects it considered strictly essential for the analysis of economic behavior (Morgan, 2006; Thaler, 2018). Thus, from Smith, only the idea that the individual is selfish and acts in their self-interest was preserved; from other notable authors such as Jeremy Bentham or John Stuart Mill, the belief that we always seek to maximize pleasure or utility and avoid pain was inherited; and in the 20th century, Frank Knight assumed that the individual has extensive knowledge of their environment and is able to accurately calculate which option will bring them the greatest utility (Ashraf et al., 2005; Hernandez, 2012; Morgan, 2006).

These ideas sowed the germ of the behavior model that most economic theories still base themselves on today: the *homo economicus* (Thaler, 2018). Essentially, the model of the *homo economicus* assumes that the human being (1) is selfish, (2) seeks the option that yields the maximum utility at the lowest cost, and in order to do so, (3) is able to perfectly analyze all available information in their environment, which always leads them to (4) use the most effective and efficient means and, therefore, (5) make optimal decisions (Mullainathan & Thaler, 2015; Thaler, 2017).

From these premises, developed and refined for over 200 years through different economic theories, the concept of economic rationality arises. Simply put, economic rationality is the degree to which an individual resembles the *homo economicus*. Thus, since we should always pursue maximum benefit in every decision we make and we should be capable of accurately calculating which option provides that benefit, choosing that option would be rational. In contrast, choosing any other alternative would be irrational. In economics, irrationality is often considered synonymous with error as it represents calculation errors or difficulties in following the laws of logic (Felin et al., 2017; Kahneman, 2003; Koehler & Harvey, 2004). Even when we choose an option that is also good, it would still imply a deficit, as the optimal option was left unchosen. Therefore, anyone who does not adhere to economic rationality would be demonstrating "ineptitude" or a poor ability to make decisions.

3. A “nudge” towards rationality

Herbert Simon (1955) criticized homo economicus' infinite processing capabilities and advocated for limited and context-dependent rationality (Simon, 1956). He argued that biological constraints can limit decision-making options. Additionally, imperfect environmental information and human cognitive limitations, such as finite working memory and fatigue, make it impractical to always pursue maximum utility. Simon proposed a simpler strategy based on satisfying needs rather than optimizing outcomes (Simon, 1955, 1956). This strategy allows for fast and frugal decision-making, even if it may result in suboptimal outcomes. Simon's approach acknowledges the complexity of decision-making contexts where finding an optimal decision may be impossible and resource-intensive (Hernandez, 2012). Ultimately, Simon's ideas challenged the classical criterion of economic rationality, both as a description of human behavior and as a normative ideal.

However, if an approach transcended and revolutionized both economics and cognitive sciences, it was the one initiated by Tversky and Kahneman with their *program of heuristics and biases* (1974). These authors identified mental shortcuts or *heuristics* that humans would use when making decisions. In line with the dual processing models of information (Evans, 2008; Mega et al., 2015), these heuristics would arise from system 1, automatic, emotional and intuitive, which governs our decisions unless we make an effort to use system 2, effortful, logical and reflective. While system 1 could lead us to satisfactory decisions with little effort, it could also lead us to incur cognitive biases that systematically violate the axioms of economic rationality (Kahneman, 2003). Tversky and Kahneman's data reflected a reality that was very different from that of *homo economicus*, which once again questioned the validity of economic rationality as a descriptive criterion. In fact, the authors developed *prospect theory* (Kahneman & Tversky, 1979; Tversky & Kahneman, 1992) with the aim of providing a model that more accurately described how humans make decisions. This theory became the new gold-standard for the study of decision-making.

Yet, even though prospect theory (Kahneman & Tversky, 1979) posits that our decisions do not resemble those of the *homo economicus*, Tversky and Kahneman's approach does not break away from economic rationality as an ideal of behavior. On the contrary, they still assume that it would be optimal to maximize utility or adhere to the laws of logic, but due to our cognitive limitations and biases we have difficulties reaching

that ideal. In fact, a prescriptive current has emerged from this approach, which seeks to develop strategies to curb biases and bring us closer to economic rationality. This is the case of the "nudge" (Sunstein, 2014), or the *libertarian paternalism* policies (Gigerenzer, 2015; Thaler & Sunstein, 2003). In this sense, it is suggested that a good way to prevent decision errors is by "nudging" us towards the best alternative. Choice freedom is not restricted, but the optimal option is pre-set by default.

This approach has been hardly criticized, highlighting the potential risks of paternalistic policies, such as conflicts of interest that may arise from those who are responsible for nudging us in a particular direction (Gigerenzer, 2015). These issues have only served to further intensify the debate on the validity of the economic rationality criterion (Chater et al., 2018) and the notion of bounded rationality derived from prospect theory (Kahneman & Tversky, 1979). It is worth remembering that libertarian paternalism is based on our differences from the *homo economicus*. Would it make sense to talk about errors of judgment and decision-making for not being adjusted to a criterion that idealizes human nature? In the following section, we will summarize the main criticisms which support the need to disengage from the economic rationality criterion. Then, in section 5, we will describe the new trends in decision-making that have emerged from these criticisms and to which this doctoral thesis is added.

4. Criticisms of the bounded rationality approach

4.1. Overly simple contexts with low ecological validity

Most decisional environments used to identify biases are known as small worlds or risk contexts (Chater et al., 2018; Felin et al., 2017; Gigerenzer, 2021; Volz & Gigerenzer, 2012). These are simplified environments where the structure and rules are clear and both decision alternatives and probabilities of outcomes are well defined. Furthermore, these contexts assume the existence of an optimal solution (Felin et al., 2017). But in the real world, these contexts are not abundant. Instead, we use to find large worlds or ambiguous contexts (Chater et al., 2018; Felin et al., 2017; Gigerenzer, 2021; Volz & Gigerenzer, 2012) where the structure and information are imperfect, either due to an excess or a lack of it. In line with Simon's proposals, Gigerenzer (2021) developed the *ecological rationality* approach. This suggests that it might be possible to make the best decision in small worlds, where using heuristics may not be the most advantageous strategy. However, in complex and ambiguous environments there may not be a single optimal decision, and attempting to maximize outcomes could be fruitless, being

advisable to rely on heuristics. Gigerenzer states that heuristics are adaptive tools that have been acquired through natural selection and it is essential to study their usefulness in ecological, complex contexts, instead of risk contexts (Gigerenzer & Gaissmaier, 2011; Raab & Gigerenzer, 2015; Y. Wang et al., 2022).

4.2.Lack of knowledge about heuristics and biases

In line with the previous criticism, another problem arises from the few efforts made to deepen our understanding of the identified heuristics and biases. Thus, it is difficult to assert whether they are phenomena that affect all decisions or, on the contrary, could be measurement artifacts promoted by the specific small worlds. Similarly, it is difficult to clarify if they really decrease our decision-making performance. This is because they were merely labeled *post hoc* (Gigerenzer, 2021; Hertwig et al., 2020; Marewski et al., 2010; Y. Wang et al., 2022). That is, it was observed an anomalous behavior, usually with respect to economic rationality criterion, and it was named. However, their nature was not deeply explored: why and when these heuristics are used, when biases arise, or what psychobiological bases support them. Also, unlike utility maximization, heuristics and biases usually do not have a mathematical description, that is, they are not operationalized through formal models. This makes it difficult to test which strategy —utility maximization vs. use of heuristics— better predicts our decisions, as well as its effectiveness and efficiency in different contexts (Hertwig et al., 2020; Wang et al., 2022). Only by developing models could we verify whether the optimal strategy to reach the best option —when it is possible— is always deliberative, slow, and effortful, processing all the information; or if, on the contrary, a more intuitive strategy based on fast and frugal heuristics, not only better explains our behavior but also improves the performance of our decisions.

4.3.Lack of criteria to evaluate our decisions.

The final criticism is directed at the use of classical economic rationality as the sole criterion for evaluating our decision-making capacity. We have pointed out that this criterion is based on idealizations of human nature (Morgan, 2006). It may not be necessary to eliminate it as it could still be suitable for evaluating decisions in certain contexts, such as the small worlds. However, it may lack validity when evaluating decisions in other contexts where there may not exist an optimal decision. In more complex environments, it could be more useful to adopt another criterion such as the one proposed by Simon (1955, 1956), assessing whether humans are able to satisfy their needs.

Or, in line with the studies of Bechara & Damasio (2005), it could be assessed whether decisions are adaptive. In fact, it would be necessary to adopt the ecological rationality perspective proposed by Gigerenzer (2021) as what is adaptive in one environment can be detrimental in another. For example, following a utility maximization strategy may be good in an individualistic context but not in social or moral decisions (Camerer, 2003). Recent studies show how individuals with autism are very good at maximizing utility but at the same time exhibit more selfish decisions in social contexts, which hinder their adaptation (Hinterbuchinger et al., 2018). Therefore, the field of decision-making research should not forget about the constraints of the environment and expand its repertoire to evaluate decision-making capacity. Referring to Simon's scissors metaphor: "Human rational behavior is shaped by a scissors whose blades are the structure of the task environment and the computational capabilities of the actor" (Simon, 1990, p. 7).

5. New lines in the study of decision-making

In recent years, multiple disciplines, ranging from biology to computer science, have made significant strides that could address many of the criticisms described in the previous section. As a result, the field of decision-making research is beginning to update, and even slowly displace, classical approaches, giving rise to new ecological approaches that address the issue in a more naturalistic way, truly considering human capabilities and the influence of context.

5.1.Decoding heuristics and biases

Firstly, formal models have been developed to mathematically describe heuristics, enabling an objective analysis of decision-making strategies (e.g., Marewski et al., 2010; Wang et al., 2022). Recent studies challenge the notion that maximizing utility is always the best approach, showing that simple heuristics can outperform utility maximization even in small worlds (Hertwig et al., 2020; Wang et al., 2022). These advances align with the ecological rationality approach (Gigerenzer, 2021), emphasizing the importance of understanding when heuristics can be advantageous or harmful. In the same way, neuroeconomics, a field in neuroscience, examines heuristics and biases from a psychobiological perspective (Bossaerts & Murawski, 2015; Dolan & Sharot, 2011; Kenning & Plassmann, 2005). It aims to uncover the psychobiological basis for these behaviors and shed light on their occurrence. Recent studies also investigate factors that modulate the expression of biases, revealing their variability based on internal and external contexts (e.g., Mrkva et al., 2020). Consequently, individuals may exhibit

different levels of bias depending on their environment or physiological state, alternating between biased and rational decision-making.

5.2.Extending the evaluation criteria

All previous evidence supports the insufficiency of economic rationality as a sole criterion to analyze human decision-making capacities. However, developments have been made based on this criterion. For instance, the Decision-Making Competences questionnaire (Bruine de Bruin et al., 2012) evaluates 7 domains related to economic rationality, expanding the classical view by acknowledging that rationality can vary across different domains. Nonetheless, the current approach, as proposed by Geisler & Allwood (2015), advocates for evaluating decisions using multiple criteria simultaneously. One alternative criterion worth highlighting is the level of satisfaction derived from our choices. This can be approached from two perspectives: satisfying the minimum level of benefit an individual requires, according to Simon's classical approach (Simon, 1955, 1956), or considering the pleasure and happiness our decisions provide. Tools such as the Positive And Negative Affect Scale (PANAS) (Watson et al., 1988) or physiological measures like the activity of the zygomatic major muscle (Schmidt et al., 2006) can be used to assess this aspect. Other alternative criteria indicating decision quality include education level, socioeconomic status, substance abuse, and self-destructive practices (Brugnach et al., 2011; Geisler & Allwood, 2015).

The process followed in decision-making also becomes informative of one's ability since outcomes can be influenced by uncontrollable factors. This approach has gained significance, particularly in organizational contexts (Brugnach et al., 2011; Gore et al., 2006). External factors like competitors or clients may prevent the expected outcome, but workers who have employed appropriate strategies for the given circumstances still demonstrate good decision-making ability. Different contexts require specific cognitive capacities during the decision-making process. Some environments prioritize self-control, working memory, and planning ability, while others emphasize sensitivity to feedback and reinforcement-learning. Technological advancements now enable the analysis of these cognitive sub-processes, offering more detailed insights instead of viewing decision-making as a one-dimensional skill (Alacreu-Crespo et al., 2020). Neurocomputational models have been developed to represent the cognitive processes involved in decision-making (Ahn et al., 2017; Serrano et al., 2022), aligning with the approach initiated by Bechara & Damasio (2005). These models help identify

decision-making deficits and assess specific affected abilities. Furthermore, they open possibilities for establishing new normative criteria tailored to human nature. By studying representative groups, it becomes feasible to obtain standard scores for the underlying cognitive abilities of the decision-making process, providing a descriptive view and detecting anomalies deviating from these benchmarks. Such anomalies differ greatly from those identified using the caricature of *homo economicus* as a benchmark (Morgan, 2006).

5.3. Building large worlds

In the quest for new evaluation criteria, it becomes necessary to assess decision-making in ecological or real-world contexts. Small worlds offer the advantage of isolating decision-making from confounding factors, but the simplicity of these environments raises concerns about biased results and limited generalizability outside the laboratory (Gigerenzer, 2021; Gigerenzer & Gaissmaier, 2011; Wang et al., 2022). Alternative approaches propose observing decision-making processes and outcomes in natural contexts, such as work environments (Brugnach et al., 2011; Gore et al., 2006) or emergency situations involving doctors or firefighters (Gonzalez et al., 2017). Some authors further advocate for deliberate use of effective heuristics in real-world settings, such as hospitals (Gigerenzer et al., 2007; Marewski & Gigerenzer, 2012) or personnel selection processes (Luan et al., 2019).

While observational approaches provide valuable insights, experimental manipulations for causal explanations are challenging. To overcome this limitation, animal models have been proposed (Constantinople et al., 2019). By recreating environments like those encountered by humans, researchers can study the decisions animals make while controlling and manipulating variables that impact the decision-making process. Variables such as place preference, preferred feeders, fight-or-flight responses, and time spent scrutinizing an environment before entering can be evaluated. Importantly, this evaluation eliminates factors like social desirability, acquiescence, and lack of motivation for experimental tasks. Virtual environments are also emerging to recreate real-world situations while maintaining the control of laboratory settings. Serious games like the Assessment on Decision Making in Risk Environments (AEMIN) (De-Juan-Ripoll et al., 2021) or the Spheres & Shield Maze Task (SSMT) (De-Juan-Ripoll et al., 2020) have been developed. These games simulate mazes where individuals can earn money or energy as they progress, presenting risky situations to assess conservative or risky decision-making. Although data analysis can be complex due to the abundance of

information obtained, advancements in machine learning methodologies (Alcañiz Raya et al., 2020; De-Juan-Ripoll et al., 2021) and techniques like data mining (Zhao, 2012) facilitate the identification of relevant variables and their interconnections, providing more interpretable results.

6. State of the art and specific framework of the thesis

In summary, we have seen that the normative criterion that still prevails when evaluating whether we make good decisions is economic rationality, derived from classical economic theories and the model by which they are governed: the *homo economicus* (Thaler, 2017). This standard has faced many criticisms over the past two centuries. Kahneman and Tversky's Prospect Theory (1979) showed that cognitive biases systematically influence human decision-making, leading us away from economic rationality. However, instead of questioning whether the normative standard accurately reflects human nature, they interpreted these biases as errors that need correction to bring us in line with the normative standard (Kahneman, 2003). Consequently, the concept of economic rationality remained unchanged. Today, there are many more criticisms of the abstract —even unreal— nature of the economic rationality criterion (Morgan, 2006), along with those specifically directed at Prospect Theory and the negative connotation it has on cognitive biases (e.g., Gigerenzer, 2021). This has led to important lines of research that, in recent decades, have enriched the field of decision-making. Essentially, these lines could be classified into two major pillars.

On the one hand, beyond just identifying and labeling biases, current approaches aim to decipher their nature: their possible psychobiological bases and why they manifest. They also focus on discovering what factors modulate their expression, as it does not always have to be stable (Nagaya, 2021). In addition, they analyze what role a particular bias plays in different environments, seeing that, far from always being negative, they could provide an adaptive advantage in certain decision-making contexts (Haselton et al., 2009; Santos & Rosati, 2015). On the other hand, there is a growing trend to move away from evaluating decision-making —and the role of biases— only in simplified contexts, pursuing an ecological evaluation whose results are more extrapolable to the real world (Gigerenzer, 2021; Volz & Gigerenzer, 2012). From animal models of decision-making (Constantinople et al., 2019), to virtual environments (e.g., De-Juan-Ripoll et al., 2021), all are focused on a more complex and representative decision-making process. In turn, this approach entails a change in the evaluation criterion, which is no longer limited to

economic rationality. Satisfaction, adaptability, health, and even the decision-making process itself —e.g., learning, impulsivity, or risk during the process— are indicators that are beginning to be integrated into new studies on decision-making and that provide a more complete picture (e.g., Geisler & Allwood, 2015). For example, a bias could steer you away from economic rationality, but be useful in avoiding risks or dangers, following a biological rationality.

Both pillars essentially constitute the theoretical framework of this doctoral thesis. The aim is to continue shedding light on the field of decision-making, following the path of cutting-edge studies. However, even with well-defined lines, this field of study remains very broad, and it seems convenient to delimit it to make it more manageable. Thus, from among the many cognitive biases that affect the decision-making process and that could be addressed from the proposed theoretical framework, we have decided to focus the thesis on what is undoubtedly the most notable bias. This is the central pillar of Prospect Theory (Kahneman & Tversky, 1979) and the basis for many other biases that depend on this phenomenon. We are talking about loss aversion (Kahneman et al., 1991).

7. A fundamental bias: loss aversion

Loss aversion bias is the phenomenon according to which "losses loom larger than gains" (Kahneman et al., 1991; Kahneman & Tversky, 1979). Specifically, scientific literature suggests that losses would have a psychological impact 2 to 2.5 times greater than that of proportional gains. Thus, when faced with a decision involving a potential gain versus a potential loss, the magnitude of the former should be twice as large as the latter for gain and loss to be processed proportionally. Similarly, the pain of losing an amount would be approximately twice the pleasure of gaining that same amount, something that is empirically observable, for example, through the disproportionate autonomic response produced by losing (Sokol-Hessner et al., 2009; Stancak et al., 2015). Therefore, due to the loss aversion bias, we will be more easily moved towards avoiding losses than towards seeking gains, conditioning our decisions.

It is important not to confuse loss aversion with risk aversion. Risk aversion specifically refers to the preference for safe options over those that involve risk. For example, most people would prefer to keep 100€ insured rather than play a bet in which they would win 200€ if it comes up heads but win nothing if it comes up tails. Economics has tried to integrate this effect into its models, giving it a logical explanation and

considering it a rational behavior (Bernoulli, 1738, 1954). However, Kahneman and Tversky (1984) observed that this preference is not stable and depends on context. Thus, the same people who avoid risking in the previous example tend to choose risk when the safe option involves a loss. For example, losing 100€ for sure versus playing a bet in which, if it comes up heads, you lose 200€, but if it comes up tails, you do not lose anything. This change in preferences depending on the context is known as the framing effect (Kahneman & Tversky, 1984; Tversky & Kahneman, 1989) and violates one of the main axioms of economic rationality: invariance, according to which our preferences would be independent of the context (Kahneman, 2003; Kahneman & Tversky, 1984). In addition, framing effect would depend on loss aversion, as people would change their attitude towards risk —choosing the bet— to avoid the psychological impact produced by a certain loss (Kahneman & Tversky, 1984; von Neumann & Morgenstern, 1944). Like the framing effect, in recent decades many other phenomena have been described that affect our decisions and violate the axioms of rationality, such as the endowment effect, the status quo bias or the disposition effect, which have also been justified as possibly having their origin in loss aversion (see Nagaya, 2021).

7.1.How and where to measure this bias?

Loss aversion is one of the most accepted judgmental biases in the social sciences and uses to be considered a fundamental and generalizable principle (Gal & Rucker, 2018), or even a stable behavioral trait (Hadlaczky et al., 2018). The usual way to measure loss aversion is through decision-making tasks involving risk or small worlds, with the most common ones being those that present mixed bets with a 50% chance of winning and a 50% chance of losing. The economic amounts that can be gained/lost change in each trial and generate different scenarios where each participant must decide whether to play the bet or reject it. Based on the responses that participants give to the different bets, the behavior of loss aversion can be estimated by calculating the parameter λ.

This estimation can be done simply, assuming that the utility of gains and losses follows a linear function and checking the relative weight of $-\beta_{losses}$ with respect to β_{gains}, where β are the slopes extracted from a logistic regression in which gains and losses are the independent variables and the acceptance or rejection of the bet is the dependent variable (Tom et al., 2007). However, in their Prospect Theory, Kahneman and Tversky (1979) considered that the utility of gains and losses was not linear, but rather curved as the amounts increased. To obtain a measure of λ in line with this theory, the utility of

gains and losses is usually estimated separately. The utility for gains is estimated through the equation $u(x^{gain}) = x^{\rho}$, and the utility for losses through the equation $u(x^{loss}) = -\lambda \times (-x)^{\rho}$. Finally, the probability of accepting a gamble is estimated through the SoftMax function, $P_{(Accept)} = 1/(1 + e^{-\mu(U(Accept)-U(Reject))})$. As can be seen, three parameters are derived from this model: λ (loss aversion coefficient), ρ (the curvature of the utility function or risk aversion), and μ (the logit parameter). Focusing on loss aversion, λ values usually described in the literature are between 2-2.5 (Duke et al., 2018; Kahneman & Tversky, 1979; Tom et al., 2007). This means that participants accepted gambles if gains were at least 2 times as large as losses.

In addition to small worlds, loss aversion has also been estimated in more complex decision-making contexts, extending this phenomenon beyond risk contexts. Recently, computational models have been developed that allow the breakdown of decision-making into its different subcomponents, with loss aversion being one of the main ones (see Serrano et al., 2022 for a review). Thanks to these models, we can estimate the level of this bias in complex decision-making tasks such as the prominent Iowa Gambling Task (IGT) (Bechara et al., 1997; Chiu et al., 2018), widely used in the clinical field to discriminate deficits in emotional processing that affect our reinforcement-learning capacity and lead to bad decisions. Currently, loss aversion has been described in more than fifty countries (Wang et al., 2017), from cab drivers (Camerer et al., 1997) to professional golfers —including Tiger Woods— (Pope & Schweitzer, 2011); in the field management (Jarrow & Zhaou, 2006), and politics (Berejikian & Early, 2013), but also in areas far from economics, such as the response to potential harmful stimuli —for example, aggressive faces or odors (Stancak et al., 2015; Viswanathan et al., 2015)—; and even in other species, such as rats (Constantinople et al., 2019) or capuchin monkeys (Santos & Rosati, 2015).

In contrast, its ubiquity has been recently questioned. Gal & Rucker (2018) stressed that there is no firm evidence to support that losses have always more impact than gains and labeled this phenomenon as a fallacy. In fact, even when people are more responsive to losses at the physiological level, it does not always translate into greater behavioral loss aversion (Hochman & Yechiam, 2011). Moreover, Ert & Erev (2013) stated that loss aversion only would emerge under certain very specific experimental manipulations such as when there are large amounts at stake or when people is submitted to long experiments in which no feedback is provided. Nevertheless, the current position

is that loss aversion has moderators and a more contextualized view is advisable (Gal & Rucker, 2018; Mrkva et al., 2020; Nagaya, 2021). This has led to the need to better understand its origin and which factors modulate its expression.

7.2.Possible emotional origin of loss aversion

Neuroscience has found a stable neural basis for loss aversion that appears to link this phenomenon with the limbic system and, therefore, with our emotions. Neuroimaging studies reveal that our brain has an aversive system mainly composed of the amygdala and insula, which responds disproportionately to losses compared to how our appetitive system —whose central node is the striatum— responds to gains (Molins & Serrano, 2019; Sokol-Hessner & Rutledge, 2019). Moreover, the resting-state activity of these systems could predict whether loss aversion will be higher or lower during the decision-making process, explaining why not all individuals show the same level of loss aversion (Canessa et al., 2017). This individual variability is also beginning to be addressed from a genetic perspective, with certain polymorphic genes, especially those involved in dopamine and serotonin neurotransmission —and therefore linked to our emotions— showing a higher or lower level of loss aversion depending on the present allele (Voigt et al., 2015). However, these studies are scarce and their results very heterogeneous, requiring further research to draw firm conclusions.

By the other side, both Kahneman (2011), from the field of risky decision-making, and Kanouse (1984), from the impression formation literature, proposed the connection between loss aversion and a more basic emotional phenomenon: the negativity bias. Negativity bias refers to the greater sensitivity to negative emotional stimuli compared with positive stimuli (Cacioppo & Berntson, 1994; Joseph et al., 2020), which conditions the processing of these stimuli. Thus, negative emotional stimuli would have a greater influence on our perception, judgement, and decision-making (Barros et al., 2017; Kauschke et al., 2019; Zeelenberg et al., 2006). As we can see, the connection between both phenomena seems to make theoretical sense, however, to our knowledge, only the study by Sheng et al. (2020) has shown that the negativity bias could, at least in part, predict loss aversion. It would be relevant to further address this issue because, if the connection between these two phenomena were confirmed, this would constitute further evidence of the emotional origin of loss aversion.

In line with this possible emotional origin, several studies have suggested that the greater expression of loss aversion is negatively related to individuals' capacity for

emotional regulation (Sokol-Hessner et al., 2009, 2013). This relationship has been also observed between loss aversion and resting heart rate variability —HRV— (Mintoft et al., 2012; Sütterlin et al., 2011), which is closely linked to emotional regulation (Laborde et al., 2017; Molins et al., 2021; Park & Thayer, 2014). However, to better understand the origin of loss aversion, it is important to delve into the mechanisms by which it relates to emotional regulation. Recent studies indicate that other more specific constructs such as interoception —the ability to detect and process subtle internal bodily sensations (Shah, Hall, et al., 2016; Zamariola et al., 2018)— or alexithymia —a personality construct consisting of difficulties in identifying and describing one's emotions (Shah, Catmur, et al., 2016; Swart et al., 2009)—, which play a key role in our capacity to regulate emotions (da Silva et al., 2017; Zamariola et al., 2018), are in turn related to the greater or lesser influence of emotions during decision-making processes. In fact, some studies suggest that the lower interoception or the higher alexithymia, the lesser framing effect in an economic decisional task (Shah, Catmur, et al., 2016). However, the possible connection between these constructs and loss aversion must be studied in-depth to shed more light on the possible emotional origin of this phenomenon and the underlying mechanisms that modulate its expression.

7.3.Stress modulates loss aversion

From individual variables such as personality traits (Boyce et al., 2016) to contextual aspects such as culture (Wang et al., 2017), many studies are focused on understanding which factors can shape loss aversion's expression. Since the incidence of stress has risen markedly over the past two decades (Ward et al., 2020), and many decisions are made under stress, this is one of the most studied factors.

Stress can significantly influence decision-making (Starcke & Brand, 2012), and specifically loss aversion (Margittai et al., 2018), although the direction remains unclear. In fact, currently two opposing hypotheses coexist. The "salience-of-losses" hypothesis proposes that acute stress reallocates resources in the brain, favoring the activation of the salience-network (Metz et al., 2020). This network contains regions such as the amygdala, which also constitutes one of the main neural bases of loss aversion (Molins & Serrano, 2019). So, stress would enhance loss aversion (Metz et al., 2020). However, the most accepted is the "alignment" hypothesis (Metz et al., 2020), supported by the STARS model (Stress Triggers Additional Reward Salience) (Mather & Lighthall, 2012). It has been seen that, in rats, acute stress increases nucleus accumbens extracellular levels of

dopamine and firing rates in their midbrain dopamine neurons (Anstrom & Woodward, 2005; Kalivas & Duffy, 1995). In addition, positron emission tomography (PET) studies suggested similar results in humans, where stress enhances striatal dopamine (Scott et al., 2006; Wood et al., 2007). These regions play a key role in representing reward value (Mather & Lighthall, 2012; Rangel et al., 2008). So, with their STARS model, Mather & Lighthall (2012, p. 2) proposed that "stress enhances reward salience via modulation of the dopamine system, resulting in reward-biased learning"; i.e., stress could bias in weighing positive over negative aspects during the decision-making process. Therefore, the alignment hypothesis suggests that stress would balance the susceptibility to gains and losses, the former seeming more attractive, thereby reducing loss aversion (Metz et al., 2020).

Although seemingly contradictory, both hypotheses may not be mutually exclusive and may reflect different stress phases, depending on their two main physiological pathways: the fast activation of the sympathetic nervous system (SNS), which triggers catecholamines release; and the slower hypothalamus-pituitary-adrenal axis (HPA-axis) activation, resulting in a secretion of cortisol (Hidalgo et al., 2019). In this line, a positive relationship was found between norepinephrine brain levels and loss aversion (Sokol-Hessner & Rutledge, 2019; Takahashi et al., 2013). Yet, concurrent glucocorticoid and catecholaminergic activity significantly reduced loss aversion (Margittai et al., 2018). So, it seems that depending on the SNS and HPA-axis activity, both hypotheses may be supported. Nevertheless, it is also necessary to consider that, depending on their nature, stressors can vary in the expression and magnitude of their physiological and psychological responses (Hidalgo et al., 2019). For example, it is known that physical or systemic stressors produce a robust Sympathetic Nervous System (SNS) response, whereas psychosocial stressors elicit the activation of both the SNS and the Hypothalamic-Pituitary-Adrenal (HPA) axis (Hidalgo et al., 2019). Thus, it is important not to study stress in the singular, but how different stressors —and their different stages— impact on loss aversion. Only then can we obtain specific answers about how the expression of this bias is modulated by stress.

7.4.Possible adaptive role of loss aversion

So far, we have talked about approaches that try to understand the nature of loss aversion without evaluating whether this phenomenon would be adaptive or not. However, another line of research seeks to analyze whether the presence of loss aversion, far from

being a bias that leads us to irrationality, can favor good decision-making. Some authors theorize about the possible natural origin of loss aversion —in line with the possible genetic bases already mentioned and its connection to our affective system—, and affirm that this bias would have been evolutionarily selected because it fosters a conservative attitude in our species, avoiding dangers over the search for rewards (Haselton et al., 2009; Santos & Rosati, 2015). This argument has also been used in relation to the negativity bias (Thayer & Lane, 2009).

Empirically, it has been shown that loss aversion seems to be increased in people who suffer from anxiety disorders or major depression, in line with the poorer decision-making manifested in these patients (Klumpp et al., 2012; Laeger et al., 2012; Stein et al., 2007); this seems to contradict the possible adaptive role of this bias. However, the classic studies of Bechara & Damasio (2005) already revealed that patients with lesions in brain regions involved in emotional processing and regulation —e.g., amygdala and ventromedial prefrontal cortex (vmPFC)— expressed less risk aversion. These patients, while making more rational decisions in small worlds, were unable to learn by reinforcement and avoid the bad consequences of their choices when they decided in contexts closer to the real world. Similarly, recent evidence points to the potential protective role that loss aversion would play, related to less tobacco consumption (Thrailkill et al., 2022), less self-harm (Sagiv et al., 2019), and even fewer suicide attempts (Hadlaczky et al., 2018; Sagiv et al., 2019).

Thus, new lines of research point towards the adaptive advantage that loss aversion could confer, although further research is required to confirm this. For this purpose, future studies should consider new approaches to decision-making, incorporating new normative criteria that go beyond economic rationality —such as satisfaction or health derived from our choices— and analyzing the decision-making process and its consequences in more ecological environments, closer to the real world.

8. Objectives

Based on all the above, the overall objective of this doctoral thesis is to learn more about the nature of the loss aversion bias and its potential adaptive role. Why, how, and when this bias is expressed, as well as in what contexts it may be favorable to us, are the questions from which the more specific objectives of the thesis are derived, which will be detailed below. This objective, in turn, is part of the cutting-edge lines of study in

decision-making and aims to contribute to this field, shedding more light on the nature of human decisions and biases, moving a little further away from the classic *homo economicus* and the reign of economic rationality.

8.1.Exploring the emotional origin of loss aversion

The first specific objective of the thesis is focused on gathering further evidence that sheds light on the possible emotional origin of loss aversion. Before starting the doctoral program, our team had conducted a systematic review on the neural basis of this bias (Molins & Serrano, 2019), which already indicated the involvement of the limbic system in the imbalanced processing of gains and losses, resulting in greater brain activity for the latter. Now, the thesis begins with a new systematic review, this time regarding the genetic bases that could support this bias. It compiles published studies that address how various polymorphisms relate to a greater or lesser expression of loss aversion and analyzes whether the implicated genes are also related to our affective system and the expression of emotions. Given the scarcity of genetic studies specifically focused on loss aversion, this review also includes other phenomena that, as previously noted, are closely linked to it: these are risk aversion and the framing effect. This work has recently been published in the *International Journal of Environmental Research and Public Health* and can be found in the following section, under the name of **Study 1**.

On the other hand, although in line with the same objective, **Study 2** was conducted. It empirically addresses the theoretical proposals put forth by Kahneman (2011) and Kanouse (1984), which suggest that the negativity bias, a basic emotional phenomenon, may underlie loss aversion. If this is the case, individuals with greater sensitivity towards negative stimuli should also exhibit greater loss aversion. Since the negativity bias has been clearly linked to our affective system, demonstrating that loss aversion is related to this phenomenon would provide further evidence that its expression originates from an emotional response where negative events, such as losses, have a greater impact and are prioritized over positive events. Study 2 examines these ideas and provides further insights into the emotional origins of loss aversion; it was also published in the *International Journal of Environmental Research and Public Health*.

Finally, if loss aversion has an emotional origin, its expression could be influenced by the individual's ability to regulate their emotions. Several studies have already explored this idea and have found that greater emotional regulation —as measured through questionnaires or peripheral physiology such as HRV— is associated with lower

levels of loss aversion during economic decision-making tasks (Mintoft et al., 2012; Sokol-Hessner et al., 2009, 2013; Sütterlin et al., 2011). However, to better understand the origins of loss aversion, it is necessary to explore the specific mechanisms underlying this relationship. In **Study 3**, we investigate how interoception and alexithymia, two constructs that underlie our capacity for emotional regulation, interact with each other and relate to emotional decision-making: that is, if decisions are affected to a greater or lesser extent by biases such as loss aversion. Study 3 addresses loss aversion through the framing effect and was published in the *International Journal of Psychophysiology*.

8.2.Analyzing how stress modulates the expression of loss aversion

The manifestation of loss aversion is not as ubiquitous and stable as originally believed. Rather, there seem to be many differences between individuals and within individuals depending on various moderating factors (Mrkva et al., 2020; Nagaya, 2021). One of the most extensively studied factors is stress, but the results obtained so far have been heterogeneous. Although it is clear that stress affects loss aversion, the direction and mechanisms of its influence are still unclear. This may be due to the fact that stress itself is also heterogeneous, and its influence may differ depending on the nature and phase of the stressor —such as early catecholamine release versus late cortisol release—. To shed light on the relationship between stress and loss aversion, this doctoral thesis includes five studies that examine the influence of different stressors on this bias.

The first two studies examine the effects of an acute stressor in the early phase, specifically 5 minutes after the stressor onset. **Study 4** uses vigorous exercise as a physical stressor that triggers physiological stress but does not affect mood or subjective perception of stress. This study has been published in the journal *Anxiety, Stress & Coping*. On the other hand, **Study 5** uses a video of a circumcision as an emotional stressor that induces both physiological and psychological stress. This study has been published in the journal *Stress*. Both studies aim to investigate whether the two dimensions of stress — physiological and psychological— have different effects on loss aversion. In contrast, **Study 6** focuses on the later phase of acute stress, specifically 30 minutes after the stressor onset. This study uses the Trier Social Stress Test (TSST), which is considered the gold standard of laboratory stressors. It has been published in the journal *Physiology & Behavior* and aims to investigate whether the later phase of stress has a different impact on loss aversion compared to the earlier phase.

All three of the studies employ acute laboratory stressors, which have concluded by the time decision-making is assessed. This is a standard approach when studying the relationship between stress and loss aversion. However, the influence of these stressors may differ from that of natural stressors that occur outside of the laboratory and may still be present during decision-making. **Study 7** was designed to address this issue during the context of the COVID-19 pandemic, which provided a unique opportunity. We examined whether the pandemic situation and the confinement measures were stressors capable of causing psychological distress. After confirming this, we investigated how this distress affects loss aversion, measured both before and during confinement. The results of this study have been published in the journal *Retos, Revista de Ciencias de la Administración y Economía*.

Finally, the aforementioned studies have evaluated loss aversion through the most commonly used method in the scientific literature, the mixed gamble task (Tom et al., 2007). These gambles represent risky or small-world decision-making scenarios in which individuals are aware of the decision options and probabilities of outcomes. However, as Volz & Gigerenzer (2012) noted, cognitive processes can differ during risky decisions versus ambiguous decisions in large worlds. Therefore, the impact of stress on decision-making in these contexts may also differ. With the help of recent computational models that allow us to estimate the level of loss aversion in large worlds (Serrano et al., 2022), we conducted **Study 8**. This study utilizes vigorous exercise as an acute physiological stressor in its early phase but employ the IGT, a prominent ambiguous decisional task from which we estimate several subcomponents underlying decision-making, one of which is loss aversion. This study has been published in the journal *Physiology & Behavior* and investigates the influence of acute stress not only on loss aversion, but on the overall complex decisional process that takes place during IGT.

8.3.Exploring the potential adaptive role of loss aversion

Loss aversion has long been considered a "bias" with negative implications for our ability to make logical decisions according to the normative criteria of economic rationality. However, recent research suggests that many biases, including loss aversion, may have adaptive value and serve a biological rationality (Haselton et al., 2009; Santos & Rosati, 2015). In fact, they may be beneficial in our daily lives, particularly when faced with complex decisions where intuition may be more valuable than reason. This doctoral thesis aims to explore this question from different perspectives.

On the one hand, **Study 1** itself, by reviewing the genetic basis of loss aversion, would also be providing evidence that this phenomenon is rooted in our genes and therefore, given that it has been preserved through natural selection, may have some adaptive value for our species. While this study would not provide a direct link between loss aversion and adaptive decisions, it does seek to emphasize that biases may be part of our most basic nature. Consequently, fighting against them may be less intelligent than trying to adjust the normative criteria that govern the evaluation of decision-making.

On the other hand, the aforementioned **Study 2**, in addition to connecting loss aversion with the negativity bias, also tries to show that the latter bias can be very useful in large worlds. Thus, given that people with a greater negativity bias would have greater sensitivity to negative stimuli, they should also be more sensitive to the punishments —economic losses— that they suffer during an ambiguous decisional task such as IGT. This would contribute to better reinforcement-learning and to the improvement of subsequent decisions made throughout the task. If negativity bias underlies loss aversion —considered a decisional error in the small worlds— and in turn improves decisions in large worlds such as IGT, this could constitute evidence in favor of Gigerenzer's ecological rationality approach (Gigerenzer, 2021). That is, the same bias can be good or bad, adaptive or maladaptive, depending on the environment in which it is analyzed.

Returning to **Study 8**, it addressed whether acute stress affects decision-making in an ambiguous environment such as the one proposed by the IGT. To this end, a computational model was used to disentangle the subcomponents of this decision-making, including loss aversion. This study allows us not only to test whether the level of loss aversion is altered by stress but also how it is related to the rest of the decision-making process. In line with Study 2, which linked loss aversion to the negativity bias and the sensitivity that everyone has towards negative stimuli —punishments—, stress-induced alteration of loss aversion may condition the ability to learn by reinforcement during IGT. Thus, this study aims to shed light on the adaptive role that this bias might play within the decision-making process.

Finally, analyzing how the absence of loss aversion affects a population that tends not to manifest this phenomenon, such as autism spectrum disorder (ASD), can provide insights into the potential adaptive role of this bias. Individuals with ASD tend to make cooler and more logical decisions in individual risk contexts, less influenced by biases such as loss aversion (Shah, Catmur, et al., 2016). Thus, from economic models,

individuals with ASD would make fully rational and therefore adequate decisions (Camerer, 2003). However, these same individuals often struggle to adapt to the environment, especially when making decisions with a social component, which are characterized by excessive utilitarianism (Hinterbuchinger et al., 2018; Trovato, 2019). It has been hypothesized that these deficits could be linked to problems with emotional processing (Shah, Catmur, et al., 2016; Swartz et al., 2013), which could also lead to such logical decisions in risky contexts. However, to our knowledge, it has never been empirically tested whether the lower occurrence of biases in risky decisions is actually associated with higher utilitarianism in social contexts. To fill this gap, we conducted **Study 9**, which is currently under review in the journal *Cognitive Processing*. The study aims to provide evidence that loss aversion, as measured by the framing effect, may indicate good emotional processing, which is necessary to adapt appropriately in more complex decisions, such as those in social contexts.

Section 2: Studies

1. The Genetics of Risk Aversion: A Systematic Review

International Journal of
Environmental Research and Public Health

MDPI

Review

The Genetics of Risk Aversion: A Systematic Review

Francisco Molins, Fatmanur Sahin and Miguel Ángel Serrano *

Department of Psychobiology, Universitat de València, Av. Blasco Ibáñez, 13, 46010 Valencia, Spain
* Correspondence: m.angel.serrano@uv.es

Abstract: Risk and loss aversion are phenomena with an important influence on decision-making, especially in economic contexts. At present, it remains unclear whether both are related, as well as whether they could have an emotional origin. The objective of this review, following the PRISMA statements, is to find consistencies in the genetic bases of risk and loss aversion with the aim of understanding their nature and shedding light on the above issues. A total of 23 empirical research met the inclusion criteria and were included from PubMed and ScienceDirect. All of them reported genetic measures from human samples and studied risk and loss aversion within an economic framework. The results for risk aversion, although with many limitations, attributed mainly to their heterogeneity and the lack of control in the studies, point to the implication of multiple polymorphisms related to the regulation of the serotonergic and dopaminergic pathways. In general, studies found the highest levels of risk aversion were associated with alleles that are linked to lower (higher) sensitivity or levels of dopamine (serotonin). For loss aversion, the scarcity of results prevents us from drawing clear conclusions, although the limited evidence seems to point in the same direction as for risk aversion. Therefore, it seems that risk aversion could have a stable genetical base which, in turn, is closely linked to emotions, but more research is needed to answer whether this phenomenon is related to loss aversion, as well as if the latter could also have an emotional origin. We also provide recommendations for future studies on genetics and economic behavior.

Keywords: risk aversion; loss aversion; genetics; polymorphism; decision-making; emotions; serotonin; dopamine

Citation: Molins, F.; Sahin, F.; Serrano, M.Á. The Genetics of Risk Aversion: A Systematic Review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14307. https://doi.org/10.3390/ijerph192114307

Academic Editor: Paul B. Tchounwou

Received: 7 September 2022
Accepted: 27 October 2022
Published: 2 November 2022

1. Introduction

According to classical economics, a rational decision-maker would follow the principle of optimization and should always choose the prospect (decision option) with the highest utility [1,2]. Mathematically, "the utility of a monetary gamble is a weighted average, where each possible outcome is weighted by its probability of occurrence" [3], p. 341. However, consider the following example: you must choose between prospect A, which offers an 85% chance to gain 1000 EUR (with a 15% chance to gain nothing), or prospect B: a certain chance of obtaining 800 EUR. In this example, prospect A would have a utility of 850 EUR ($0.85 \times 1000 + 0.15 \times 0$), while prospect B would have a utility of 800 EUR (1×800). Thus, a rational decision-maker should choose option A. However, it has been demonstrated that most people prefer the safe option despite its lower utility, thus avoiding the risky option [3]. This preference for a sure outcome over a gamble with higher or equal utility is called risk-aversion [3,4] and could constitute an anomaly regarding economic theory.

Bernoulli [5,6] provided a logical explanation whereby risk aversion could be saccommodated within the classical economics assumptions: people would not evaluate prospects based on the objective outcome, but on the subjective value of that outcome. Furthermore, Bernoulli [6] proposed that this subjective or expected utility follows a concave function, where the difference between the utilities of 200 EUR and 100 EUR is greater than the difference between the utilities of 1200 EUR and 1100 EUR. Therefore, the expected utility attached to a gain of 800 EUR would be higher than the expected utility of 1000 EUR with

a probability of 80%, even if both prospects had the same (mathematic) utility. Thus, risk aversion may still have a place as a rational behavior within the established framework. However, when Kahneman and Tversky [7] developed the prospect theory, they reported anomalies that could not be easily accounted for under rational assumption. They found that the tendency to be risk-averse is reversed, turning people into risk-seekers, when decisions are framed in terms of loss. This phenomenon was called framing effect [3,4,8] and is considered an anomaly since it violates one of the main axioms of rationality: the invariance axiom [3,9], whereby the preference between prospects should not depend on the way they are described [3,10].

An explanation to this anomaly is that human beings do not always act rationally nor follow the strategic decision-making proposed by the classical models [11]. Many of our decisions are fast and frugal, influenced by cognitive limitations and biases [1,9,12]. In this line, both risk aversion and framing effect could be built on the basis of a more basic, automatic, and emotional phenomenon [4,13]: the loss aversion bias [9,14]. In the words of Rabin and Thaler [4], p. 226, "loss aversion is the tendency to feel the pain of a loss more acutely than the pleasure of an equal-sized gain". This phenomenon could account for the framing effect, since people would not risk losing if they could choose a certain gain but would prefer to risk rather than accept a certain loss.

There is still a debate on these issues and many economists are trying to accommodate anomalies within the already established, orthodox model to demonstrate that their statements are valid. However, neuroscience is providing increasing evidence that, in fact, risk aversion, framing effect, and loss aversion are part of the same reality, sharing a neural bases and producing similar physiological responses [15–20]. Furthermore, such evidence would give strength to the argument that these phenomena are automatic and emotional in nature, rather than the result of thoughtful, planned thinking that fits into the rationality axioms. Thus, their neural bases are composed by structures such as the amygdala, insula or striatum [15,17], regions that constitute fundamental nodes in the salience network and the brain's reward system, which, in turn, are key to the production of emotional responses [21–25].

Moreover, risk aversion is not exempt from individual variability. This heterogeneity seems to depend on multiple factors such as age, gender or level of education, although these only predict a small fraction of the variance in risk-taking [26]. Multiple studies with twins (homozygous and heterozygous) have shown that risk aversion could depend between 20% [27,28] and almost 60% [29] on genetic variations. In fact, more specifically, studies such as Kuhnen & Chiao [30] have located some of these variations, indicating that certain polymorphisms, such as DRD4 or 5-HTTLPR, which are related, respectively to the differential expression of dopamine and serotonin receptors, are also associated with different levels of risk-taking. A polymorphism denotes that the same gene can take different forms or alleles, which will translate into different phenotypes or expressions of that gene. Depending on the form the gene takes, risk aversion is manifested to a greater or lesser extent. Moreover, it has been also found a relationship between the different alleles of the 5-HTTLPR or DRD2 (similar to DRD4) polymorphisms and the different levels of loss aversion [31,32]. As can be seen, these studies also point to the link between these phenomena, as well as to their emotional nature, given that serotonin and dopamine are the main neurotransmitters involved in processes of emotional regulation and response to threats and rewards [33–35]. However, most of these studies are recent and show heterogeneity in both methods and results.

The present study carries out a systematic review covering the published literature on genetics and risk aversion (including framing effect and loss aversion given their possibly close links), with the aim of clarifying the debate between the prospect theory and classical economics by shedding light on the question of whether risk aversion is a behavior that fits within the rationality assumptions or, on the contrary, has an emotional origin connected to loss aversion. Our first hypothesis (hypothesis 1) states that there would be a consistent genetic base for risk aversion. On the other hand, (hypothesis 2) states that risk aversion

and loss aversion would have a common genetic origin, with both phenomena being connected. Finally, (hypothesis 3) this origin would be related to our affective system.

2. Materials and Methods

A systematic review of the genetic bases of risk aversion (also including related phenomena: framing effect and loss aversion) has been carried out, following the guidelines of the PRISMA declaration [36] for the correct performance of systematic reviews. The elaboration phases will be detailed below (and see Figure 1).

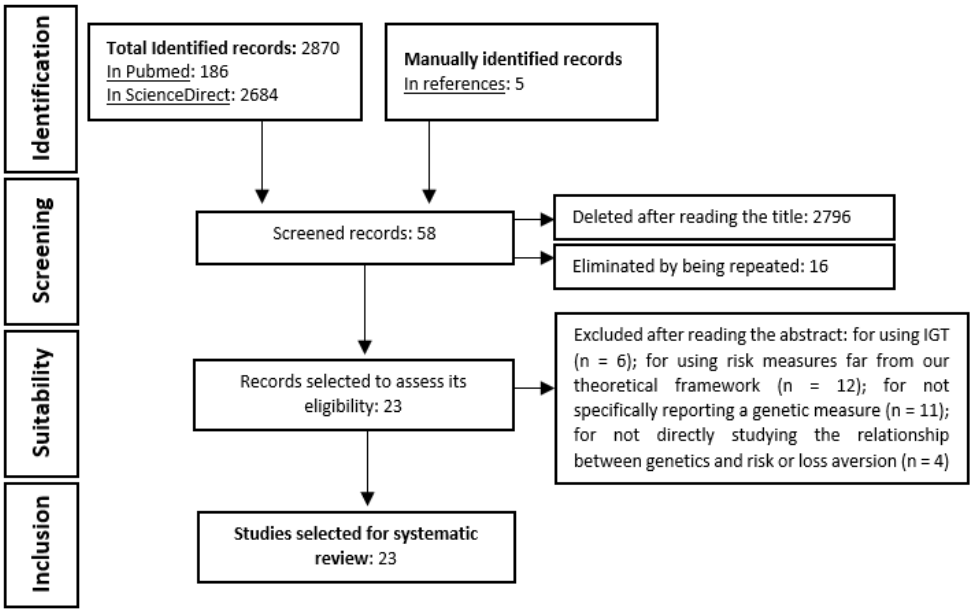


Figure 1. Revision flowchart.

2.1. First Searches

The first searches were conducted in November 2021. To obtain an overview of the available results, as well as to see which terms worked best, Boolean operators AND and OR were used, trying different combinations of the following terms: 'loss aversion', 'losses aversion', 'risk aversion', 'risk avoidance', 'risk seeking' 'risk taking', 'framing effect', 'genetic', 'genetics', 'genetic bases', 'gene', 'genes', and 'polymorphism'. These searches yielded a considerable number of results, many repeated or of little utility, but provided a preview and allowed for us to check that no previous review had been carried out on the topic. As the results of Scopus were the scarcest and did not provide any new studies, they was removed from the systematic search.

2.2. Systematic Search

The systematic search was conducted again in November 2021, in PubMed and ScienceDirect. The combination of terms that yielded the best results in both search engines was as follows: ((“loss aversion”) OR (“losses aversion”) OR (“risk aversion”) OR (“risk taking”) OR (“risk avoidance”) OR (“risk seeking”) OR (‘framing effect’)) AND (“genetic”). Specifically, 186 results were obtained in PubMed and 2684 in ScienceDirect. Before selecting articles, inclusion and exclusion criteria were defined.

2.2.1. Inclusion Criteria

- Empirical research and not revisions, single case studies, theoretical frameworks, books or manuals.
- That specifically and directly report genetic measures (e.g., how different alleles of a polymorphism are related to risk aversion levels).
- That use human samples.

- That study risk aversion, framing effect, and loss aversion understood within the economic framework.
- That measure risk aversion, framing effect, and loss aversion with economic tasks.

2.2.2. Exclusion Criteria

- Those that approach risk aversion, framing effect, or loss aversion from a far perspective from economics (e.g., risk taking related to sexual risk behavior, gambling disorder or substance abuse).
- Those who use non-economic tasks or use self-reports of risk preferences (i.e., questionnaires).
- Those that are studied in twins, or in terms of biological aspects, but do not report specific genetic measures.
- Those who study risk aversion with Iowa Gambling Task (IGT) [37]. As recently noted Lin et al. [38], the measure of risk inferred from this task is not as direct and is influenced by other factors, such as reward-learning or the sensitivity to feedbacks, which may make it difficult to interpret results in this review. In addition, IGT can be considered a decision-making measure in the face of ambiguity rather than risk, which is a different approach to this study [39].

According to the established criteria, and after only reading the title, 58 articles were considered as adequate (after eliminating sixteen duplicates between the two databases). The abstract was read and, from the identified group, 40 were discarded: for using IGT (n = 6), for using risk measures far from our theoretical framework (n = 12), for not specifically reporting a genetic measure (n = 11) and for not directly studying the relationship between genetics and risk aversion, framing effect, or loss aversion (n = 4). The remaining 18 articles comply with the criteria described above.

2.3. Manual Search

After an in-depth reading of the 18 selected studies and based on their references, five new articles that had not appeared in the databases were included. All referred to risk aversion (although three of them approached risk aversion trough the framing effect). Finally, Google Scholar was used with different combinations of the mentioned search terms to check whether any article could have been left out. These searches did not reveal any new relevant studies.

Finally, the systematic review includes a total of 23 empirical articles, all of them written in the English language. Nineteen referring to risk aversion; 2 to both risk aversion and loss aversion, and 3 only to the latter. In addition, most used gambling tasks, investment tasks or similar, with the exception of 4, which used the Balloon Analogue Risk Task (BART) [40], a task that is far from the others in terms of dynamics, but we decided to include it because it provides a direct indicator of risk-aversion that is comparable to the other tasks.

3. Results

The results are summarized in Tables 1 and 2: the first one for risk aversion (including framing effect) and the second one for loss aversion. This division was made to facilitate the comparison between both phenomena. The explanation of the results follows the same division. Moreover, the results within each block were organized based on the genetic measure used, with all those referring to the same measure being reported together (e.g., to the same polymorphism).

An article (only for risk aversion) [26], comprehensively addressed the possible association between more than 2 million single nucleotide polymorphisms (SNPs) extracted from the U.S. Health and Retirement Study (HRS), and the risk-aversion level, measured with hypothetical gambles on lifetime income, in a sample of 10,455 adults. The remaining articles included in the review dealt with more specific genetic measures, known as "candidate-gene" studies [41]. They studied specific genetic markers (one or several genes,

or regions thereof), since, based on prior knowledge of their biological functions, these could be related to the phenotype of interest (in this case, risk or loss aversion). Thus, we could compare whether the allele "x" that can adopt a gene, which, in turn, is related, for example, to higher serotonin levels, also implies a higher risk or loss aversion level with respect to the allele "y" of the same gene. Figure 2 was developed to facilitate reading.

Finally, to avoid over- or under-representing the role that an allele plays in the relationship between genes and risk or loss aversion, possible confusing variables must be controlled. Some examples could be a certain level of impulsiveness, a sensation-seeking personality or suffering from Reward Deficiency Syndrome (RDS). The health and behavioral profile of the participants was included in the results (see Tables 1 and 2). However, as can be noted, few articles considered these aspects beyond "including a healthy sample" (without psychopathologies, illness, and medication/drug consumption). Only two articles conducted a more exhaustive screening, but they did so when choosing the sample and did not control for these variables when contrasting the level of bias as a function of the gene alleles (e.g., covariating the level of impulsivity).

Table 1. Risk Aversion.

Authors	Sample	Genetical Measures	Health & Behavioral Profile	Risk Aversion Measures	Results
Crişan et al. [33]	32 participants (23 women, *M* = 26.75 years, *SD* = 6.69)	Genotyping for the 5-HTTLPR: s/s, s/l and l/l	Healthy volunteers *. s-carriers show higher anxiety trait. No other behavioral variables were reported	Risk-taking with BART; Framing effect with a gambling task	The s-carriers showed higher risk aversion and framing effect than l-homozygotes, without controlling for anxiety trait
Khunen and Chiao, [30]	65 participants (48 women, *M* = 22.4 years, *SD* = 4.9)	Genotyping for the 5-HTTLPR: s/s, s/l and l/l; and for the DRD4: 7R+ vs. 7R− allele	No health or behavioral variables were reported	Risk-taking with investment task	s/s homozygotes took less risk than s/l or l/l-; 7R+ carriers took more risk than 7R− carriers
Roe et al. [42]	67 participants (29 women, *M* = 20.6 years, *SD* = 3.2)	Genotyping for COMT Val^{158}Met: Met/Met, Met/Val and Val/Val	55 healthy volunteers * and 12 participants diagnosed with depression, bipolar disorder or another. No other behavioral variables were reported	Risk attitudes with a gambling task	Risk attitudes were not associated with COMT polymorphism. Analysis did not control for the pathological conditions
Roiser et al. [43]	30 participants	Genotyping for the 5-HTTLPR: s/s and l/l	Healthy volunteers *. Personality, impulsiveness and state-trait anxiety were not reported, but controlled in further analysis	Framing effect with a gambling task	The s/s genotype group exhibited a greater amygdala activity and framing effect while making choices than s/l or l/l genotype (controlling for behavioral and health variables)
Zhong et al. [44]	350 participants (188 women, *M* = 28.2, *SD* = 10.8)	Genotyping for the 5-HTTLPR: s/s, s/l and l/l; and for the DAT1: 9R vs. 10R allele	No health or behavioral variables were reported	Risk attitudes with multiple price list design	l-carriers of 5-HTTLPR tended to be (not significant) more risk-tolerant over losses than s-carriers; 9R carriers of DAT1 were more risk-tolerant over gains than 10R
Dreber et al. [18]	98 male participants (ranging from 18 to 23 years)	Genotyping for the DRD4: 7R+ vs. 7R− allele; and for the DRD2 Taq1a/ANKK1: A1+ vs. A1-	Healthy volunteers *. No other behavioral or health variables were reported	Risk preferences with an investment task	No associations were found between the A1+ carriers and risk preferences. 7R+ carriers were more risk loving than 7R−
Dreber et al. [45]	237 participants	Genotyping for the DRD4: 7R+ vs. 7R− allele	No health or behavioral variables were reported	Risk-taking in the card game bridge, and an investment task	7R+ men showed higher risk-taking in bridge and investment task than 7R−. No effects in women
Eisenegger et al. [46]	205 male participants (*M* = 23.5 years, *SD* = 3.6)	Genotyping for the DRD4: 7R+ vs. 7R− allele	Healthy volunteers *. No other behavioral or health variables were reported	Risk-taking with a gambling task	No relation between genotype and risk-taking was found directly, but 7R+ carriers showed an increased gambling propensity after dopaminergic stimulation
Frydman et al. [47]	83 male participants	Genotyping for the 5-HTTLPR: s/s, s/l and l/l; for the DRD4: 7R+ vs. 7R− allele; and for the MAOA: MAOA-H vs. MAOA-L	No health or behavioral variables were reported	Risk-taking with a gambling task	MAOA-L carriers were more likely to take financial risks. No differences among the 5-HTTLPR and DRD4 polymorphisms

Table 1. *Cont.*

Authors	Sample	Genetical Measures	Health & Behavioral Profile	Risk Aversion Measures	Results
Amstadter et al. [48]	223 children (44.4% female, *M* = 11.3 years)	Genotyping for the COMT Val^{158}Met: Met/Met, Met/Val and Val/Val	Healthy * volunteers. No other behavioral or health variables were reported	Risk-taking with BART	Females Met-carriers, but not males, showed higher risk taking compared to Val homozygotes
Dreber et al. [49]	135 participants (women 8%, median age was 43 years)	Genotyping for the DRD4: 7R+ vs. 7R− allele; and for MAOA gene: MAOA-H vs. MAOA-L	No health or behavioral variables were reported	Risk-taking with an investment task	No significant relations were found between genes and risk-taking
Heitland et al. [50]	60 females (*M* = 20.87 years, *SD* = 1.98)	Genotyping for the DAT1: 9R+ vs. 9R− allele; for the COMT Val^{158}Met: Met/Met, Met/Val and Val/Val; and for the 5-HTTLPR: s/s, s/l and l/l	Healthy volunteers *. No other behavioral or health variables were reported	Risk-taking with a gambling task	DAT1 9R+ allele showed a trend toward increased risk-taking following losses (no significant effect). Genotypes of COMT did not show any relation with risk-taking. 5-HTTLPR s-carriers showed decreased risk-taking following gains.
Mata et al. [51]	322 participants (234 women; *M* = 23.8 years, *SD* = 6.2)	Genotyping for the DAT1: 9R vs. 10R allele	Healthy volunteers *. No other behavioral or health variables were reported	Risk-taking with BART	10R allele showed increased risk-taking respect to 9R
Harrati, [26]	10,455 adults	Over 2.5 million Single Nucleotide Polymorphisms (SNPs) from respondents	No health or behavioral variables were reported	Risk aversion through responses to a series of hypothetical gambles on lifetime income from HRS	None of the single-nucleotide polymorphisms were found to be determinants of risk aversion
Anderson et al. [52]	174 participants	Genotyping for the 5-HTTLPR polymorphism: s/s, s/l and l/l; and for the DRD4 gene: 7R+ vs. 7R− allele	No health or behavioral variables were reported	Risk-taking with a multiple price listing	No significant correlations between the two genes and risk-taking
Gao et al. [53]	111 students (36% women, *M* = 21.78 years, *SD* = 61.92)	Genotyping for the COMT Val^{158}Met: Met/Met, Met/Val and Val/Val	Healthy volunteers *. No other behavioral or health variables were reported	Framing effect with a gambling task	The Met-carriers showed greater framing effect than Val/Val homozygotes and this was mediated by resting-connectivity between orbitofrontal cortex and bilateral amygdala
Gao et al. [42]	1582 students (80.1% women, *M* = 18.66 years, *SD* = 60.90)	Gene-based approach considering 26 genes from the serotoninergic and dopaminergic pathways	Healthy volunteers *. Normal range of depressive and anxiety symptoms. No other behavioral or health variables were reported	Framing effect with a gambling task	Genetic variations of the SLC6A4, the COMT and DDC genes were associated with the framing-effect
Wagels et al. [54]	105 male participants	Genotyping for the MAOA LPR: MAOA-S vs. MAOA-L	Healthy volunteers *. Anxiety and aggressiveness were not reported but controlled in further analysis. No other behavioral or health variables were reported	Risk-taking with BART	MAOA s-carriers showed less automatic harm avoidance, but no differences were found in BART. MAOA s-carriers were more risk-taking after testosterone administration. These results were found controlling for anxiety and aggressiveness
Muda et al. [55]	113 investors, *M* = 33.70 years, *SD* = 9.95 & 104 non-investors, *M* = 32.34, *SD* = 10.00)	Genotyping for the DRD4: 7R+ vs. 7R− allele	No health or behavioral variables were reported	Risk-taking with a gambling task	No differences in risk-taking between 7R+ and 7R− individuals
Neukam et al. [56]	577 participants	Genotyping for the 5-HTTLPR: s/s and l/l	Healthy volunteers *. No other behavioral or health variables were reported	Risk-taking with Value-based decision-making battery	s/s homozygotes were more risk-seeking for losses compared to s/l and l/l

M, mean; *SD*, standard deviation; BART, Balloon analogue risk task. * These participants were screened for no history of neuropsychiatric or chronic somatic conditions (including substance abuse disorder and pathological gambling) and no medication or drug consumption.

Table 2. Loss aversion.

Authors	Sample	Genetical Measures	Health & Behavioral Profile	Loss Aversion Measures	Results
He et al. [31]	572 participants (312 females, *M* = 20.47 years, *SD* = 1.01)	Genotyping for the 5-HTTLPR: s/s, s/l and l/l	Healthy volunteers *. No other behavioral or health variables were reported	Loss aversion with a mixed gamble task	s/s individuals had higher loss aversion and these effects were stronger for males than females
Ernst et al. [57]	66 adolescents	Genotyping for the 5-HTTLPR: s/s, s/l and l/l	27 participants with (only) anxiety disorder and 39 healthy *. No other behavioral or health variables were reported.	Loss aversion with a mixed gamble task	No differences between genotypes in healthy controls. Lower loss aversion in l/l anxious individuals. No effect in s/s anxious adolescents
Anderson et al. [52]	174 participants	Genotyping for the 5-HTTLPR: s/s, s/l and l/l; and for the DRD4: 7R+ vs. 7R− allele	No health or behavioral variables were reported	Loss aversion with hypothetical choices in a survey	No significant correlations between the two genes and loss aversion
Voigt et al. [32]	143 participants (114 females, *M* = 21.8 years, *SD* = 4.04)	Genotyping for the BDNF $Val^{66}Met$: Val/Val, Val/Met and Met/Met; and for the DRD2 Taq1a/ANKK1: A1A1, A1A2 and A2A2	No health or behavioral variables were reported	Loss aversion with a mixed gamble task	Significant interaction of the 2 polymorphisms: carriers of the genetic constellation Met+/A1+ show the lowest loss aversion
Neukam et al. [56]	611 participants	Genotyping for the 5-HTTLPR: s/s, s/l and l/l	Healthy volunteers *. No other behavioral or health variables were reported	Loss aversion with a mixed gamble task	No significant results were found

M, mean; *SD*, standard deviation; BART, Balloon analogue risk task. * These participants were screened for no history of neuropsychiatric or chronic somatic conditions (including substance abuse disorder and pathological gambling) and no medication or drug consumption.

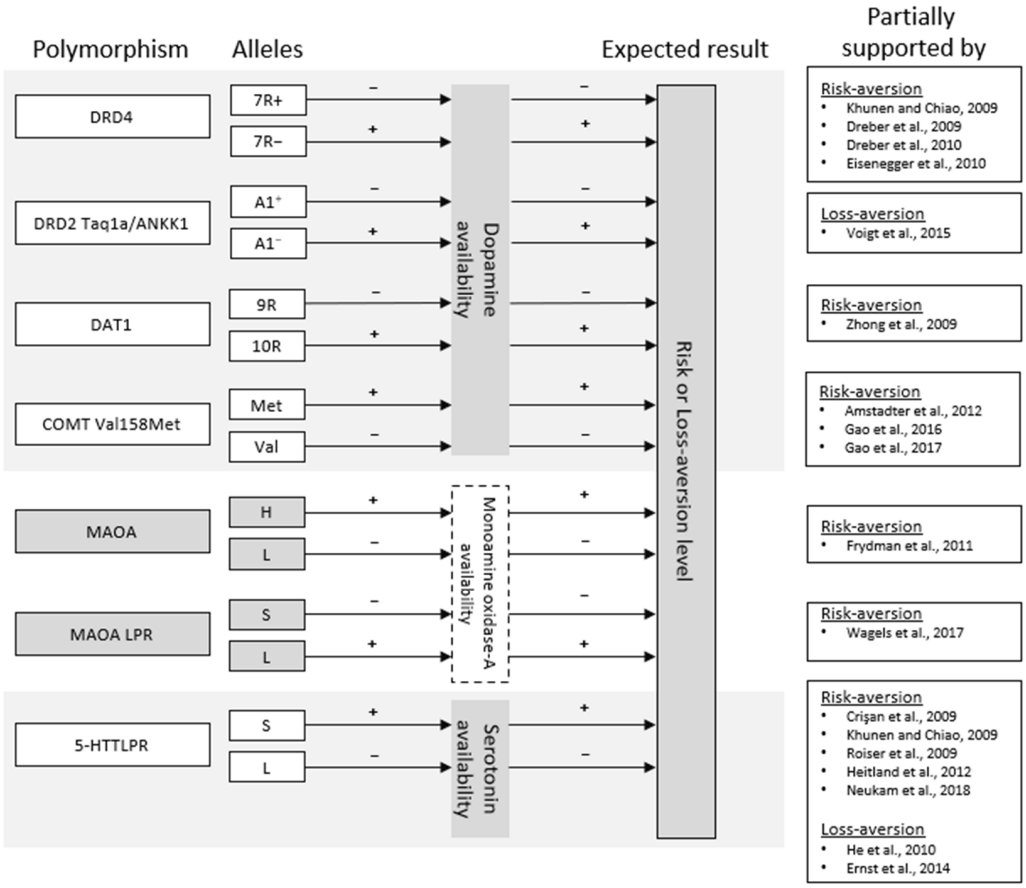


Figure 2. Scheme of the connection between the alleles of the different polymorphisms, the level of neurotransmission and the expected behavioral outcome (risk or loss aversion). On the right, the articles that support, at least partially, the expected result are shown, indicating if the support is found in risk or loss aversion.

3.1. Risk-Aversion

3.1.1. Single Nucleotide Polymorphisms

According to Harrati [26], none of the multiple SNPs included in the study revealed a significant causal effect on risk aversion, pointing to greater phenotype complexity, as well as their possible polygenic origin. No other measures of health or behavior were considered in the study.

3.1.2. SLC6A4 Candidate Gene

One of the most-studied candidate genes in relation to risk aversion was the SLC6A4, the only gene that encodes the serotonin transporters (5-HTT), responsible for the reuptake of serotonin from the synaptic cleft [33]. In the SLC6A4 regulatory region, there is a polymorphism, known as linked polymorphic region (5-HTTLPR). This involves an insertion or deletion of 44 nucleotide pairs (or 44-base pair), which may result in a short (s) or a long (l) allele. The transcriptional activity of 5-HTT will be modulated by the form this polymorphism takes. Thus, if the allele s is present, less 5-HTT will be expressed and its function will be reduced with respect to allele l, implying limited serotonin reuptake and greater serotonin availability in the synaptic cleft. Many studies that included in this review examined whether risk aversion varied with these alleles. In general, when analyzing the genotype for 5-HTTLPR, a distinction was made between homozygous individuals, whose two alleles are short or long (s/s or l/l), and heterozygous, with each allele in one form (s/l).

Genotyping 32 healthy participants (23 women), the study by Crişan et al. [33] found that those who carry even one s allele of 5-HTTLPR made fewer attempts to inflate the balloon at BART than homozygous l/l. That is, s-carriers showed greater risk aversion. However, s-carriers also showed a higher anxiety trait measured with STAI and EMAS. This trait was studied in parallel, but was not controlled to extract the above result.

A similar result can be seen in Heitland et al. [50], where s-carriers also had higher risk aversion, but only when they were in a gain context, using a gambling task. It should be noted that only healthy women participated in this study (n = 60).

With 65 participants (48 women), Kuhnen & Chiao [30] also showed similar results to Crişan et al. [33], this time using an investment task. However, here it was specified that only homozygous s/s, with respect to l/l or s/l, and not only those carrying a short allele, had a higher risk aversion.

Neukam et al. [56], with 577 healthy participants and an economic decision-making task, indicated the opposite result, reporting that s/s-carriers presented greater risk-seeking than s/l or l/l, but only in a loss context. No other significant result was found for the gain context.

Focusing specifically on framing effect, Roiser et al. [43] pointed out that, after genotyping 30 healthy participants and using a gambling task, homozygotes s/s showed the highest framing effect with respect to the s/l or l/l. That is, s/s-carriers risked significantly more in the loss contexts than in the gain contexts, a difference that was not observed with the s/l or l/l-carriers. The greater framing-effect was also accompanied by increased amygdalin activity. These results were extracted, controlling for personality traits, impulsiveness, and state-trait anxiety.

Turning again to Crişan et al. [33], with the same sample, but using a gambling task, the authors also studied framing effect. Again, it seems that the short allele favored a higher framing-effect; however, on this occasion, a homozygous genotype (s/s) did not seem necessary, and was enough to transport a single allele s.

On the other hand, in Frydman et al. [47], with a male sample (n = 83), using a gambling task; in Anderson et al. [52], with 174 inverters; or Zhong et al. [44] with 350 participants (188 women), using a multiple price list design (a task with a dynamic similar to a gambling task), no relationship was foud between the different alleles of 5-HTTLPR and the risk aversion measure. However, the latest study [49], reported that l-carriers

tended to tolerate risk better (less risk aversion) in the context of losses than s-carriers. None of these studies reported data on health or other behavioral aspects of the sample.

3.1.3. DRD4 Candidate Gene

The other candidate gene that, together with 5-HTTLPR, appeared more frequently in the articles of this review, was the dopamine receptor D4 gene (DRD4), involved in the regulation of the dopaminergic system [18]. There is a region in DRD4 where several repeats of a DNA base pairs sequence can appear. Each individual of the same species can present a different number of repetitions of this sequence, which is most frequent between 2 and 11 repetitions [49]. When the genotype for this gene is extracted, it is usually dichotomized. If both alleles of the gene have fewer than 7 repeats, it is assigned the term 7R−; if either allele has more than 7 repeats, then it is assigned 7R+. The presence of 7R+ is usually associated with a lower effectiveness in the receptor-ligand junction [18]; in other words, this means that the dopamine receptor needs more dopamine to produce the effect which, in the case of individuals with 7R−, would be achieved with less dopamine. Again, an attempt has been made to study whether this polymorphism can be related to different levels of risk aversion.

First, this gene appeared in the Kuhnen and Chiao study [30] mentioned in 5-HTTLPR. Thus, with the same sample of 65 participants (48 women) and using an investment task, it was observed that the 7R+ carriers assumed more risks (lower risk aversion) than the 7R− carriers.

On the other hand, Dreber et al. [18], found the same result using the same task (investment task), but including only healthy men in their sample (n = 98).

With a larger sample (237 participants) and again including women, but this time, not controlling for health or behavioral variables, Dreber et al. [49] used the same task again, and also added the card game bridge, similar to a gambling task, but with the more playful context of card games. Here, the same result found in previous studies was reported (lower risk aversion in 7R+ carriers), in both tasks, but only in men. Women showed no difference in risk aversion between 7R+ and 7R−.

The remaining articles referring to DRD4 found no differences in risk aversion depending on their alleles. Frydman et al. [47] included 83 male participants and used a gambling task. In Dreber et al. [45], 125 participants (8% women) were included, and an investment task was used. In Anderson et al. [52], 174 investors were included and a task similar to a gambling task was used. In Muda et al. [55], 113 investors and 104 non-investors were included and the Holt–Laury test was used. Finally, in Eisenegger et al. [46], 205 healthy male participants were included and a gambling task was used again. Although no study reported significant relationships between DRD4 and risk aversion, the latest study used a dopamine administration protocol to compare whether, after this, the alleles of DRD4 behaved differently. In this sense, the 7R+ carriers seemed to have a lower risk aversion than the 7R− after the administration of dopamine. Except for this last study, the other three did not even control for whether the participants were healthy.

3.1.4. ANKK1 Candidate-Gene

Another gene involved in the regulation of the dopaminergic system was the Ankyrin repeat and kinase domain containing 1 (ANKK1), linked to the gene of the dopaminergic receptor D2 (DRD2) and affecting the expression and functioning of this receptor [32]. ANKK1 has a polymorphism known as Taq1a, which can have two different forms on its alleles: A1 or A2. These give rise to three possible combinations: A1/A1, A1/A2 and A2/A2, although it is usually dichotomized in A1+ versus A1-, depending on whether the A1 allele is present or not. The A1 allele is usually associated with a less striatal D2/3 receptor-binding which, like DRD4, could indicate that more dopamine is required to produce proportional effects to those which, without this allele, would be produced with lower amounts of dopamine.

For risk aversion, only one study addressed this polymorphism. Dreber et al. [18], already mentioned in DRD4, with 98 healthy males and using an investment task, found no differences in risk aversion between the A1+ and A1- genotypes.

3.1.5. MAOA Candidate Gene

The next candidate gene was the MAOA gene that codes for the enzyme MAOA (monoamine oxidase-A). This enzyme is involved in the metabolism of serotonin and dopamine [49]. The MAOA gene also has a polymorphism. As in 5-HTTLPR, there is a base-pairs sequence that is repeated and in which, depending on the number of repetitions, the alleles are considered to be either low active (3 or 5 repetitions, MAOA-L) or highly active (3.5 or 4 repetitions, MAOA-H) [49]. MAOA-L is related to a lower transcriptional activity of the MAOA gene and, therefore, a lower amount of the MAOA enzyme. Both alleles were studied in relation to risk aversion.

Frydman et al. [47], with the sample and decisional task described above, found a relationship between the MAOA-L allele and a higher probability of assuming risks (lower risk aversion).

However, turning to Dreber et al. [49], the result was the absence of a relationship and differences between MAOA-L or MAOA-H and risk aversion.

In addition to the polymorphism described for MAOA, this gene may present another polymorphism in its promoter region, known as MAOA LPR (as in 5-HTTLPR, the acronym stands for linked polymorphic region). This depends on the number of repetitions of a sequence of 30 base pairs, which may result in the short (allele s) or long (allele l) version [54]. The allele s was related to the lower coding and effectiveness of the above MAOA.

In relation to this polymorphism, Wagels et al. [54] studied risk-taking in 105 healthy male participants using BART. They found that MAOA s-carriers did not differ from MAOA l-carriers in assuming risks in this task; however, they showed greater latency times when avoiding risk. These results were found to measure and control for anxiety and aggressiveness traits.

3.1.6. SLC6A3 Candidate-Gene

Other candidate-gene was SLC6A3, which participates in dopaminergic pathways by encoding dopamine transporters (DAT), and which, as in SLC6A4 (for 5-HTT), shows a polymorphism known as DAT1, depending on the number of repetitions of a sequence of 44 base pairs. Although these repetitions can oscillate between 3 and 13 times, the most common is to find 9 or 10 repetitions [51]. Thus, we speak of allele 9R and 10R or, depending on the presence or absence of allele 9R: 9R+ and 9R−. The 9R allele is associated with a lower expression of DAT in the striatum compared to the 10R allele, which translates into greater availability of dopamine in the synaptic clefts of this region [53].

The study of Mata et al. [51], with 322 healthy participants (234 women), and using BART, found that those genotypes that present at least one 10R allele made more attempts to inflate the balloon, implying lower risk aversion, compared to homozygous for 9R.

On the other hand, Heitland et al. [50], also studied, using the same task (a gambling task), the relationship between risk aversion and DAT1. The authors reported the absence of a relationship between any of the alleles of DAT1 and the attitude towards risk.

Finally, the study by Zhong et al. [44] included the DAT1 polymorphism approach. However, here, the authors maintained a different theoretical approach, affirming that it was the 9R allele (and not the 10R), which would imply a lower level of dopamine in the striatal synapses. Thus, when studying how this polymorphism influenced risk-aversion, they reported a relationship between the 9R−carriers and lower risk aversion levels.

3.1.7. COMT Candidate-Gene

Another candidate gene that also appeared with some frequency is the Catechol-o-methyltransferase (COMT) gene that encodes the COMT enzyme, one of the main ones responsible for the degradation of dopamine. This gene presents a polymorphism (COMT

Val158Met) in a specific base-pair where, depending on whether guanine or adenine is present, the gene will contain valine (Val) or methionine (Met), respectively [54]. Thus, homozygous (Met/Met or Val/Val) or heterozygous (Met/Val) genotypes may occur. Met alleles are usually associated with lower COMT activity and, therefore, lower dopamine degradation; in other words, higher dopamine availability, especially in the prefrontal cortex [56].

In the study by Gao et al. [42], employing a sample of 111 healthy students (36% female) and focusing on framing effect with a gambling task, they found that those genotypes that carried at least one Met allele were predisposed to assume more risks in loss contexts than in gain contexts; that is, a greater framing effect with respect to homozygous for the allele Val. Furthermore, this relationship between genes and bias seemed to be mediated by resting-state functional connectivity between orbitofrontal cortex and bilateral amygdala.

However, in both Heitland et al. [50], as described when talking about 5-HTTLPR and DAT1, and the study by Roe et al. [58], which used a gambling task to measure the attitude towards risk in 67 participants (29 women), no relationship was found between COMT Val158Met polymorphism and the different risk-aversion levels. In the last study sample, most were healthy volunteers (n = 55); however, 12 participants diagnosed with depression and bipolar disorder were also included. These participants were not monitored when the results were extracted.

Finally, Amstadter et al. [48], with a sample of 223 healthy children (44.4% female) and using BART, reported a result that could be contradictory to that of Gao et al. [42]. Here, it was shown how the Met allele was associated with lower risk aversion compared to homozygous for the Val allele; however, this result only occurred in women, and was not found in relationships in men, suggesting that the effect of sex could act as a modulator.

3.1.8. Multiple Candidate Genes at Once

Gao et al. [53] addressed framing effect with a mid-way approach between candidate-genes and the comprehensive study of SNPs. Here, the possible relationship between framing effect and multiple polymorphisms (of 26 different genes) was widely studied, but all of them can be considered candidate genes because of their influence on dopaminergic and serotonergic pathways, which, as we have seen in previous studies, seem to be involved in the differential expression of risk aversion and framing effect. These polymorphisms included all those mentioned above (except DRD4) and other new ones, such as the vesicular monoamine transporter (VMAT2), tryptophan 5-hydroxylase (TPH 1 and TPH2) or tyrosine hydroxylase (TH), among others. The sample comprised 1582 healthy students (80.1% women) and the task used to measure the framing-effect was a classic gambling task adapted to a pencil-and-paper format to collect a larger sample. In a broad way, the analyses carried out by Gao et al. [53] revealed that the genetic variations in the genes SLC6A4 and COMT, related, respectively, to the serotonergic and dopaminergic pathways, influenced individual differences in framing effect. In addition, the importance of the DDC gene (aromatic-L-amino-acid decarboxylase), involved in the two routes mentioned above, was also highlighted.

3.2. Loss-Aversion

The results found in the scientific literature for loss aversion were very scarce in relation to risk aversion (only five articles). All of them focused on candidate-gene polymorphisms that appeared in the previous block, except one. The most repeated (in 4 of the 5 articles) was 5-HTTLPR polymorphism (see previous section for an explanation).

5-HTTLPR was addressed for loss aversion in two of the studies already mentioned for risk aversion: Anderson et al. [52] y Neukam et al. [56] (see previous section for details of the sample). The first study measured loss aversion with a survey that raised hypothetical choices, in line with a typical mixed gamble task, and the second study used the latter task. However, no relationship between loss-aversion and any of the alleles of 5-HTTLPR (s or l, both homozygous and heterozygous) was found.

Something similar occurred in Ernst et al. [57], who used a mixed gamble task to study loss aversion in a sample of 66 adolescents, of whom 27 had an anxiety disorder. Therefore, the control group of healthy adolescents did not show any difference in loss aversion according to their genotype. However, something different occurred when we focus on patients with anxiety, showing the lowest level of loss aversion by those who were homozygous for allele l. No differences were found with respect to the control group for homozygous s/s.

On the other hand, the study by He et al. [31], also using a mixed gamble in a sample of 572 healthy participants (312 women), found differences between the alleles for loss aversion. Specifically, homozygous s/s had greater loss aversion than s/l or l/l. In addition, these effects were more clear in men than in women (although they were statistically significant in both sexes).

Another polymorphism that was addressed, although only in one study, was DRD4 (see more details in the risk-aversion section). Specifically, this was included in the aforementioned study by Anderson et al. [52], which suggested that different alleles of DRD4 (7R+ and 7R−) were not related to loss aversion.

The latest study included in the review was Voigt et al. [32], who focused on the relationship between loss aversion, measured with a mixed gamble and a sample of 143 participants (114 women) and two polymorphisms. The first, DRD2, was already explained in the risk aversion section; the second was BDNF Val66Met. This is found in the BDNF gene that encodes for the brain-derived neurotrophic factor (BDNF). As with the polymorphism COMT Val158Met, two genetic variants can be presented, Val and Met, depending on whether it contains valine or methionine. Again, the Met allele is associated with a lower effectiveness; in this case, in the production of BDNF [32]. Each of these polymorphisms separately (DRD2 and BDNF Val158Met) did not present significant effects on loss aversion; however, when its interaction was studied, it was found that those who have at least one Met allele in BDNF Val158Met and one A1 allele in DRD2 in their genotype displayed the lowest level of loss aversion.

4. Discussion

The main objective of this review was to synthesize the genetic bases available in the scientific literature on risk aversion and close-related phenomena: framing effect and loss aversion. Although the results are not exempt from nuances and limitations, they pointed towards a series of genetic polymorphisms, all of them involved in dopaminergic and serotonergic neurotransmission pathways and which, depending on the alleles they acquired, seem to modulate the above-mentioned behaviors. This is especially remarkable for risk aversion where, although the results are heterogeneous, there was a considerable amount of them, making it possible to more clearly show the implication of these polymorphisms in risk-taking. It is more difficult to draw conclusions with loss aversion because the results are heterogeneous, but also scarce (only five articles). This leads us to doubt whether the evidence found for this phenomenon is spurious or whether it really constitutes a good beginning to glimpse how loss aversion is modulated by genetic bases. Therefore, it is difficult to discuss if both phenomena are related and share genetic bases. Nonetheless, there are signs that make us think that this relationship could occur and that, with more research that addresses risk and loss aversion, this could be evidenced in a more robust way. In the following sections, we discuss the results for risk and loss aversion separately and in more detail.

4.1. Risk Aversion

4.1.1. Risk Aversion and Dopaminergic Pathways

Starting with risk aversion and its relationship with dopaminergic pathways, we found the involved polymorphisms DRD4, MAOA, MAOA LPR, DAT1 and COMT Val^{158}Met. All of them affect the level of dopamine that is available or the degree to which this neurotransmitter is able to act on the synaptic connections of the dopaminergic pathways,

and especially on the striatum and the prefrontal cortex [55,59,60]. According to the results, many indicated that those alleles of the different polymorphisms whose presence translates into a lower level of dopamine or its decreased effectiveness of binding with receptors are associated with the lowest level of risk aversion. Thus, 7R+ allele carriers of DRD4 polymorphism, which tend to present some resistance in the dopamine-receptor binding [18], show the lowest risk aversion according to Kuhnen & Chiao [30]. The same was pointed out by Dreber et al. [18], although only in healthy men, highlighting the importance of gender differences when dealing with this phenomenon, something that has been pointed out in other behavioral studies, where men seem more likely to assume risks than women [61,62]. Lower risk aversion was also related to the low-active allele of MAOA [47] and the short allele of MAOA LPR [54], which, in turn, are related to the lower encoding and activity of the MAOA enzyme. This enzyme is one of the main contributors to dopamine metabolism [49]. Regarding MAOA LPR, it must be noted that behavioral differences between alleles were not found in risk-taking per se, but, more indirectly, in latency and delaying more in avoiding risk, which would indicate less risk aversion automatism. On the other hand, the 10R allele of DAT1 polymorphism, associated with the higher expression of dopamine transporters in the striatum, capable of recapturing this neurotransmitter and reducing the levels available in the synapse [51], was also related to lower risk aversion [51]. The same was observed in Zhong et al. [29], with the highest level of dopamine transporters associated with the lowest risk aversion. However, in this study, it was considered that it is the 9Rs (and not the 10Rs) which presents the highest level of transporters. This discrepancy may be due to the fact that, although it seems that 9R allele is associated with the greater final dopamine availability, there was a debate about the polymorphism, and studies could be found that defend both the first relationship and the second one, and even the non-relationship between the alleles of DAT1 and the levels of dopamine [51]. Despite this, the most important is that the lowest levels of dopamine in the synaptic cleft would be those reporting the lowest risk aversion, irrespective of whether it is caused by the 9R allele or the 10R allele. Finally, in relation to the COMT Val^{158}Met, the Val allele was associated with lower dopamine levels due to the higher activity of the COMT enzyme, which is involved in the degradation of the neurotransmitter [42]. Thus, the carriers of this allele showed a reduced framing effect, which, in turn, could be explained as a smaller difference between risk-taking in loss contexts versus gain contexts due to the reduction in risk aversion in the latter context. Gao et al. [42] found that this relation between polymorphism and framing effect was mediated by the resting-state functional connectivity between orbitofrontal cortex and bilateral amygdala.

To date, we have highlighted only the studies that pointed to the same direction, but it is also possible to find several studies that found no relationship between each of the mentioned polymorphisms and risk aversion (for DRD4: [46,47,49,52,55]; for MAOA: [49], and for DAT1 and COMT Val^{158}Met: [42]), as well as Amstadter et al. [48], which could even contradict the previous relationship reported for COMT polymorphism Val^{158}Met. Finally, there was also a study [18] that investigated another polymorphism that is not mentioned above, DRD2, which affects the expression of the dopaminergic receptor D2, although no relationship with risk aversion was found. These inconsistencies could be due to several limitations. Most of the studies included in the review did not consider that the relationship between genes and risk aversion should consider all those phenotypes that could somehow influence this relationship. Thus, they tried to directly analyze whether having one allele or another presented different levels of risk aversion, but very few controlled whether other variables that could moderate or mediate this relationship. We have already seen how, for example, sex can be important. Other specific factors, such as suffering from a mental disorder (especially those linked to the reward system, e.g., RDS), age or personality, among many others, can also be important. Unfortunately, most of the studies (even those whose results were in the same direction) only considered the selection of a healthy sample without a history of pathologies and diseases and without the use of medication or drugs. In fact, some did not even specify that this selection was made [29,30,45,47,49,52,55] or,

worse, they specified that their sample included some participants with disorders but did not address their influence on the analyses (e.g., [58]). Only one study [54] measured impulsivity and aggressiveness traits and controlled for them as possible confounding variables in the extraction of their results. Additionally, the specific characteristics of the tasks used may be relevant and should be considered in further studies. A gamble where, for example, you can gain vs. gain a lower amount is not the same as a gamble where you can gain vs. lose. In the absence of homogeneous contexts, results should be viewed with caution.

Given these limitations, it is difficult to know whether the relationship that the studies shown between genes and risk aversion really exists or was influenced by uncontrolled factors. However, this relationship would find theoretical support if we consider the known implication of dopamine in the brain reward system [34,35] and the connection that this system has with risk aversion. The dopaminergic pathways arise from the brainstem, from the ventral tegmental area (VTA) and the substantia nigra, and project towards various brain regions, mainly the prefrontal cortex and the striatum complex [63]. More specifically, the tegmental–ventral route, which runs from VTA to the ventral region of the striatum, and especially to the nucleus accumbens, seems to be the most important in relation to the processing of rewards [18,64]. Receiving a reward or anticipating it would increase dopamine levels in this pathway, which translates into increased physiological activation and the sensation of pleasure [65]. This dopamine elevation is reinforcing and is associated with approach behaviors [18], increasing the probabilities of performing the behavior that generates the neurotransmitter elevation. Given that the anticipation of an economic gain in a bet can produce such an increase, the more rewarding the profit is perceived to be and, therefore, the greater this increase, the more likely to assume risk in the bet [18,55]. In this line, those people who start from lower levels of dopamine or who are less sensitive to it (e.g., because they are carriers of some of the alleles that favor these effects, such as the 7R of DRD4 or 9R in DAT1), will require more intense stimulation to obtain the same pleasant effect that the rest of people would obtain with less stimulation [55].

This may explain the increased risk-taking associated with different alleles that, in one way or another, decrease the effects of dopamine. In fact, studies with rats show that those with higher levels of dopamine transporters show more impulsivity towards small rewards [66] or in humans, for example, the 7R+ allele of DRD4 has been linked to various risk behaviors such as alcoholism [67], impulsivity [68], sexual promiscuity and even infidelities [69]. Complementary evidence would come from neuroimaging studies searching for the neural bases of risk-taking, finding a positive correlation between the activity of the ventral striatum and the nucleus accumbens and the size of the possible reward [70,71] or those studies that specifically explore the bases of risk-aversion and also highlight the role of the ventral striatum in the search for reward, in interaction with the anterior cingulate cortex (ACC) and the inferior frontal gyrus, which seem to be activated proportionally to the risk that the situation entails [17]. As we can see, the mentioned regions are involved in dopaminergic pathways, reinforcing their involvement in risk aversion.

4.1.2. Risk Aversion and Serotoninergic Pathways

On the other hand, the relationship between risk aversion and the serotonergic system must be considered. Here, we found three polymorphisms to be involved, the previously mentioned MAOA and MAOA LPR (since the enzyme MAOA is also involved in the metabolism of serotonin in addition to dopamine) and the 5-HTTLPR polymorphism. Regarding MAOA, the results were scarce and have already been discussed when talking about dopaminergic pathways. Thus, the main evidence for the involvement of serotonergic pathways in risk-aversion comes from studies focusing on 5-HTTLPR. In general, the short allele of this polymorphism is related to the lower transcription or lower activity of the serotonin transporters. As a result, serotonin transporters re-uptake less neurotransmitter, which leads to the higher availability of the neurotransmitter in the synapses [33].

Most studies suggest that the higher levels of serotonin linked to the short allele were associated with higher levels of risk aversion and susceptibility to framing effect, as indicated by Crişan et al. [33]. However, this relationship was not free of nuances either. As Heitland et al. [50] noted, the association between the short allele and the largest risk aversion was only in the gain contexts and not in loss contexts. This could be explained by the framing effect itself, given that, in loss contexts it would be more common to find risk-seeking and perhaps more difficult to find differences between the short and the long allele. However, the study was only conducted with women, which may reflect sex differences that explain this finding. Kuhnen & Chiao [30] pointed out that it was not enough to carry the short allele, but it was necessary to be homozygous s/s (two short alleles) to show greater risk aversion in both gain and loss contexts. Or Roiser et al. [43], who pointed out to the same need (to be homozygous), but this time to show greater susceptibility to framing effect, accompanied by increased amygdalin activity. It should be noted that there were also three studies that found no relationship between the alleles of 5-HTTLPR and risk aversion [44,47,52], and one [56], which could indicate an opposite result, reporting that s/s carriers show more risk-seeking, although only in contexts of loss, which could perhaps be explained by the framing-effect. Again, these inconsistencies may be due to the same reasons as those stated above. From the studies addressing 5-HTTLPR polymorphism, only four [33,43,50,56] ensured that a sample selection was free of disorders or conditions that might confound the results and only two [33,43] addressed other potentially influential factors, such as personality traits, anxiety, or impulsivity. However, only one [43] actually took these factors into account and controlled for them in the analyses when extracting results.

As in the dopaminergic pathway, these limitations make it difficult to draw firm conclusions; however, it seems evident that the serotonergic pathway and the genes that regulate it are somehow involved in the risk-aversion phenomenon. Some previous examples, but not including the genetic part, also suggest this: it seems that the elevated levels of serotonin after the administration of its precursor (tryptophan) or inhibitors of its transporters, facilitate the recognition of threatening faces in humans [72,73], and the acquisition of a conditioned fear in rats [74]; however, the depletion of tryptophan impairs the recognition of threatening faces [75] and the distinction between gain and loss contexts when making decisions [76]. Again, this would make sense if we consider that serotonin is a key neurotransmitter in the regulation of emotional processes [33] and that risk aversion seems to be closely related to, or at least influenced by, the emotions [9]. In fact, positive correlations have been found between negative emotions such as fear, anger or sadness and the level of risk aversion [60,77]. In addition, ACC, one of the neural bases of risk aversion [17], has been highlighted as an important region in emotional processing [78,79], which can modulate amygdala activity [80] and serve as a connection between the limbic system and the prefrontal cortex [81]. Finally, Shiv et al. [82] showed that patients with lesions in regions such as the amygdala or insula, which are closely related to emotions, showed less risk aversion than other patients with injuries in other regions not related to emotions or healthy controls. All this leads us to think that, if certain genes influence the availability of serotonin in the brain and this, in turn, can influence the brain's own activity (in this case, conditioning the capacity for emotional processing and regulation), behaviors such as risk aversion, which depend, at least partially, on this activity, would ultimately be affected.

The connection between genes and behavior does not seem to be direct but moderated by the final availability of neurotransmitters and by the resulting neural activity. However, most studies included in this review were looking for the relationship between genes and behavior-skipping intermediaries. This can be an important source of heterogeneity in the results, since there would be many factors (e.g., sex, age, or stress, among others), and not only carried a gene allele, which can influence the levels of neurotransmission and neural activity. Only two articles [44,54] studied genetics in parallel with the neural activity, holding that the relationship between polymorphisms and risk-aversion was mediated by

the activation of certain regions, such as the amygdala or the orbitofrontal cortex. It would be interesting to use a similar approach in the future to better address the complexity of these relationships.

Based on the above, we could conclude that risk aversion is closely linked to emotions. The genes highlighted in our review are those that directly impact on dopaminergic and serotonergic neurotransmission, pathways that are intimately linked to emotion expression and regulation. Therefore, our results support a relative implication of the dopaminergic and serotonergic neurotransmission pathways in risk-aversion. Further research addressing the modulating or mediating role of other possible confounding variables is needed. In addition, future studies will also need to consider the emotional nature of risk aversion and how it may affect even more complex economic behaviors. For example, the recent study by Liu et al. [83] assesses how to resolve difficulties in carrying out crowdfunding projects when the context is adverse, such as that arising from the COVID-19 pandemic, and points to the importance of eliminating participants' distrust and concerns. Knowing that risk aversion has an emotional origin, it could be addressed through affective regulation programs that promote more rational decision-making and facilitate people's involvement in such projects. Similarly, risk aversion should be considered when analyzing other macroeconomic aspects, such as the reduction of a country's debt [84] or the digitalization of currency [85], as these macroeconomic processes involve microeconomic behaviors, carried out by people who, in turn, are affected by emotional phenomena such as risk aversion.

4.2. Loss Aversion

Although loss aversion has been one of the most studied phenomena in social sciences since it was described, articles investigating its genetic basis were scarce, with only five studies being found, which presented a high heterogeneity.

Regarding serotonergic pathways, 5-HTTLPR polymorphism was addressed in four studies. In He et al. [31], homozygous for s/s (but not s/l or l/l carriers), presented greater loss aversion, in line with what occurred with risk aversion. However, in Anderson et al. [32], Neukam et al. [56] and Ernst et al. [57], this relationship was not confirmed. The latter also included a group of patients with anxiety disorder in which being homozygous for allele l/l was associated with lower levels of loss aversion, evidence that could be complementary to that of the study by He et al. [31]. This result again emphasizes how important is to avoid studying the relationship between polymorphisms and behavior in isolation from other aspects. The assessment of contextual and organic aspects, as in this case, the presence of pathologies or age, seems to be crucial. As with gender differences, these factors could modulate the relationship between genes and behavior [57], for example, by altering neurotransmission levels in other ways. In fact, following this example, there is also a relationship between anxiety and the genes that influence the serotonergic system [58,86]. Given that the polymorphisms seem to influence behaviors such as loss aversion through their influence on neurotransmission pathways, it is important to address the variables that also influence these pathways. This consideration would be extended to risk aversion. We can turn again to the study by Eisenegger et al. [46], where a priori relations between DRD4 polymorphism and risk aversion were not found, but manifested after the administration of a dopamine dose.

On the other hand, with regard to the dopaminergic pathways and loss aversion, only DRD4 and DRD2 polymorphisms were studied and none of their alleles were related to the level of loss aversion [32,52]. However, when DRD2 was studied in interaction with another polymorphism, BDNF $Val^{66}Met$, it shown remarkable results [32]. Specifically, the A1 allele of DRD2, which is associated with a lower dopamine-receptor junction, was related to the lower level of loss aversion. This is like what we described in risk aversion, where lower sensitivity to dopamine led to more risks, but only when it was combined with the Met allele of BDNF $Val^{66}Met$, associated with lower BDNF production [32]. This reaffirms the complexity of the relationship between genetics and behavior, as well as

the need of not studying polymorphisms in isolation. As Harrati [26] and Gao et al. [53] argued, studying polymorphisms in candidate genes constitutes an advantage with respect to the study of SNPs, given that this poses "handfuls rather than millions of statistical significance tests at stake, so much weaker associations can be found to pass thresholds for statistical significance" [26], p. 187. However, when complex behaviors such as risk or loss aversion are involved, they are most likely related to multiple genetic variants at the same time [41,53] and studying just one polymorphism may not be enough. The study by Gao et al. [53] followed a similar approach to that of Harrati [26], where millions of SNPs were taken and their relationship with behavior was analyzed (without showing significant results); however, on this occasion, addressing multiple polymorphisms and not SNPs. Specifically, the study analyzed polymorphisms of 26 different genes, and thus could approach a behavior from a broader genetic approach and overcome many of the limitations that the rest of the studies presented. With this approach, Gao et al. [53] pointed out that genes such as SLC6A4, COMT and DDC, which are involved in the serotonergic and dopaminergic pathways, would partially explain the individual differences in framing effect. However, approaches such as this have not been found to date in studies of loss aversion.

As we can see, the results for loss aversion were scarce and heterogeneous, so it is difficult to draw a conclusion about its possible genetic basis or its relationship to risk aversion. This leads us to think that it may be too early to answer this question and more research is needed. Nevertheless, the scarce evidence subtly points, as in risk aversion, to the implication of genes involved in dopaminergic and serotoninergic neurotransmission. Previously, loss aversion had also been linked to these pathways, since its neural basis indicates the involvement, again, of the brain's emotional system [15], with the amygdala, the insula, the ACC, the striatum and the prefrontal cortex being the main regions involved. In addition, some studies addressed how different emotional regulation strategies were able to reduce loss aversion [13,87], how patients with injuries in regions typically identified as emotional lacked this bias [88], or how, certain factors such as unpleasant odors, which are capable of inducing a negative emotional state, increased loss aversion [89]. This suggests that if more studies were carried out in the genetic field, the implication of a solid genetic bases, probably related to the dopaminergic and serotoninergic pathways, could be found. With this, the relationship between risk aversion and loss aversion could be more clearly demonstrated in the future.

4.3. Limitations and Future Research

As we have seen, our review is influenced by several limitations. Thus, part of the heterogeneity found in the results could derive from methodological aspects. For risk aversion, although we have limited the inclusion of studies to a specific type of tasks (investment task, gambling task and BART), these can still present variability: changing the amounts at stake, waiting times, and the way in which bets are presented, among other differences. Likewise, there is also debate about whether to measure risk-taking with tasks or with questionnaires, "ask or task". Questionnaires provide more stable measures (and probably more linked to genetics), while tasks seem to be more affected by contextual aspects at the time of the experiment [90]. Additionally, since its origin, risk aversion has been studied using similar tasks (gambling tasks), but some involved the possibility of losing and others did not. Thus, some contrast safe gains with the risk of (if heads) winning more or (if tails) losing (e.g., [30]), but others contrast safe gains against the risk of (if heads) winning more or (if tails) winning less than the safe gain (e.g., [91]). The former involves risk of loss and, although they are commonly used to measure risk aversion, it is difficult to determine whether their measurement does not rather reflect the level of loss aversion. Unfortunately, most gambling tasks used in this review included the possibility of losing in their protocols. This is another important limitation that prevents us from knowing if the similarity between the results found in risk and loss aversion comes from the

common origin of these biases or because the tasks used measure all loss aversion and not risk aversion.

Another important source of heterogeneity could come from the samples used. Thus, as previously mentioned, it is important (both in risk and loss aversion) to focus on homogeneous samples and to deal more specifically with all the possible factors that could mediate or modulate the genes–behavior relationship, an aspect that most of the studies lacked. This is a key point and, because of this, it is difficult to determine whether current results are valid or may be subject to uncontrolled factors. In addition, many sample sizes did not exceed one hundred participants (e.g., [33,43]), making it difficult to obtain firm results given the small size of the effect associated with each polymorphism separately [41,53].

Finally, as can be seen from the heterogeneity of the results, and given that they have been published in journals from very different areas (e.g., economics or biology), the results do not seem to be particularly affected by the publication bias that favors the publication of positive results. However, given that our approach to risk and loss aversion is framed in the economic field, we must warn of the presence of a specific bias stemming from this.

In order to overcome the present limitations of this review, and improve the quality of future studies, they should follow these recommendations:

1. In line with Gao et al. [53], since risk and loss aversion are complex behaviors, studies should address multiple candidate genes at once. In addition, they should be open to testing other genes outside the dopaminergic and serotonergic pathways to avoid confirmation bias.
2. Sufficient samples should be included to ensure that the multiple contrasts required have adequate power. More samples imply more effort, but only then will the studies be valuable.
3. It is necessary to control all possible confusing variables that could alter the genes–behavior relationship. Other behavioral and health measurements should be provided, but it would also be useful to rely on neuroimaging techniques and other means to measure or infer the level of neurotransmitters that is available.
4. It should be checked whether the relationship between genes and risk aversion is affected depending on whether tasks or questionnaires are used.
5. To discriminate between risk and loss aversion, it would be advisable to use only tasks whose risk does not include losses.

5. Conclusions

As far as risk aversion is concerned, the studies are heterogeneous, but most of them highlight the polymorphisms involved in dopaminergic and serotonergic neurotransmission pathways. These polymorphisms are related to higher or lower levels of risk aversion depending on the allele they adopt. This supports previous evidence connecting risk aversion to emotions, since the latter are intimately linked to these dopaminergic and serotoninergic pathways. On the other hand, regarding loss aversion, it is too early to draw conclusions and this review should only be taken as a starting point for future studies investigating the genetic basis of loss aversion and its connection with risk aversion. Those studies should follow the recommendations provided in this study to avoid falling back into the same limitations that prevent us from shedding more light on this study field. Whether risk aversion and loss aversion share a common emotional origin is a question that needs to be answered with further research.

Author Contributions: Conceptualization, M.Á.S. and F.M.; methodology, F.M. and F.S.; data curation, F.M. and F.S.; writing—original draft preparation, F.M. and F.S.; writing—review and editing, F.M. and M.Á.S.; supervision, M.Á.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Thaler, R.H. Behavioral economics: Past, present, and future. *Rev. Econ. Inst.* **2018**, *20*, 9–43. [CrossRef]
2. Morgan, M.S. Economic Man as Model Man: Ideal Types, Idealization and Caricatures. *Camb. Rev. Int. Aff.* **2006**, *28*, 1–27. [CrossRef]
3. Kahneman, D.; Tversky, A. Choices, Values, and Frames. *Am. Psychol.* **1984**, *39*, 341–350. [CrossRef]
4. Rabin, M.; Thaler, R.H. Anomalies, Risk Aversion. *J. Econ. Perspect.* **2001**, *15*, 219–232. [CrossRef]
5. Bernoulli, D. Specimen theoriae novae de mensura sortis. *Comment. Acad. Sci. Imp. Petropolitanae* **1738**, *5*, 175–192.
6. Bernoulli, D. Exposition of a New Theory on the Measurement of Risk. *Econometrica* **1954**, *22*, 23–36. [CrossRef]
7. Kahneman, D.; Tversky, A. Prospect Theory: An Analysis of Decision under Risk. *Econometrica* **1979**, *47*, 263–291. [CrossRef]
8. De Martino, B.; Kumaran, D.; Seymour, B.; Dolan, R.J. Frames, Biases, and Rational Decision-Making in the Human Brain. *Science* **2006**, *313*, 684–687. [CrossRef]
9. Kahneman, D. Maps of Bounded Rationality: Psychology for Behavioral Economics. *Am. Econ. Rev.* **2003**, *93*, 1449–1475. [CrossRef]
10. von Neumann, J.; Morgenstern, O. *Theory of Games and Economic Behavior*; Princeton University Press: Princeton, NJ, USA, 1944. [CrossRef]
11. Starcke, K.; Brand, M. Decision making under stress: A selective review. *Neurosci. Biobehav. Rev.* **2012**, *36*, 1228–1248. [CrossRef]
12. Tversky, A.; Kahneman, D. Advances in prospect theory: Cumulative representation of uncertainty. *J. Risk Uncertain.* **1992**, *5*, 297–323. [CrossRef]
13. Sokol-Hessner, P.; Camerer, C.F.; Phelps, E.A. Emotion regulation reduces loss aversion and decreases amygdala responses to losses. *Soc. Cogn. Affect. Neurosci.* **2013**, *8*, 341–350. [CrossRef] [PubMed]
14. Kahneman, D.; Knetsch, J.L.; Thaler, R.H. Anomalies: The Endowment Effect, Loss Aversion, and Status Quo Bias. *J. Econ. Perspect.* **1991**, *5*, 193–206. [CrossRef]
15. Molins, F.; Serrano, M.A. Bases neurales de la aversión a las pérdidas en contextos económicos: Revisión sistemática según las directrices PRISMA. *Rev. Neurol.* **2019**, *68*, 47. [CrossRef]
16. Sokol-Hessner, P.; Rutledge, R.B. The Psychological and Neural Basis of Loss Aversion. *Curr. Dir. Psychol. Sci.* **2019**, *28*, 20–27. [CrossRef]
17. Christopoulos, G.I.; Tobler, P.; Bossaerts, P.; Dolan, R.; Schultz, W. Neural Correlates of Value, Risk, and Risk Aversion Contributing to Decision Making under Risk. *J. Neurosci.* **2009**, *29*, 12574–12583. [CrossRef]
18. Dreber, A.; Apicella, C.L.; Eisenberg, D.T.; Garcia, J.R.; Zamore, R.S.; Lum, J.K.; Campbell, B. The 7R polymorphism in the dopamine receptor D4 gene (DRD4) is associated with financial risk taking in men. *Ethol. Sociobiol.* **2009**, *30*, 85–92. [CrossRef]
19. Wu, Y.; Van Dijk, E.; Aitken, M.; Clark, L. Missed losses loom larger than missed gains: Electrodermal reactivity to decision choices and outcomes in a gambling task. *Cogn. Affect. Behav. Neurosci.* **2016**, *16*, 353–361. [CrossRef]
20. Persson, E.; Asutay, E.; Hagman, W.; Västfjäll, D.; Tinghög, G. Affective Response Predicts Risky Choice for Fast, but Not Slow, Decisions. *J. Neurosci. Psychol. Econ.* **2018**, *11*, 197–212. [CrossRef]
21. Klumpp, H.; Angstadt, M.; Phan, K.L. Insula reactivity and connectivity to anterior cingulate cortex when processing threat in generalized social anxiety disorder. *Biol. Psychol.* **2012**, *89*, 273–276. [CrossRef]
22. Phelps, E.A. Emotion and Cognition: Insights from Studies of the Human Amygdala. *Annu. Rev. Psychol.* **2006**, *57*, 27–53. [CrossRef] [PubMed]
23. Dalgleish, T. The emotional brain. *Nat. Rev. Neurosci.* **2004**, *5*, 583–589. [CrossRef]
24. LeDoux, J.E. Emotion Circuits in the Brain. *Annu. Rev. Neurosci.* **2000**, *23*, 155–184. [CrossRef] [PubMed]
25. Thayer, J.F.; Lane, R.D. Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neurosci. Biobehav. Rev.* **2009**, *33*, 81–88. [CrossRef] [PubMed]
26. Harrati, A. Characterizing the Genetic Influences on Risk Aversion. *Biodemography Soc. Biol.* **2014**, *60*, 185–198. [CrossRef] [PubMed]
27. Le, A.T.; Miller, P.W.; Slutske, W.S.; Martin, N. Are Attitudes Towards Economic Risk Heritable? Analyses Using the Australian Twin Study of Gambling. *Twin Res. Hum. Genet.* **2010**, *13*, 330–339. [CrossRef] [PubMed]
28. Cesarini, D.; Dawes, C.T.; Johannesson, M.; Lichtenstein, P.; Wallace, B. Genetic Variation in Preferences for Giving and Risk Taking. *Q. J. Econ.* **2009**, *124*, 809–842. [CrossRef]
29. Zhong, S.; Israel, S.; Xue, H.; Ebstein, R.P.; Chew, S.H. Monoamine Oxidase A Gene (MAOA) Associated with Attitude Towards Longshot Risks. *PLoS ONE* **2009**, *4*, e8516. [CrossRef]
30. Kuhnen, C.M.; Chiao, J.Y. Genetic Determinants of Financial Risk Taking. *PLoS ONE* **2009**, *4*, e4362. [CrossRef]
31. He, Q.; Xue, G.; Chen, C.; Lu, Z.; Dong, Q.; Lei, X.; Ding, N.; Li, J.; Li, H.; Chen, C.; et al. Serotonin transporter gene-linked polymorphic region (5-HTTLPR) influences decision making under ambiguity and risk in a large Chinese sample. *Neuropharmacology* **2010**, *59*, 518–526. [CrossRef]

32. Voigt, G.; Montag, C.; Markett, S.; Reuter, M. On the genetics of loss aversion: An interaction effect of BDNF Val66Met and DRD2/ANKK1 Taq1a. *Behav. Neurosci.* **2015**, *129*, 801–811. [CrossRef] [PubMed]
33. Crişan, L.G.; Pană, S.; Vulturar, R.; Heilman, R.M.; Szekely, R.; Drugă, B.; Dragoş, N.; Miu, A.C. Genetic contributions of the serotonin transporter to social learning of fear and economic decision making. *Soc. Cogn. Affect. Neurosci.* **2009**, *4*, 399–408. [CrossRef] [PubMed]
34. Kelley, A.E.; Schiltz, C.A.; Landry, C.F. Neural systems recruited by drug- and food-related cues: Studies of gene activation in corticolimbic regions. *Physiol. Behav.* **2005**, *86*, 11–14. [CrossRef] [PubMed]
35. Wise, R.A. Brain Reward Circuitry: Insights from Unsensed Incentives. *Neuron* **2002**, *36*, 229–240. [CrossRef]
36. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
37. Bechara, A.; Damasio, A.R.; Damasio, H.; Anderson, S.W. Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition* **1994**, *50*, 7–15. [CrossRef]
38. Lin, C.-H.; Song, T.-J.; Chen, Y.-Y.; Lee, W.-K.; Chiu, Y.-C. Reexamining the Validity and Reliability of the Clinical Version of the Iowa Gambling Task: Evidence from a Normal Subject Group. *Front. Psychol.* **2013**, *4*, 220. [CrossRef]
39. Bechara, A.; Damasio, A.R. The somatic marker hypothesis: A neural theory of economic decision. *Games Econ. Behav.* **2005**, *52*, 336–372. [CrossRef]
40. Fukunaga, R.; Brown, J.; Bogg, T.; Browna, J.; Bogg, T. Decision Making in the Balloon Analogue Risk Task (BART): Anterior Cingulate Cortex Signals Loss-Aversion but not the Infrequency of Risky Choices. *Cogn. Affect. Behav. Neurosci.* **2012**, *14*, 384–399. [CrossRef]
41. Beauchamp, J.P.; Cesarini, D.; Johannesson, M.; van der Loos, M.J.H.M.; Koellinger, P.D.; Groenen, P.J.F.; Fowler, J.H.; Rosenquist, J.N.; Thurik, A.R.; Christakis, N.A. Molecular Genetics and Economics. *J. Econ. Perspect.* **2011**, *25*, 57–82. [CrossRef]
42. Gao, X.; Gong, P.; Liu, J.; Hu, J.; Li, Y.; Yu, H.; Gong, X.; Xiang, Y.; Jiang, C.; Zhou, X. COMTVal158Met polymorphism influences the susceptibility to framing in decision-making: OFC-amygdala functional connectivity as a mediator. *Hum. Brain Mapp.* **2016**, *37*, 1880–1892. [CrossRef] [PubMed]
43. Roiser, J.P.; De Martino, B.; Tan, G.C.Y.; Kumaran, D.; Seymour, B.; Wood, N.W.; Dolan, R.J. A Genetically Mediated Bias in Decision Making Driven by Failure of Amygdala Control. *J. Neurosci.* **2009**, *29*, 5985–5991. [CrossRef] [PubMed]
44. Zhong, S.; Israel, S.; Xue, H.; Sham, P.C.; Ebstein, R.; Chew, S.H. A neurochemical approach to valuation sensitivity over gains and losses. *Proc. R. Soc. B Biol. Sci.* **2009**, *276*, 4181–4188. [CrossRef] [PubMed]
45. Dreber, A.; Rand, D.; Wernerfelt, N.; Garcia, J.; Vilar, M.G.; Lum, J.K.; Zeckhauser, R. Dopamine and risk choices in different domains: Findings among serious tournament bridge players. *J. Risk Uncertain.* **2011**, *43*, 19–38. [CrossRef]
46. Eisenegger, C.; Knoch, D.; Ebstein, R.P.; Gianotti, L.R.; Sándor, P.S.; Fehr, E. Dopamine Receptor D4 Polymorphism Predicts the Effect of L-DOPA on Gambling Behavior. *Biol. Psychiatry* **2010**, *67*, 702–706. [CrossRef]
47. Frydman, C.; Camerer, C.; Bossaerts, P.; Rangel, A. MAOA-L carriers are better at making optimal financial decisions under risk. *Proc. R. Soc. B Boil. Sci.* **2011**, *278*, 2053–2059. [CrossRef]
48. Amstadter, A.; MacPherson, L.; Wang, F.; Banducci-Barker, A.; Reynolds, E.; Potenza, M.; Gelernter, J.; Lejuez, C.W. The Relationship between Risk-Taking Propensity and the COMT Val158 Met Polymorphism Among Early Adolescents as a Function of Sex. *J. Psychiatr. Res.* **2012**, *46*, 940–945. [CrossRef]
49. Dreber, A.; Rand, D.G.; Wernerfelt, N.; Montgomery, C.; Malhotra, D.K. Genetic Correlates of Economic and Social Risk Taking. *SSRN Electron. J.* **2012**. [CrossRef]
50. Heitland, I.; Oosting, R.S.; Baas, J.M.P.; Massar, S.A.A.; Kenemans, J.L.; Böcker, K.B.E. Genetic polymorphisms of the dopamine and serotonin systems modulate the neurophysiological response to feedback and risk taking in healthy humans. *Cogn. Affect. Behav. Neurosci.* **2012**, *12*, 678–691. [CrossRef]
51. Mata, R.; Hau, R.; Papassotiropoulos, A.; Hertwig, R. DAT1 Polymorphism Is Associated with Risk Taking in the Balloon Analogue Risk Task (BART). *PLoS ONE* **2012**, *7*, e39135. [CrossRef]
52. Anderson, A.; Dreber, A.; Vestman, R. Risk taking, behavioral biases and genes: Results from 149 active investors. *J. Behav. Exp. Financ.* **2015**, *6*, 93–100. [CrossRef]
53. Gao, X.; Liu, J.; Gong, P.; Wang, J.; Fang, W.; Yan, H.; Zhu, L.; Zhou, X. Identifying new susceptibility genes on dopaminergic and serotonergic pathways for the framing effect in decision-making. *Soc. Cogn. Affect. Neurosci.* **2017**, *12*, 1534–1544. [CrossRef] [PubMed]
54. Wagels, L.; Votinov, M.; Radke, S.; Clemens, B.; Montag, C.; Jung, S.; Habel, U. Blunted insula activation reflects increased risk and reward seeking as an interaction of testosterone administration and the MAOA polymorphism. *Hum. Brain Mapp.* **2017**, *38*, 4574–4593. [CrossRef] [PubMed]
55. Muda, R.; Kicia, M.; Michalak-Wojnowska, M.; Ginszt, M.; Filip, A.; Gawda, P.; Majcher, P. The Dopamine Receptor D4 Gene (DRD4) and Financial Risk-Taking: Stimulating and Instrumental Risk-Taking Propensity and Motivation to Engage in Investment Activity. *Front. Behav. Neurosci.* **2018**, *12*, 34. [CrossRef]
56. Neukam, P.T.; Kroemer, N.B.; Araujo, Y.I.D.; Hellrung, L.; Pooseh, S.; Rietschel, M.; Witt, S.H.; Schwarzenbolz, U.; Henle, T.; Smolka, M.N. Risk-seeking for losses is associated with 5-HTTLPR, but not with transient changes in 5-HT levels. *Psychopharmacology* **2018**, *235*, 2151–2165. [CrossRef] [PubMed]

57. Ernst, M.; Plate, R.C.; Carlisi, C.O.; Gorodetsky, E.; Goldman, D.; Pine, D.S. Loss aversion and 5HTT gene variants in adolescent anxiety. *Dev. Cogn. Neurosci.* **2014**, *8*, 77–85. [CrossRef]
58. Roe, B.E.; Tilley, M.R.; Gu, H.H.; Beversdorf, D.; Sadee, W.; Haab, T.C.; Papp, A.C. Financial and Psychological Risk Attitudes Associated with Two Single Nucleotide Polymorphisms in the Nicotine Receptor (CHRNA4) Gene. *PLoS ONE* **2009**, *4*, e6704. [CrossRef]
59. Smolka, M.; Schumann, G.; Wrase, J.; Grüsser, S.M.; Flor, H.; Mann, K.; Braus, D.F.; Goldman, D.; Büchel, C.; Heinz, A. Catechol-O-Methyltransferase val158met Genotype Affects Processing of Emotional Stimuli in the Amygdala and Prefrontal Cortex. *J. Neurosci.* **2005**, *25*, 836–842. [CrossRef]
60. Williams, L.M.; Gatt, J.M.; Grieve, S.M.; Dobson-Stone, C.; Paul, R.H.; Gordon, E.; Schofield, P.R. COMT Val108/158Met polymorphism effects on emotional brain function and negativity bias. *NeuroImage* **2010**, *53*, 918–925. [CrossRef]
61. Nguyen, Y.; Noussair, C.N. Risk Aversion and Emotions. *Pac. Econ. Rev.* **2014**, *19*, 296–312. [CrossRef]
62. Van den Bos, R.; Harteveld, M.; Stoop, H. Stress and decision-making in humans: Performance is related to cortisol reactivity, albeit differently in men and women. *Psychoneuroendocrinology* **2009**, *34*, 1449–1458. [CrossRef] [PubMed]
63. Ernst, M.; Luciana, M. Neuroimaging of the dopamine/reward system in adolescent drug use. *CNS Spect.* **2015**, *20*, 427–441. [CrossRef] [PubMed]
64. Pierce, R.C.; Kumaresan, V. The mesolimbic dopamine system: The final common pathway for the reinforcing effect of drugs of abuse? *Neurosci. Biobehav. Rev.* **2006**, *30*, 215–238. [CrossRef] [PubMed]
65. Peterson, R.L. The neuroscience of investing: fMRI of the reward system. *Brain Res. Bull.* **2005**, *67*, 391–397. [CrossRef]
66. Adriani, W.; Boyer, F.; Gioiosa, L.; Macrì, S.; Dreyer, J.-L.; Laviola, G. Increased impulsive behavior and risk proneness following lentivirus-mediated dopamine transporter over-expression in rats' nucleus accumbens. *Neuroscience* **2009**, *159*, 47–58. [CrossRef]
67. MacKillop, J.; Menges, D.P.; E McGeary, J.; A Lisman, S. Effects of craving and DRD4 VNTR genotype on the relative value of alcohol: An initial human laboratory study. *Behav. Brain Funct.* **2007**, *3*, 11. [CrossRef]
68. Congdon, E.; Lesch, K.-P.; Canli, T. Analysis of DRD4 and DAT polymorphisms and behavioral inhibition in healthy adults: Implications for impulsivity. *Am. J. Med. Genet. Part B Neuropsychiatr. Genet.* **2008**, *147*, 27–32. [CrossRef]
69. Garcia, J.R.; MacKillop, J.; Aller, E.L.; Merriwether, A.M.; Wilson, D.S.; Lum, J.K. Associations between Dopamine D4 Receptor Gene Variation with Both Infidelity and Sexual Promiscuity. *PLoS ONE* **2010**, *5*, e14162. [CrossRef]
70. Knutson, B.; Adams, C.M.; Fong, G.W.; Hommer, D. Anticipation of Increasing Monetary Reward Selectively Recruits Nucleus Accumbens. *J. Neurosci. Off. J. Soc. Neurosci.* **2001**, *21*, RC159. [CrossRef]
71. Knutson, B.; Cooper, J.C. Functional magnetic resonance imaging of reward prediction. *Curr. Opin. Neurol.* **2005**, *18*, 411–417. [CrossRef]
72. Attenburrow, M.-J.; Williams, C.; Odontiadis, J.; Reed, A.; Powell, J.; Cowen, P.J.; Harmer, C.J. Acute administration of nutritionally sourced tryptophan increases fear recognition. *Psychopharmacology* **2003**, *169*, 104–107. [CrossRef] [PubMed]
73. Browning, M.; Reid, C.; Cowen, P.; Goodwin, G.; Harmer, C. A single dose of citalopram increases fear recognition in healthy subjects. *J. Psychopharmacol.* **2007**, *21*, 684–690. [CrossRef] [PubMed]
74. Burghardt, N.S.; Bush, D.; McEwen, B.; Ledoux, J.E. Acute SSRIs Increase Conditioned Fear Expression: Blockade with a 5-HT2C Receptor Antagonist N.S. *Biol. Psychiatry* **2007**, *62*, 1111–1118. [CrossRef]
75. Harmer, C.J.; Rogers, R.D.; Tunbridge, E.; Cowen, P.; Goodwin, G.M. Tryptophan depletion decreases the recognition of fear in female volunteers. *Psychopharmacology* **2003**, *167*, 411–417. [CrossRef] [PubMed]
76. Blair, K.S.; Finger, E.; Marsh, A.A.; Morton, J.; Mondillo, K.; Búzás, B.; Goldman, D.; Drevets, W.C.; Blair, R.J.R. The role of 5-HTTLPR in choosing the lesser of two evils, the better of two goods: Examining the impact of 5-HTTLPR genotype and tryptophan depletion in object choice. *Psychopharmacology* **2008**, *196*, 29–38. [CrossRef]
77. Campos-Vazquez, R.M.; Cuilty, E. The role of emotions on risk aversion: A Prospect Theory experiment. *J. Behav. Exp. Econ.* **2014**, *50*, 1–9. [CrossRef]
78. Bush, G.; Luu, P.; Posner, M.I. Cognitive and emotional influences in anterior cingulate cortex. *Trends Cogn. Sci.* **2000**, *4*, 215–222. [CrossRef]
79. Davis, K.D.; Taylor, K.S.; Hutchison, W.D.; Dostrovsky, J.O.; McAndrews, M.P.; Richter, E.O.; Lozano, A. Human Anterior Cingulate Cortex Neurons Encode Cognitive and Emotional Demands. *J. Neurosci.* **2005**, *25*, 8402–8406. [CrossRef]
80. Etkin, A.; Egner, T.; Peraza, D.M.; Kandel, E.R.; Hirsch, J. Resolving Emotional Conflict: A Role for the Rostral Anterior Cingulate Cortex in Modulating Activity in the Amygdala. *Neuron* **2006**, *51*, 871–882. [CrossRef]
81. Stevens, F.L.; Hurley, R.A.; Taber, K.H. Anterior Cingulate Cortex: Unique Role in Cognition and Emotion. *J. Neuropsychiatry Clin. Neurosci.* **2011**, *23*, 121–125. [CrossRef]
82. Shiv, B.; Loewenstein, G.; Bechara, A.; Damasio, H.; Damasio, A.R. Investment Behavior and the Negative Side of Emotion. *Psychol. Sci.* **2005**, *16*, 435–439. [CrossRef] [PubMed]
83. Liu, Z.J.; Panfilova, E.; Mikhaylov, A.; Kurilova, A. Assessing Stability in the Relationship Between Parties in Crowfunding and Crowdsourcing Projects During the COVID-19 Crisis. *J. Glob. Inf. Manag.* **2022**, *30*, 1–18.
84. Barykin, S.E.; Mikheev, A.A.; Kiseleva, E.G.; Putikhin, Y.E.; Alekseeva, N.S.; Mikhaylov, A.Y. An Empirical Analysis of Russian Regions' Debt Sustainability. *Economies* **2022**, *10*, 106. [CrossRef]
85. Mikhaylov, A.Y. Development of Friedrich von Hayek's Theory of Private Money and Economic Implications for Digital Currencies. *Terra Econ.* **2021**, *19*, 53–62. [CrossRef]

86. Sen, S.; Burmeister, M.; Ghosh, D. Meta-analysis of the association between a serotonin transporter promoter polymorphism (5-HTTLPR) and anxiety-related personality traits. *Am. J. Med. Genet.* **2004**, *127B*, 85–89. [CrossRef]
87. Sokol-Hessner, P.; Hsu, M.; Curley, N.G.; Delgado, M.R.; Camerer, C.F.; Phelps, E.A. Thinking like a trader selectively reduces individuals' loss aversion. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 5035–5040. [CrossRef]
88. De Martino, B.; Camerer, C.F.; Adolphs, R. Amygdala damage eliminates monetary loss aversion. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 3788–3792. [CrossRef]
89. Stancak, A.; Xie, Y.; Fallon, N.; Bulsing, P.; Giesbrecht, T.; Thomas, A.; Pantelous, A.A. Unpleasant odors increase aversion to monetary losses. *Biol. Psychol.* **2015**, *107*, 1–9. [CrossRef]
90. Lönnqvist, J.-E.; Verkasalo, M.; Walkowitz, G.; Wichardt, P.C. Measuring individual risk attitudes in the lab: Task or ask? An empirical comparison. *J. Econ. Behav. Organ.* **2015**, *119*, 254–266. [CrossRef]
91. Holt, C.; Laury, S. Risk aversion and incentive effects. *Am. Econ. Rev.* **2002**, *92*, 1644–1655. [CrossRef]

2. Implicit Negativity Bias Leads to Greater Loss Aversion and Learning during Decision-Making

International Journal of
Environmental Research and Public Health

MDPI

Article

Implicit Negativity Bias Leads to Greater Loss Aversion and Learning during Decision-Making

Francisco Molins, Celia Martínez-Tomás and Miguel Ángel Serrano *

Department of Psychobiology, Universitat de València, Av. Blasco Ibáñez, 13, 46010 Valencia, Spain
* Correspondence: m.angel.serrano@uv.es

Abstract: It is widely accepted there is the existence of negativity bias, a greater sensitivity to negative emotional stimuli compared with positive ones, but its effect on decision-making would depend on the context. In risky decisions, negativity bias could lead to non-rational choices by increasing loss aversion; yet in ambiguous decisions, it could favor reinforcement-learning and better decisions by increasing sensitivity to punishments. Nevertheless, these hypotheses have not been tested to date. Our aim was to fill this gap. Sixty-nine participants rated ambiguous emotional faces (from the NimStim set) as positive or negative to assess negativity bias. The implicit level of the bias was also obtained by tracking the mouse's trajectories when rating faces. Then, they performed both a risky and an ambiguous decision-making task. Participants displayed negativity bias, but only at the implicit level. In addition, this bias was associated with loss aversion in risky decisions, and with greater performance through the ambiguous decisional task. These results highlight the need to contextualize biases, rather than draw general conclusions about whether they are inherently good or bad.

Keywords: negativity bias; loss aversion; reinforcement-learning; decision-making; Iowa Gambling Task

Citation: Molins, F.; Martínez-Tomás, C.; Serrano, M.Á. Implicit Negativity Bias Leads to Greater Loss Aversion and Learning during Decision-Making. *Int. J. Environ. Res. Public Health* **2022**, *19*, 17037. https://doi.org/10.3390/ijerph192417037

Academic Editor: Paul B. Tchounwou

Received: 25 November 2022
Accepted: 15 December 2022
Published: 19 December 2022

1. Introduction

Most events and experiences in our daily living can be classified along a hedonic dimension, according to the positive or negative emotions they produce [1]. The emotional significance of a stimulus enhances its processing [2,3]. Therefore, this stimulus would have a greater influence on our perception, judgement, and decision-making. In addition, its valence (positive or negative) could provide an extra boost in that processing [1].

It is widely accepted there is the existence of negativity bias in human beings [4–7], referring to the greater sensitivity to negative stimuli compared with positive stimuli [4,8], and to the higher predisposition to consider ambiguous emotional stimuli as negative than positive [9]. The origin of this bias has been addressed from multiple perspectives (see Kanouse [10] for a review) and it is still an open question, however, its existence has been evidenced in both verbal and non-verbal stimuli [1,11]; in affective judgments [9], social information processing [12], during the child development [6], and on consumer behavior [13]; also when using event-related potentials [14], and peripherical physiological measures [15,16]. However, this generalizability was recently challenged. In their review, Kauschke et al. [1] concluded that this bias does not always arise and that, in fact, a positivity bias sometimes occurs, especially during childhood. Nevertheless, the meta-analysis of Joseph et al. [8], conducted in 874 samples and 53,509 participants, consistently revealed the presence of negativity bias. Therefore, current research points to negativity as the most widespread phenomenon, although it may be subject to variability depending on individual and contextual factors, such as age, stimulus modality, or task [1,9]. In addition, since some tasks only measure explicit or conscious responses, they could not be sensitive enough to capture the emotional bias; it is also important to address implicit automatic responses [9].

Following an ecological-rationality approach [17,18], classifying the negativity bias as advantageous or disadvantageous depends on the context. Focusing on decision-making and according to classical-rationality models, in risky contexts (where decision-rules are explicit and outcomes probabilities are known), individuals should take decisions strategically, following the rules of probability, logic, and maximizing the utility [19–21]. However, emotional biases can produce a jumping-to-conclusion effect that impairs this mathematical calculation and could lead to non-rational choices [20,22]. This is the case of the prominent loss aversion bias, whereby losses loom larger than gains [21,23]. So, losses have a greater psychological impact [24] and could produce 'anomalies', such as the framing or the endowment effect [23], that violate classical-rationality axioms just to avoid losses at any price. Recently, it has been proposed that loss aversion could be decomposed into the response bias and the valuation (or negativity) bias [25]. Consequently, those with a greater negativity bias should also express greater loss aversion and therefore make more biased decisions in risky decision-making contexts. This relationship between loss aversion and negativity bias was also theoretically stated by Kahneman [26], from the field of risky decision-making, and Kanouse [10], from the impression formation literature but, to our knowledge, it has not been empirically tested to date.

On the other side, under ambiguous decisions (compared to risky decision-making), i.e., when uncertainty is high and there exist several outcomes with unknown probabilities [20,27,28], people would not be able to follow strategies such as utility maximization [19] and would rely on the reward or punishment experiences after each decision. These experiences produce emotions that are linked to the different decision alternatives and act as somatic markers that guide following decisions [27,29]. Sensitivity to rewards and punishments plays a key role in this reinforcement-learning process [20]. In this case, having a greater negativity bias could enhance the effect of the punishments and would help to avoid those stimuli that produce them [3,30]. As learning research evidenced, this negative reinforcement would lead to faster learning [6,31]. Thus, it would be expected that having a higher negativity bias would be conducive to better decision-making under ambiguity since this bias could improve the reinforcement-learning. However, this hypothesis has never been tested to date.

Based on the above, the aim of our study is to provide new evidence of the existence of negativity bias, as well as to explore its role when risky and ambiguous decisions are made. This would shed light on the generalizability of the negativity bias and, on the other hand, help to better contextualize the adaptive/disadaptive role of this bias depending on the decisional environment. We hypothesize that, in a classification task of emotional faces [9], ambiguous faces will be more often classified as negative, showing the presence of the negativity bias. In addition, the higher level of negativity bias will predict the higher level of loss aversion when taking risky decisions, and a better performance on an ambiguous decisional task.

2. Materials and Methods

2.1. Participants

Based on the effect size found in a previous work [9], an a priori power analysis using G*Power indicated a requisite of 34 participants ($\eta 2p = 0.2$, power = 80%, $\alpha = 0.05$) to detect whether participants display negativity bias, both at the explicit and at the implicit level. Seventy students were recruited by the means of a non-probabilistic sampling method, by asking them during their classes in the University if they wish to participate in a study in exchange for academic credits. Those interested filled out a self-administered questionnaire to ensure that they met the following inclusion criteria when first contacted: not having any neurological or psychiatric diseases; not consuming drugs habitually; and not having experienced a highly stressful event in the last month. In addition, participants were asked to not perform extenuating exercise or take drugs or alcohol in the last 24 h, and not smoke or take stimulant drinks in the 2 h before the experimental session. One participant was

eliminated due to technical issues. A total of 69 participants (age: M = 22.33, SD = 2.29; women: N = 52, (75.3%)) were finally included in the study.

2.2. Procedure

Experimental sessions were carried out between 15:00 p.m. and 19:00 p.m. and lasted approximately an hour. Participants were collected in the University hall and accompanied to the laboratory. The general procedure was explained (see Figure 1), and informed consent was signed. Before starting the protocol, participants fulfilled a short, self-administered questionnaire to control the consumption of psychoactive substances and stimulants. Then, they performed the Face Rating Task [9] to measure their negativity bias level. Five minutes later the Lottery Choice Task [32] was employed to measure loss aversion in a risky decision-making context, and the Iowa Gambling Task [33] was used to assess decision-making under ambiguity. Both tasks were counterbalanced among participants. This study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki.

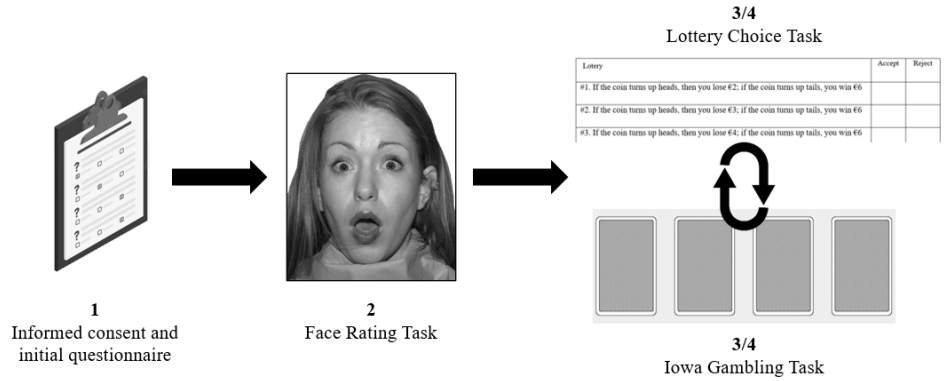


Figure 1. Experimental session procedure. The order in which the tasks were performed during the experimental session is shown. The Iowa Gambling Task and Lottery Choice Task were counterbalanced across participants.

2.3. Face Rating Task (FRT)

The FRT was utilized to measure the negativity bias. This task included 16 faces (8 surprised, 4 happy, and 4 angry), each presented four times in randomized order, for a total of 64 trials. Faces (8 male and 8 female) were extracted from the NimStim standardized facial expression stimulus set [34] with the consent of its developers. Each trial was composed of a black fixation cross which appeared in the center of a white background for 500 ms, and a 500 ms face presentation. After that, participants indicated whether they thought the expression was positive or negative by clicking a start button at the bottom of the display and clicking one of the two response option buttons (positive or negative) in the upper left- or upper right-hand corner of the display.

It was checked whether the happy and angry faces were correctly classified as positive and negative, respectively. On the other hand, it was compared whether the rate of surprised (or ambiguous) faces classified as negative was higher than that of ambiguous faces classified as positive. This corresponds to the explicit measure of the negativity bias. In addition, MouseTracker 2.83 software [35] was used to obtain a more sensitive measure of negativity beyond explicit valence ratings. This software tracked the mouse's trajectory as participants determined the valence of ambiguous facial expressions. During a trial, the trajectory can reflect either a straight line (when participant's mouse moves directly from the start button to the response), or it can show a curvature (when it is pulled toward the opposite response during the decision process). This curvature reflects the implicit competition between positive and negative ratings. Thus, the maximum deviation (MD) was obtained for ambiguous faces classified as positive (positive-MD), and for those classified as negative (negative-MD). MD quantifies the attraction toward the unselected

response by measuring the largest perpendicular deviation away from the most direct trajectory to the selected response [9]. The greater the MD, the greater the competition of the alternative response. A higher positive-MD indicates a greater implicit negativity bias since it reflects that, although the positive rating is finally chosen, the automatic response tends towards negative rating. Moreover, a lower negative-MD also indicates a greater implicit negativity bias since it reflects that negative ratings are more automatic.

In sum, three variables of the negativity bias were included in the study: (1) explicit negativity bias, (2) positive-MD, and (3) negative-MD. The last two refer to the implicit level.

2.4. Lottery Choice Task (LCT)

The LCT [32] was employed to measure loss aversion in a risk context. In this task, participants decide in six lotteries whether they accept or reject the bet. In each lottery the profit is fixed at 6€ and the loss varied through the bets (from 2 to 7€), yielding a successively decreasing expected value for each lottery. Following Gächter et al. [32], loss aversion was scored as the gain/loss ratio obtained from the highest bet accepted. This ratio shows how big the potential gain must be in relation to the potential loss for someone to accept the bets. Thus, the higher the ratio, the greater the loss aversion. Loss aversion values usually reported in the literature are 2–2.5 [36,37], which indicates that gains have to be at least twice as large as losses to accept a bet. As Rabin & Thaler [38] noted, loss aversion is not the same as risk aversion (tendency to avoid risky choices), therefore, it would be reasonable to ask whether this task really measures loss aversion and not risk aversion. However, as Gächter et al. [32] pointed out, based on the arguments of Rabin & Thaler [38], since this task offers small-stake gambles, behavior cannot be explained by risk aversion, otherwise, when someone had to deal with choices that involved large amounts at stake, "absurd degrees of risk aversion" [32] (p. 8) would be observed.

2.5. Iowa Gambling Task (IGT)

Decision-making under ambiguity was evaluated through the computerized version of the IGT [33,39]. Participants should get the maximum benefit possible from over 100 consecutive decisions where they can win and lose money. They can choose from four decks of cards: two disadvantageous (A and B) and two advantageous (C and D). A and B provide large immediate gains, but large losses in the long run. C and D provide lower short-term gains, but lower long-term losses, so their choice leads to higher profits. After each decision, the participant receives feedback that can be used to adjust future decisions. Performance was assessed by calculating the Iowa Gambling (IG) index: selections of C and D minus selections of A and B. The higher the IG, the higher the performance. This index was calculated for the entire task (IGTOTAL), and in blocks of 20 trials to study the learning curve.

2.6. Statistical Analyses

Outliers' presence was checked with the 2.5 standard deviations method and the Kolmogorov-Smirnoff with Lilliefors correction was used to check normality. Analyses included repeated measures ANOVAs to examine both the differences between ambiguous faces classified as negative and positive (explicit negativity bias), and differences between negative and positive-MD (implicit level). General linear models were also performed to study associations between the negativity bias, and both loss aversion and the IGT performance. Finally, as a complementary analysis, the sample was divided into two groups (high and low negativity bias) taking the median as reference. Their loss aversion level and IGT performance were compared between them through ANOVAs. The α significance level was set at 0.05 and partial eta square ($\eta 2p$) symbolizes the effect size. All analyses were performed with IBM SPSS Statistics 25.

3. Results

3.1. Negativity Bias

Firstly, it was checked whether the clearly positive and negative faces had been properly classified. The accuracy for both positive and negative faces was almost perfect, 99.81% (SD = 1.05). On the other hand, a repeated measures ANOVA was carried out to study whether there were differences between the ambiguous faces classified as positive and negative. At the explicit level, no differences were observed ($F(1, 68) = 1.09$, $p = 0.30$, and $\eta 2p = 0.02$); finding that ambiguous faces were classified as positive (M = 17.09, SD = 8.37) and as negative (M = 14.9, SD = 8.37) with a similar proportion. However, differences were found at the implicit level ($F(1, 68) = 9.85$, $p = 0.003$, and $\eta 2p = 0.14$), with a higher positive-MD (M = 0.31, SD = 0.31) than negative-MD (M = 0.15, SD = 0.25). That is, ambiguous faces showed a greater deviation of the mouse towards the opposite response (negative rating) when they were classified as positive. However, when ambiguous faces were classified as negative, the mouse's trajectory reflected a straight response without attraction towards the positive ratings (see Figure 2). Finally, Pearson's correlations revealed that positive-MD and negative-MD were not related with each other ($r(69) = 0.053$, $p = 0.67$); but both markers were related to the overall percentage of ambiguous faces classified as negative. Specifically, the higher the positive-MD, the higher the percentage of ambiguous faces classified as negative ($r(69) = 0.366$, $p = 0.002$), and the higher the negative-MD, the lower this percentage ($r(69) = -0.320$, $p = 0.009$).

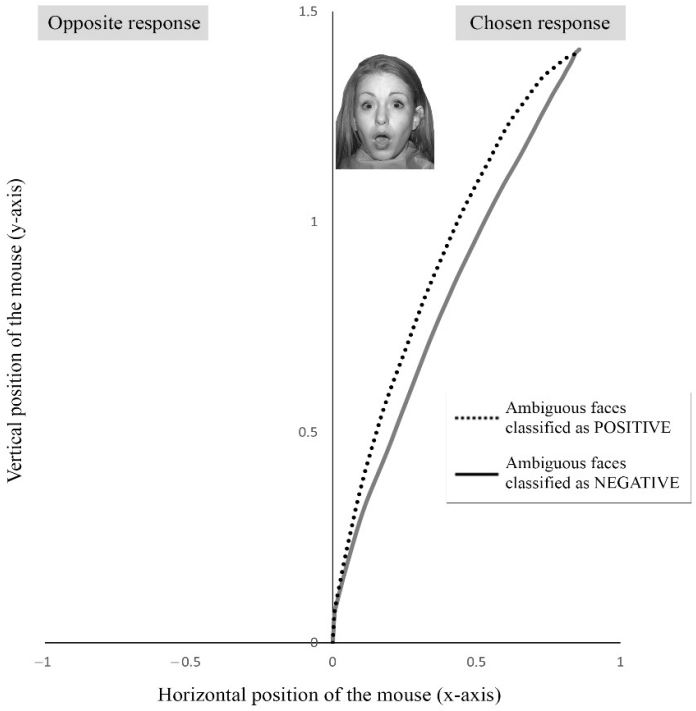


Figure 2. Mouse trajectory when classifying ambiguous faces as negative or positive. There was a greater maximum deviation of the mouse when classifying ambiguous faces as "positive" than "negative". When participants classified ambiguous faces as "positive", they showed response trajectories that indicated a greater attraction towards the competitive option (negative), as opposed to when they classified an ambiguous face as "negative", which they did more automatically.

3.2. Negativity Bias and Loss Aversion

First, it was necessary to identify whether the sample had loss aversion. The average value obtained in the lottery choice task was 2.63 (SD = 1.48), which is very close to that usually reported in the literature (2–2.5). In addition, it was studied whether negativity bias predicted loss aversion. Both the percentage of ambiguous faces classified as negative (explicit level), and negative-MD (implicit level) showed no associations with loss aversion

(p's > 0.05). However, positive-MD was significantly associated with the level of this bias (β = 1.91, SE = 0.54, t = 3.52, p = 0.001, and η2p = 0.17); i.e., the greater the attraction for the opposing option when ambiguous faces were classified as positive, the greater the loss aversion. In addition, dividing positive-MD by their median, it was compared whether there were differences in loss aversion between those who showed the greater and those who showed the lower positive-MD. When the ambiguous faces were classified as positive, the group that showed more deviation towards the opposing response (greater positive-MD), also had higher loss aversion (M = 2.99, SD = 1.74) than the group with a lower deviation (M = 2.24, SD = 1.03); F(1, 67) = 9.37, p = 0.035, and η2p = 0.07.

3.3. Negativity Bias and Iowa Gambling Task (IGT) Performance

It was studied whether negativity bias predicted performance on the IGT. Having a greater or lesser negativity bias, either at the explicit or implicit level, showed no associations with the IGTOTAL (p's > 0.05). Similarly, no association was found between the explicit measure of negativity bias and performance in any of the 5 blocks of the IGT (p's > 0.05). However, negative-MD was significantly associated with performance in the second block (β = −4.02, SE = 3.27, t = −1.23, p = 0.045, and η2p = 0.08) and the third block (β = −5.46, SE = 3.15, t = −1.72, p = 0.006, and η2p = 0.11). That is, the more automatic the negative rating for ambiguous faces, the higher the performance in those blocks.

Again, by dividing negative-MD by their median, it was studied whether participants with greater or lesser negative-MD differed in performance on IGT. Repeated measures ANOVA for the 5 blocks of the IGT, including the groups formed by dividing negative-MD as the between-subject factor, was carried out. It was found to be a main effect for the moment factor (the 5 IGT blocks), F(4, 64) = 9.43, p < 0.001, and η2p = 0.30; this indicated that performance varied throughout the task, regardless of the group. In addition, a significant interaction moment*negative-MD groups (greater and lower negative-MD) was observed (F(4, 64) = 4.15, p = 0.005, and η2p = 0.21) which indicated that this evolution was different for each group. As can be seen in Figure 3 and Table 1, when contrasting the performance of both groups in each IGT block, the group that most automatically rated the ambiguous faces as negative was also the one that performed significantly better in blocks 2 and 3, as well as showing a significant trend towards better performance in block 4. No other negativity bias variable reported significant results in relation to IGT performance.

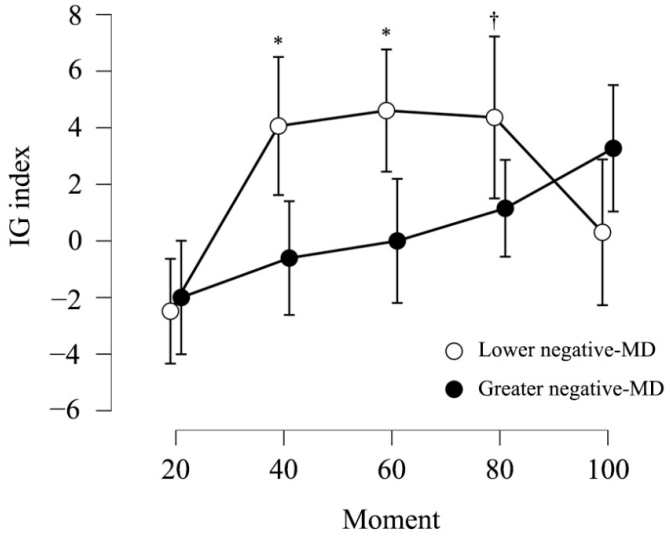


Figure 3. Performance in the IGT blocks depending on the group (higher or lower negative-MD). Participants who classified surprise or ambiguous faces as negative more directly, i.e., showed more negative bias at the implicit level, performed significantly better (*) in blocks 2 and 3 of the IGT. In addition, they showed a trend (†) towards better performance in block 4. Means ± 95% confidence interval.

Table 1. Inter-subject effect tests for the different IGT blocks.

		Lower Negative-MD (N = 34)	Greater Negative-MD (N = 35)	F	Gl Hypothesis	Gl Error	p-Value	η2p
IGT	Block 1	$M = -2.48 \pm 5.22$	$M = -2.00 \pm 5.65$	0.13	1	64	0.719	0.002
	Block 2	$M = 4.06 \pm 6.88$	$M = -0.61 \pm 5.66$	9.04	1	64	0.004 **	0.124
	Block 3	$M = 4.60 \pm 6.09$	$M = 0.00 \pm 6.18$	9.28	1	64	0.003 **	0.127
	Block 4	$M = 4.36 \pm 8.06$	$M = 1.15 \pm 4.82$	3.85	1	64	0.054 †	0.057
	Block 5	$M = 0.30 \pm 7.265$	$M = 3.27 \pm 6.30$	3.14	1	64	0.081	0.47

IGT, Iowa Gambling Task; M, mean; ± standard deviation; ** significant contrast at the 0.01 level. † significant trend.

4. Discussion

The aim of this research was to provide new evidence of the existence of negativity bias when processing emotional stimuli and, furthermore, to study how this bias influences decision-making depending on the context. Results evidenced the presence of the bias, although only at an unconscious level. In addition, this bias was associated with both a more biased risky decision-making and a better decision-making under ambiguity. These results will be discussed in depth below.

Regarding our first hypothesis, results showed the presence of the negativity bias when classifying ambiguous emotional faces, however, this evidence occurred only at an implicit level; mouse's trajectory when rating these faces as positive showed a significant deviation towards the opposing response, indicating that, although the trend was corrected at the explicit level, the initial impulse was to classify faces as negative. Yet, faces rated as negative showed a straight trajectory that reflects the absence of opposition. On the one hand, as in Brown et al. [9], this indicates that negativity bias could remain hidden if a methodology that explores beyond the conscious response is not used. Therefore, many studies that argued the absence of this bias (for a review see 1), should be revisited using new methods that replicate or modify results obtained. On the other hand, it seems that although there was negativity bias, it was not strong enough to affect the conscious response when classifying faces. According to dual-processing approaches [22,40], this emotional bias may be corrected by top-down mechanisms managed by the neocortex. Therefore, even when the initial impulse was to classify ambiguous faces as negative, a balanced rating between positive and negative valences was finally made. Nevertheless, individual and contextual factors, such as age, stimulus modality, or task could favor the conscious negativity bias expression [1]. For example, stress can increase the bias level [9]. It produces a relocation of resources in the brain, favoring subcortical regions activity over the prefrontal cortex [41]. In this situation, top-down processes may not function properly, and negativity bias may be more easily manifested at the conscious response. Therefore, it will be necessary to explore a wide range of factors to understand when we are particularly vulnerable to this bias.

The fact that the bias only appeared at the implicit level when judging ambiguous faces does not imply that it could not be influencing other cognitive domains. Thus, regarding risky decision-making, results confirmed the hypothesis that negativity bias would be conducive to more biased decisions. Specifically, the greater the unconscious attraction towards negative ratings when classifying ambiguous faces as positive, the higher the loss aversion. These results would be in line with Sheng et al. [24], who highlighted that loss aversion could be explained, at least partially, by the negativity bias. In addition, authors found that this bias was unconsciously manifested through increased visual attention to losses. This may also fit with our results, which showed that only the implicit negativity bias was significantly associated with loss aversion. Nevertheless, to clarify these issues, it would be necessary to address, through instruments such as an eye-tracker [42], if the negativity bias measure used in this study could be also related to the heightened focus on losses reported by Sheng et al. [25], as well as whether it is

behaviorally meaningful, influencing other complex decisions as reflected in recent studies, where even the predisposition to adopt innovative technologies would depend on the level of negativity bias [13].

On the other side, regarding decision-making under ambiguity, our last hypothesis stated that negativity bias would increase the IGT performance since this bias would favor reinforcement-learning. The overall score was similar for the different levels of the negativity bias; however, in line with our hypothesis, this bias was associated with faster learning and greater performance through the task. Specifically, those who most automatically rated ambiguous faces as negative performed better in the second and third blocks of the IGT and showed a trend towards better performance in the fourth block. Since our sample was composed of healthy, young participants and they should not face difficulties in learning the appropriate strategy in IGT [33], the margin for improvement attributed to the negativity bias may not be large enough to be observed in the overall score. However, studying the learning curve through the different blocks allowed for further exploration.

According to Bechara et al. [43], during the pre-punishment period (first block), participants do not know how the task works and must explore. Therefore, negativity bias could not explain their performance as the choices would be random. However, during the second and third blocks, called hunch periods, participants begin to develop anticipatory emotional signals based on their experiences [27,29] and their sensitivity to feedback [20]. Since the negativity bias would help to focus attention on negative information [3,30], it could help to generate such anticipatory markers and facilitate the avoidance of disadvantageous decks, improving the performance, as our results showed. Finally, Brand et al. [44] argued that the last blocks are less ambiguous, and participants rely on the attributions developed during the task. Yet, these attributions may be affected by multiple factors such as personality, working-memory, and impulsiveness, among others [45,46]. Thus, negativity bias could become particularly important only in ambiguous phases where it is still difficult to decide based on conscious information. Nevertheless, more research is needed to verify whether the bias really becomes secondary when participants form their hypotheses. In this line, Bechara et al. [43] studied participants' attributions throughout the task by asking them at the end of each block about their beliefs. It would be useful to replicate this approach in future studies also addressing negativity bias.

This study is not exempt from limitations, mainly related to potential variability of the negativity bias. Firstly, it was found that men would have a lower negativity bias [47]. Although the role of sex was considered by adjusting results by sex, the disproportionate sample (mostly women) makes it difficult to draw conclusions. On the other hand, all participants were young. Authors such as Carstensen & DeLiema [48] suggested that the negativity bias present in youth would decrease with age. Moreover, the measure of the bias was based on only one type of stimuli (emotional faces) and may differ if addressed with others [1]. Thus, it would be appropriate to replicate our study with a proportionate sample of men and women, covering different ages, and using different measures of negativity bias, to check if results can be generalized.

5. Conclusions

Our work highlights that the same bias could lead to different results depending on the context. In risky contexts, under the classical-rationality framework [19], it could be concluded that negativity bias is leading to less rational decisions, which are often interpreted as negative. In fact, these approaches have resulted in libertarian paternalism policies [49] that consider we need a "nudge" [50] to avoid biases that affect us when deciding. However, negativity bias could favor good decisions in ambiguous contexts such as the IGT. Here, this bias could act as an enhancer of reinforcement-learning by providing greater sensitivity to punishment, which would help to avoid future negative consequences. In fact, from evolutionary perspectives, this bias represents an adaptive advantage that errs on the side of caution, maximizing survival [51,52]. But again, this would depend

on the context. The IGT is designed to "reward" caution but in an ambiguous task that rewards risk-taking, negativity bias would be negative once again. Our data therefore seem to support the ecological rationality approach [17,18] and the need to contextualize rather than draw general conclusions about whether a phenomenon is inherently good or bad. As Simon [53] stated: "Human rational behavior is shaped by a scissors whose blades are the structure of task environments and the computational capabilities of the actor". It is important that, in the future, the scientific community properly explores the role of biases, rather than simply criticizing them, as in some contexts they may even be a useful tool for making good decisions faster and at lower cost.

Author Contributions: Conceptualization, M.Á.S. and F.M.; Methodology, M.Á.S. and F.M.; Formal analysis, F.M.; Investigation, C.M.-T.; Data curation, F.M. and C.M.-T.; Writing—original draft, M.Á.S., F.M. and C.M.-T.; Writing—review & editing, M.Á.S. and F.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kauschke, C.; Bahn, D.; Vesker, M.; Schwarzer, G. Review: The role of emotional valence for the processing of facial and verbal stimuli—Positivity or negativity bias? *Front. Psychol.* **2019**, *10*, 1654. [CrossRef]
2. Zeelenberg, R.; Wagenmakers, E.J.; Rotteveel, M. The impact of emotion on perception: Bias or enhanced processing? *Psychol. Sci.* **2006**, *17*, 287–291. [CrossRef] [PubMed]
3. Barros, P.; Parisi, G.I.; Weber, C.; Wermter, S. Emotion-modulated attention improves expression recognition: A deep learning model. *Neurocomputing* **2017**, *253*, 104–114. [CrossRef]
4. Cacioppo, J.T.; Berntson, G.G. Relationship between Attitudes and Evaluative Space: A Critical Review, with Emphasis on the Separability of Positive and Negative Substrates. *Psychol. Bull.* **1994**, *115*, 401–423. [CrossRef]
5. Corns, J. Rethinking the Negativity Bias. *Rev. Philos. Psychol.* **2018**, *9*, 607–625. [CrossRef]
6. Vaish, A.; Grossmann, T.; Woodward, A. Not All Emotions Are Created Equal: The Negativity Bias in Social-Emotional Development. *Psychol. Bull.* **2008**, *134*, 383–403. [CrossRef]
7. Norris, C.J. The negativity bias, revisited: Evidence from neuroscience measures and an individual differences approach. *Soc. Neurosci.* **2021**, *16*, 68–82. [CrossRef]
8. Joseph, D.; Chan, M.; Heintzelman, S.; Tay, L.; Diener, E.; Scotney, V. The manipulation of affect: A meta-analysis of affect induction procedures. *Psychol. Bull.* **2020**, *146*, 355–375. [CrossRef]
9. Brown, C.C.; Raio, C.M.; Neta, M. Cortisol responses enhance negative valence perception for ambiguous facial expressions. *Sci. Rep.* **2017**, *7*, 15107. [CrossRef]
10. Kanouse, D.E. Explaining negativity biases in evaluation and choice behavior: Theory and research. *ACR N. Am. Adv.* **1984**, *11*, 703–708.
11. Pinkham, A.E.; Griffin, M.; Baron, R.; Sasson, N.J.; Gur, R.C. The Face in the Crowd Effect: Anger Superiority When Using Real Faces and Multiple Identities. *Emotion* **2010**, *10*, 141–146. [CrossRef] [PubMed]
12. Fiske, S.; Taylor, S. *Social Cognition*, 2nd ed.; McGraw-Hill: New York, NY, USA, 1991.
13. Frank, D.; Chrysochou, P.; Mitkidis, P. The paradox of technology: Negativity bias in consumer adoption of innovative technologies. *Psychol. Mark.* 2022, *preprint*. [CrossRef]
14. Ito, T.A.; Larsen, J.T.; Smith, N.K.; Cacioppo, J.T. Negative information weighs more heavily on the brain: The negativity bias in evaluative categorizations. *J. Pers. Soc. Psychol.* **1998**, *75*, 887–900. [CrossRef] [PubMed]
15. Bradley, M.M. Natural selective attention: Orienting and emotion. *Psychophysiology* **2009**, *46*, 1–11. [CrossRef] [PubMed]
16. Wangelin, B.C.; Löw, A.; McTeague, L.M.; Bradley, M.M.; Lang, P.J. Aversive picture processing: Effects of a concurrent task on sustained defensive system engagement. *Psychophysiology* **2011**, *48*, 112–116. [CrossRef] [PubMed]
17. Raab, M.; Gigerenzer, G. The power of simplicity: A fast-and-frugal heuristics approach to performance science. *Front. Psychol.* **2015**, *6*, 1672. [CrossRef]
18. Gigerenzer, G.; Gaissmaier, W. Heuristic decision making. *Annu. Rev. Psychol.* **2011**, *62*, 451–482. [CrossRef]
19. von Neumann, J.; Morgenstern, O. *Theory of Games and Economic Behavior*; Princeton University Press: Princeton, NJ, USA, 1944.
20. Starcke, K.; Brand, M. Decision making under stress: A selective review. *Neurosci. Biobehav. Rev.* **2012**, *36*, 1228–1248. [CrossRef]

21. Kahneman, D.; Tversky, A. Prospect theory: An analysis of decision under risk. *Econometrica* **1979**, *47*, 263–291. [CrossRef]
22. Kahneman, D. Maps of bounded rationality: Psychology for behavioral economics. *Am. Econ. Rev.* **2003**, *93*, 1449–1475. [CrossRef]
23. Kahneman, D.; Knetsch, J.L.; Thaler, R.H. Anomalies: The endowment effect, loss aversion, and status quo bias. *J. Econ. Perspect.* **1991**, *5*, 193–206. [CrossRef]
24. Sokol-Hessner, P.; Rutledge, R.B. The Psychological and Neural Basis of Loss Aversion. *Curr. Dir. Psychol. Sci.* **2019**, *28*, 20–27. [CrossRef]
25. Sheng, F.; Ramakrishnan, A.; Seok, D.; Zhao, W.J.; Thelaus, S.; Cen, P.; Platt, M.L. Decomposing loss aversion from gaze allocation and pupil dilation. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 11356–11363. [CrossRef] [PubMed]
26. Kahneman, D. *Thinking, Fast and Slow*; Macmillan: New York, NY, USA, 2011.
27. Bechara, A.; Damasio, A.R. The somatic marker hypothesis: A neural theory of economic decision. *Games Econ. Behav.* **2005**, *52*, 336–372. [CrossRef]
28. Volz, K.G.; Gigerenzer, G. Cognitive processes in decisions under risk are not the same as in decisions under uncertainty. *Front. Neurosci.* **2012**, *6*, 105. [CrossRef]
29. Poppa, T.; Bechara, A. The somatic marker hypothesis: Revisiting the role of the 'body-loop' in decision-making. *Curr. Opin. Behav. Sci.* **2018**, *19*, 61–66. [CrossRef]
30. Vuilleumier, P. How brains beware: Neural mechanisms of emotional attention. *Trends Cogn. Sci.* **2005**, *9*, 585–594. [CrossRef]
31. Öhman, A.; Mineka, S. Fears, phobias, and preparedness: Toward an evolved module of fear and fear learning. *Psychol. Rev.* **2001**, *108*, 483–522. [CrossRef]
32. Gächter, S.; Johnson, E.; Herrmann, A. Individual-Level Loss Aversion in Riskless and Risky Choices. *Theory Decis.* **2022**, *92*, 599–624. [CrossRef]
33. Bechara, A.; Damasio, A.R.; Damasio, H.; Anderson, S.W. Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition* **1994**, *50*, 7–15. [CrossRef]
34. Tottenham, N.; Tanaka, J.W.; Leon, A.C.; McCarry, T.; Nurse, M.; Hare, T.A.; Marcus, D.J.; Westerlund, A.; Casey, B.J.; Nelson, C. The NimStim set of facial expressions: Judgments from untrained research participants. *Psychiatry Res.* **2009**, *168*, 242–249. [CrossRef] [PubMed]
35. Freeman, J.B.; Ambady, N. MouseTracker: Software for studying real-time mental processing using a computer mouse-tracking method. *Behav. Res. Methods* **2010**, *42*, 226–241. [CrossRef] [PubMed]
36. Duke, É.; Schnuerch, R.; Heeren, G.; Reuter, M.; Montag, C.; Markett, S. Cortical alpha asymmetry at central and posterior—But not anterior—Sites is associated with individual differences in behavioural loss aversion. *Pers. Individ. Dif.* **2018**, *121*, 206–212. [CrossRef]
37. Tom, S.M.; Fox, C.R.; Trepel, C.; Poldrack, R.A. The neural basis of loss aversion in decision-making under risk. *Science* **2007**, *315*, 515–518. [CrossRef] [PubMed]
38. Rabin, M.; Thaler, R.H. Anomalies, Risk Aversion. *J. Econ. Perspect.* **2001**, *15*, 219–232. [CrossRef]
39. Chiu, Y.C.; Huang, J.T.; Duann, J.R.; Lin, C.H. Editorial: Twenty years after the Iowa Gambling Task: Rationality, emotion, and decision-making. *Front. Psychol.* **2018**, *8*, 2353. [CrossRef]
40. Evans, J.S.B.T. Dual-processing accounts of reasoning, judgment, and social cognition. *Annu. Rev. Psychol.* **2008**, *59*, 255–278. [CrossRef]
41. Metz, S.; Waiblinger-Grigull, T.; Schulreich, S.; Chae, W.R.; Otte, C.; Heekeren, H.R.; Wingenfeld, K. Effects of hydrocortisone and yohimbine on decision-making under risk. *Psychoneuroendocrinology* **2020**, *114*, 104589. [CrossRef]
42. Holmqvist, K.; Nyström, M.; Andersson, R.; Dewhurst, R.; Jarodzka, H.; van de Weijer, J. *Eye Tracking: A Comprehensive Guide to Methods and Measures*; OUP Oxford: Oxford, UK, 2011.
43. Bechara, A.; Damasio, H.; Tranel, D.; Damasio, A.R. Deciding Advantageously before Knowing the Advantageous Strategy. *Science* **1997**, *275*, 1293–1295. [CrossRef]
44. Brand, M.; Recknor, E.C.; Grabenhorst, F.; Bechara, A. Decisions under ambiguity and decisions under risk: Correlations with executive functions and comparisons of two different gambling tasks with implicit and explicit rules. *J. Clin. Exp. Neuropsychol.* **2007**, *29*, 86–99. [CrossRef]
45. Barry, D.; Petry, N.M. Predictors of decision-making on the Iowa Gambling Task: Independent effects of lifetime history of substance use disorders and performance on the Trail Making Test. *Brain Cogn.* **2008**, *66*, 243–252. [CrossRef] [PubMed]
46. Dunn, B.D.; Dalgleish, T.; Lawrence, A.D. The somatic marker hypothesis: A critical evaluation. *Neurosci. Biobehav. Rev.* **2006**, *30*, 239–271. [CrossRef] [PubMed]
47. Norris, C.J.; Leaf, P.T.; Fenn, K.M. Negativity bias in false memory: Moderation by neuroticism after a delay. *Cogn. Emot.* **2019**, *33*, 737–753. [CrossRef] [PubMed]
48. Carstensen, L.L.; DeLiema, M. The positivity effect: A negativity bias in youth fades with age. *Curr. Opin. Behav. Sci.* **2018**, *19*, 7–12. [CrossRef]
49. Thaler, R.H.; Sunstein, C.R. Libertarian paternalism. *Am. Econ. Rev.* **2003**, *93*, 175–179. [CrossRef]
50. Sunstein, C.R. *Why Nudge?: The Politics of Libertarian Paternalism*; Yale University Press: New Haven, CT, USA, 2014.

51. LeDoux, J. *The Emotional Brain*; Simon and Schuster: New York, NY, USA, 1996.
52. Thayer, J.F.; Lane, R.D. Claude Bernard and the heart-brain connection: Further elaboration of a model of neurovisceral integration. *Neurosci. Biobehav. Rev.* **2009**, *33*, 81–88. [CrossRef]
53. Simon, H.A. Invariants of human behavior. *Annu. Rev. Psychol.* **1990**, *41*, 1–20. [CrossRef]

3. Interoception moderates the relation between alexithymia and risky-choices in a framing task: A proposal of two-stage model of decision-making

International Journal of Psychophysiology 162 (2021) 1–7

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Interoception moderates the relation between alexithymia and risky-choices in a framing task: A proposal of two-stage model of decision-making

Namra Manzoor [1], Francisco Molins [1], Miguel Ángel Serrano [*]

Department of Psychobiology, University of Valencia, Department of Psychobiology, Av. Blasco Ibáñez, 13, 46010, Valencia, Spain

ARTICLE INFO

Keywords:
Decision-making
Framing effect
Interoception
Alexithymia
Somatic markers
Emotions

ABSTRACT

Decision-making depends on the context (frame) in which questions and alternatives are presented. Moreover, research has showed that the ability to detect bodily sensations (interoception) and being able to attribute these changes to emotions correctly (alexithymia) influence how we make decisions. The aim of the present research was to study how interoception and alexithymia might affect the Framing effect (FE), a cognitive bias closely related to emotional system. 42 healthy participants completed the Risky-choice Framing task and their interoception and alexithymia levels were measured. Results showed that the participants were more risk-taking under the negative frames in comparison to the positive ones. In addition, we found that alexithymia and interoception were negatively and positively correlated with the FE, respectively. Finally, the moderation analyses revealed that alexithymia predicted a lower FE only when the interoception was high. Based on previous literature and in our results, we propose a two-stage model of intuitive decision-making.

1. Introduction

Our day-to-day decisions are characterized by violation of rationality premises. In daily life ambiguous situations and due to our cognitive and time limitations, instead of analyzing the whole problem and calculating all the possible outcomes, we rely on our "gut feelings" or constantly let our emotions dictate our decisions (Bechara and Damasio, 2005; De Martino et al., 2008; Kahneman and Tversky, 1979; Poppa and Bechara, 2017). Therefore, we tend to take cognitive "shortcuts", known as *heuristics*. These heuristics can lead to biases and systematic errors (Kahneman and Tversky, 1979). One of the most studied biases is the "Framing effect" (FE).

FE, one of the main pillars of the Prospect theory (Kahneman and Tversky, 1979), contradicts the main premise of the rational choice theory (Mellers et al., 1998): logical consistency across decisions, regardless of the context. This bias consists of the idea that changes in the context, it means, changes in the way alternatives are presented, affect relative desirability of these alternatives, in the way that people tend to prefer the sure option in the positive frame and the risky option in the negative frame (Tversky and Kahneman, 1981). In other words, choices involving gains make people more risk aversive and choices involving losses, more risk taking. This bias has also been observed in animal studies (see Kacelnik and Bateson, 1996, 1997 for review) and seems to have its roots in emotional system since studies have observed that prefrontal-amygdala circuit (De Martino et al., 2006; Roiser et al., 2009) and insular cortex (Preuschoff et al., 2008) play an important role in this process. Different studies have shown that these brain circuits are involved in emotions processing (e.g. Bechara et al., 1994; Chakravarthy and Chakravarthy, 2019; Craig 2009; Ledoux, 2000; Phelps, 2006; Poppa and Bechara, 2017; Trepel et al., 2005). For instance, several lines of research, working with patients with brain damage in this circuit, support the idea that this leads to excess risk-taking without anticipating the negative costs that this may entail (Bechara and Damasio, 2005; De Martino et al., 2010; Phelps, 2006) and it is believed that this is because of their inability to detect emotional body cues triggered by aversive stimuli (Bechara et al., 1994). Other studies (De Martino et al., 2008; Ring, 2015; Sarlo et al., 2013) using more peripheral indictors of emotional arousal, such as skin conductance responses (SCRs), observed a differential physiological pattern depending on how the problems and the possible alternatives were presented: higher SCRs being positively correlated with negative frames and also with high risk-taking under this context. Put in another way, a higher arousal was linked to a higher FE.

* Corresponding author.
E-mail address: m.angel.serrano@uv.es (M.Á. Serrano).
[1] These authors contributed equally to the work.

https://doi.org/10.1016/j.ijpsycho.2021.01.002
Received 30 July 2020; Received in revised form 23 December 2020; Accepted 4 January 2021
Available online 20 January 2021

Thus, these findings, on central and peripheral nervous system level, show that emotions play an essential role in this process, it means, how a certain situation makes us feel or how we "label" those feelings can alter our perspective and affect our decisions.

Talking about the role of emotions in our decision-making, De Martino et al. (2006) highlighted that studies with the FE emphasize the fact that intuition and emotional responses, instead of analytical processing, play a key role in guiding choice behavior. Though, more research is needed to get a deeper perspective of the situation; nevertheless, this limited data still manages to make it obvious that emotions are an indispensable part of human decision-making process, as well as, how we process and regulate them. However, this would be highly depending on the individual's emotional awareness level; in fact, it has been shown that higher emotional awareness is linked to a better performance in complex decision-making tasks (Evans et al., 2005). For this reason, it would be interesting to consider the role the constructs involving these variables, such as alexithymia and interoception.

Alexithymia, first introduced by Sifneos (1973), with a 10–13% prevalence rate in general population depending on the cutoff we use (Salminen et al., 1999), is a personality construct which consists in having difficulties in identifying and describing one's emotions and feelings. These symptoms can result in having trouble in emotional regulation and awareness (da Silva et al., 2017; Hsing et al., 2013; Laloyaux et al., 2015; Zamariola et al., 2018) and deficits in the perception of emotional stimuli (Aleman, 2005; Lane et al., 2000). Working with the FE, Shah et al. (2016) demonstrated that higher levels of alexithymia predicted lower FE, concluding that individuals with alexithymia tend to rely more on "rationality" than intuition or "gut feeling" since they are not in touch with their emotions properly, thus, are not affected by the FE as much, as this is an emotionally induced bias.

On the other hand, interoception is one's ability to detect and process subtle internal bodily sensations (e.g. hunger, thirst, changes in respiration or cardiac signals, etc.) triggered by external stimuli related to an emotional experience. Studies show that higher level of interoception is related to higher intensity of emotional awareness and more detailed emotional processing (Herbert et al., 2011; Pollatos et al., 2007). Moreover, it has also been linked to better decision-making. For instance, studies with decision-making under risk have shown that participants' interoceptive abilities affect their performance in these tasks (Bechara et al., 1997; Dunn et al., 2010; Sütterlin et al., 2013). It is believed that interoception affects decision-making by increasing our subjective emotional experience triggered by our bodily responses to external stimuli (Barrett et al., 2012; Critchley et al., 2004; Wiens et al., 2000; Zaki et al., 2012). Even though the studies linking interoception and the FE are scarce, some research has been done to give us few clues. Sütterlin et al. (2013) and Shah et al. (2016) in their studies concluded that high interoception was positively correlated with a higher susceptibility to the FE. It makes sense, as we described above, the FE has emotional bases, therefore accurate emotional processing can determine its level of influence on the decisions by triggering somatic responses in the individual and making them more prone to be affected by this bias.

Although the relationship between alexithymia or interoception and the FE has been studied separately, to our knowledge, it has not been explored to date how both constructs interact and influence decision-making, more specifically, the FE in healthy people. This possible relationship has been tested in the clinical settings. For instance, recently, Palser et al. (2018) concluded that a high level of alexithymia could be a risk factor for anxiety, but especially in people with a high level of interoception. However, in the case of having poor interoception, having more or less alexithymia did not seem so relevant. Thus, it seems that having more or less alexithymia becomes especially relevant *only* when the individual is already aware of the interoceptive signals coming from the body. Therefore, returning to decision-making, it makes sense that a greater alexithymia explains a lower FE, but especially in people who have a good interoception level and, as we propose, this occurs because the interoceptive signals are misattributed to emotions due to the presence of alexithymia. However, first the person must be able to detect those signals; perhaps that is why alexithymia is less important in people who have poor interoception.

Taking this into account, the aim of this study is to explore these relationships and how these variables interact with each other to influence decision-making under risk. As we mentioned above, data on the relationship between the moderating role of high or low ability of emotions detection and regulation, measured in interoception and alexithymia, and the susceptibility to the FE is scarce, our study is intended to dig into this question and provide more scientific evidence of the directionality of the possible relationships. Firstly, we hypothesize (hypothesis 1) that participants would choose to accept the bet (take more risk) under the negative frames more than the positive ones, in other words, they would show FE. Secondly, we expect that interoception would positively and alexithymia would negatively predict the FE level (hypothesis 2), since higher emotional awareness would facilitate the emotional feedback loop leading to a more intuitive decision-making and inability to do that would hinder the process. Finally, we predict that (hypothesis 3) the interaction between interoception and alexithymia would have a significant effect and interoception would moderate the relationship between alexithymia and the FE, in a way that depending on the levels of interoception, alexithymia would play more or less relevant role in this process. It would happen because first one needs to be aware of owns bodily changes, it means having high interoception, and *only* then, whether the person is able to regulate and attribute these sensations to emotions effectively or not (level of alexithymia) would be significant.

2. Method

2.1. Participants

Based on the effect size found in a previous work on the FE and alexithymia (Shah et al., 2016), an a priori power analysis using G*Power (Erdfelder et al., 1996) indicated a requisite of 33 participants ($\eta^2_p = 0.44$, power = 80%, $\alpha = 0.05$) to perform a general lineal model studying interoception, alexithymia and their interaction to predict the FE. We oversampled 10 participants to account for possible exclusions. 43 healthy participants were recruited by the mean of non-probabilistic sampling method, from which one was eliminated due to a physical disability and for not having been able to perform the framing task well on the computer. Hence, the final number of participants was 42, (women: $N = 27$; age: M = 22.50, SD = 2.734). All of them fulfilled the exclusion criteria as follow: not having physical, neurological or psychiatric diseases; not consuming 10 or more cigarettes a day; not consuming drugs on regular bases; not having consumed drugs 24 h before and not having taken stimulant drinks in the 2 h before the experimental session; sleep deprivation and BMI.

The study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki. All participants signed informed consent before starting the experimental session and were informed about which activities they had to perform and which equipment was going to be used (electrodes to measure electrocardiogram, ECG, for instance), also insisting on that they were free to withdrawal their consent at any point of the study.

2.2. Instruments

2.2.1. Framing task

2.2.1.1. Risky-choice framing task. Participants completed a computerized version economical risky-choice framing task adapted from De Martino et al. (2006). First of all, a screen appeared for 2 s informing

them that they received an amount of money (€25, €50, €75 and €100). Next, a screen with two options appeared simultaneously for 4 s, where they were asked to choose between a "sure" option and a "risky" option. The reason behind the time constraining was to enhance the effects of implicit information processing, as proposed by the original authors.

On the one hand, the "sure" option could be presented either in a negative frame (e.g. "You lose €75") or in a positive frame ("You keep €25"). Point to be noticed, the actual monetary value is equal in both options and the only difference is how they are worded. On the other hand, the "risky" option consisted of gambling to either win or lose the whole amount of money announced before. The probabilities to win the risky option were 20%, 40%, 60% and 80%; and the trials were equally balanced between these probabilities, it means, same number of trials for each percentage of riskiness. Types of frame, positive or negative, were randomly presented; however, the number of trials for each type of frame was equal (32 loss and 32 gain frames). In addition, the "risky" option in a specific positively framed trial was equivalent to its complementary negative frame's "risky" option. It means, for every positive trial (e.g. "You keep €60 of €100" vs. a 60% chance of keeping the whole €100), there was a complementary negative trial (e.g. "You lose €40 of €100" vs. 60% chance of keeping the whole €100). As you can see, "risky" option remains the same, but "sure" option changes depending on how it is framed (a visual representation of two complementary framed trials is represented in the Fig. 1).

Following the protocol from the original authors, participants were not given any feedback if they lost or won the gamble, in order to avoid a possible decisions shift because of the context dependence of risk preferences (Tversky and Kahneman, 1992; Vermeer and Sanfey, 2015; Xue et al., 2011). For example, studies have shown that participants prefer risky options after a financial loss, while choosing safer options after a monetary gain. Another important reason was that each trial was intended to be a unique bet and a trial-by-trial feedback could promote learning by reward/punishment-based conditioning, which could result in adapting a strategy to gain more money (Bechara et al., 1994; Chiu et al., 2018; Turnbull et al., 2014). This feedback based learning could introduce bias to our data since the purpose of our study was to measure risk-taking in each independent bet under different contexts (frames).

In addition 32 "catch" trials were included; where one of the alternatives was notably beneficial in comparison to the other one (e.g. 95% chances to win/lose the whole amount vs. keeping/losing 50% of the initial amount). These were to assess the participant's engagement and to assure that the answers were not random. Following the design developed by De Martino et al. (2006), any participant failing in more than 20% of these "catch" trials were excluded from the study.

2.2.2. Interoception

We used the *Schandry heartbeat tracking task* (Dunn et al., 2010; Schandry, 1981). This task is divided into six trials. In each trial, the participants have to count how many heartbeats they felt during changing time of intervals - two trials of 25 s; two of 35 s and last two ones of 40s - without being permitted to take their pulse. Afterwards, these results are compared with their real heartbeats they had during those intervals measured by the ECG. Heartbeats were recorded using the third Einthoven derivation with 3 re-usable electrodes, using BIOPAC MP150, a transducer ECG-100C and the AcqKnowledge 4.2.0 software.

2.2.3. Alexithymia

We used the *Toronto Alexithymia Scale* (TAS-20; Bagby et al., 1994). It is the most extensively used self-report to measure alexithymia construct. It consists of 20 items, and participants must answer the questions in 5-point Likert scale, where "1" means "completely disagree" and "5" means "completely agree". The score can range from 20 to 100, with higher score indicating a high level of alexithymia (a score higher than 71 indicates clinical-level alexithymia diagnosis).

We used the Spanish version of TAS-20 (Martínez-sánchez, 1996); Cronbach's alpha for our sample was 0.63.

2.3. Procedure

Participants who showed interest in participating in the study were asked to provide us their contact information (email and mobile number) and the day and time they preferred for the session. Through an online questionnaire, all the participants provided information about their socioeconomic variables, as well as their physical and psychological health. In addition, we asked them about their lifestyle style (psychostimulant drug uses, drug addiction, physical activity, etc.). In this same questionnaire TAS-20 was included to measure alexithymia. The reason behind to add the questionnaire here was to avoid any influence that the framing task could have on their emotional expression. Participants were instructed to wait in the faculty hall and were guided to the lab by the main researcher in the elevator avoiding the stairs to avoid any fluctuations in their physical or physiological states (fatigue or increasing heartbeat). Once in the lab, they all signed informed consent and were informed about the study and equipment used, without revealing the exact purpose and variables of the study. Next, to measure ECG, electrodes were attached to their body and they were left alone for 10 min to take a baseline. After this habituation phase, they performed the heartbeat tracking task to assess interoception, which was followed by the Risky-choice framing task with a 5 min rest in between. Instructions for this task were printed on a paper with visual examples for a better comprehension. Participants also performed few test trials in order to grasp the task well before really starting.

2.4. Data reduction

2.4.1. Risky choice framing task

First, to guarantee a sufficient internal validity, any participant who failed more than 20% of "catch" trials was excluded from the further analysis. In addition, it was assured that the positioning of the frames

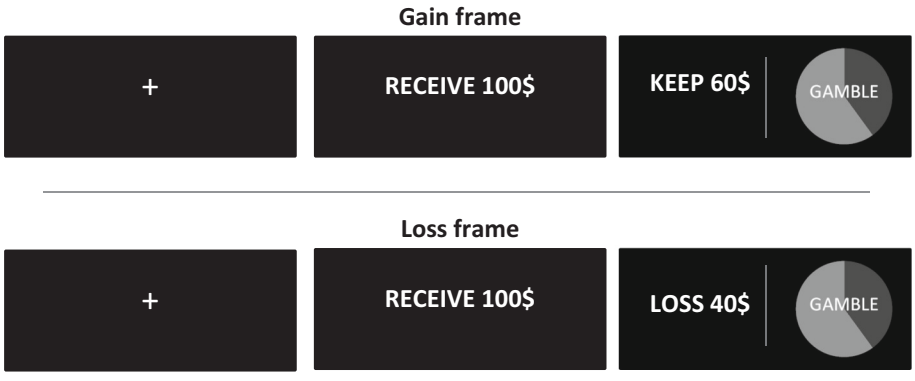


Fig. 1. Risky-choice framing task. Two complementary trials are presented. First a screen with a "+" symbol appears for 3 s in order to prepare the participant for the trial. Second, participants receive an initial amount (2 s). Third slide appears (for 4 s only) with a "sure" (on the left) and a "risky" option (green being the probability to win and red the probability to loss all the initial amount). The "sure" option can either be framed as a gain ("keep") or as a loss ("loss"). Types of frame, positive or negative, were randomly presented; however, the number of trials for each type of frame was equal (32 loss and 32 gain frames). No feedback was given if the bet resulted in a win or a loss. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(right vs left) did not have a significant influence on the decisions. Finally, the FE was measured by calculating the difference between the preference (in percentage) to choose the "gamble" option over the "sure" option within each frame. In other words, the difference between the percentages of trials the individual chose to gamble in a positive frame versus a negative frame.

2.4.2. Schandry heartbeat task

The participants' performance on this task was measured by using the following formula: $((Actual - Estimated) \div Actual) \times 100$, where "Actual" is the heartbeats the participant really had at that interval of time as estimated by ECG and "Estimated" are the number of heartbeats participants felt they had, it means, the answer they gave. These results are presented in the percentage form. We calculated the percentages for the six trials and computed the average. The scores can be interpreted as a continuous scale, where higher scores mean better interoception.

2.5. Statistics analysis

First step was to check outliers and test variables normality with Kolmogorov-Smirnov normality test. Variables that did not follow normal distribution were converted using the Ig10 conversion method. First, we tested for the FE through a repeated-measures ANOVA, comparing risk taking in positive vs negative frames. After that, we did a two stepped analysis, as previously mentioned. First, to study if interoception, alexithymia and their interaction predicted the FE, we carried out a general linear model. Once the significant interaction was assured, we followed the Johnson-Neyman procedure with the PROCESS macro for SPSS (Hayes, 2017). Johnson-Neyman method identifies important transition or critical points (JN) where the effect of the moderator variable (in this case, interoception), on Y (effect of alexithymia on the FE), transitions from significant to nonsignificant, or vice versa (see Montoya (2019) for a detailed explanation).

All analyses were performed using IBM SPSS Statistics 25, with the α significance level set at 0.05.

3. Results

3.1. Descriptive statistics

In the Table 1, descriptive characteristics of our variable of interest are presented.

3.2. Framing effect

First, we checked if any participant failed more than 20% of the "catch" trials. In our case, no participant was excluded for this reason. Secondly, we discarded the possibility that the positioning of the frames (right vs left) could be affecting participants' choices by conducting a mean comparison ($M = 0.2068$, $SD = 0.1845$ and $M = 0.2068$, $SD = 0.1875$, respectively) and no significant differences were observed, $F(1, 41) = 0.00$, $p = 1.00$. After assuring the internal reliability with these two steps, we got into our specific hypotheses testing.

As far as our first hypothesis is concerned, participants indeed tended to take more risk (accepting to bet) in loss frames than in gain frames ($M = 0.4896$, $SD = 0.2227$ and $M = 0.2827$, $SD = 0.1955$, respectively), $F(1, 41) = 169.083$, $p < .001$, $\eta^2_p = 0.805$.

Table 1
Descriptive statistics ($N = 42$).

	M	*SD*
Framing effect	0.21	0.17
Bet acceptance under positive frame	0.28	0.19
Bet acceptance under negative frames	0.49	0.22
Interoception trial 1	65.95	17.42
Interoception trial 2	66.27	18.71
Interoception trial 3	64.42	22.61
Interoception trial 4	63.78	21.49
Interoception trial 5	62.70	19.36
Interoception trial 6	63.38	20.61
Final interoception	63.93	16.47
Alexithymia	40.52	7.12

M = mean; SD = standard deviation; framing effect score, is measured by calculating the difference between the proportion of trials the participant chose to gamble in the positive frames versus at the negative frames; final interoception score (in percentage) is calculated by averaging the interoceptive precision (also in percentages) in 6 heartbeat tracking trials; alexithymia (ranging between 20 and 100), sum 20 items of TAS-20.

3.3. Alexithymia and interoception

Only as a verification that there is no correlation between alexithymia and interoception so that the following analysis can be done well, we ran Pearson correlation between them, which resulted not significant ($r(42) = -0.031$; $p = .845$). Then, once having assured the independence of these two variables, using a general linear model to see how interoception, alexithymia and their interaction predicted the FE, we observed that there were significant main effects of interoception ($B = 0.019$, $SE = 0.008$, $t = 2.34$, $p = .024$, $\eta 2p = 0.12$), and alexithymia ($B = -0.128$, $SE = 0.048$, $t = -2.68$, $p = .01$, $\eta 2p = 0.15$). It means both constructs are significant predictors of the performance in the FE task, interoception being positively and alexithymia negatively correlated with the FE. In addition, we found a significant Interoception*Alexithymia interaction ($B = -0.013$, $SE = 0.005$, $t = -2.64$, $p = .01$, $\eta 2p = 0.15$), indicating that interoception moderates the effects of alexithymia on the FE. The model was significant, $F(3, 38) = 3.35$, $p = .02$, and explained the 20.9% of the FE's variance. In order to deepen even more in this interaction, the Johnson-Neyman procedure was followed, which revealed that having a punctuation of 59.45 in interoception was a critical point (see Fig. 2). Scores lower than this point did not show significant associations between alexithymia and the FE, contrary to those who scored higher, which showed a negative association between alexithymia and the FE.

4. Discussion

In the present study we aimed to study how the FE, a cognitive bias, may be influenced by alexithymia and interoception. Not much research has been done exploring these variables under the same experiment design and the main objective of our study was to dig into these relationships and provide more evidence on this topic. We hypothesized that people would be more conservative when encountering positively framed alternatives and more risk-taking with negatively framed alternatives, i.e., they would show a framing effect (Tversky and Kahneman, 1981). In addition, these differences in preferences would be negatively and positively associated with alexithymia (Shah et al., 2016) and interoception (Sütterlin et al., 2013), respectively. It would happen because this cognitive bias is routed in our emotional system (De Martino et al., 2006; Ring, 2015; Roiser et al., 2009; Sarlo et al., 2013) and an inability or ease to detect, process and regulate our bodily sensations and emotions would affect this. Going even further, we suggested that interoception would moderate the relationship between alexithymia and the FE. Our results seem to support these hypotheses and show that interoception and alexithymia indeed play a significant role in the decision-making involving the FE.

The main result from our study is that alexithymia only predicted low FE in those individuals who displayed a high interoception. It means: a good level of body awareness (high interoception) was a necessary condition for alexithymia to have a significant effect on our decisions. In order to explain that, we propose that this happens because of a two independent stages process: when encountered with an emotional stimulus (a bet in our case), our body sends us signals via somatic responses (SCRs, heartbeat change, sweating…), which an

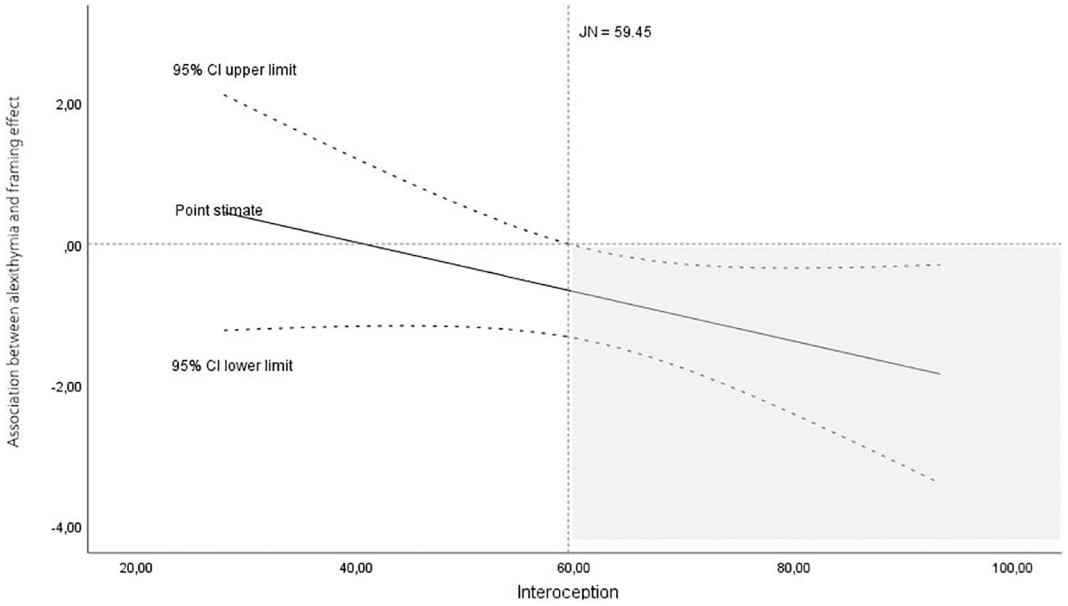


Fig. 2. Johnson-Neyman graph. Graph of the conditional association between alexithymia and the Framing effect, as a linear function of Interoception including the Johnson–Neyman transition point (*JN*). The *JN* point is where the confidence interval around the condition effect intersects zero on the y-axis. Thus, the shaded quadrant is the region of significance, i.e. those values of interoception for which the association between alexithymia and the framing effect was significant.

individual can become aware of or not depending in their interoception level (level 1). If there is a defect in this level, it means, if one is not aware of the signals sent by their bodies, it does not matter how and how well we label these signals (level 2). Put in another way, alexithymia, which is attributing somatic responses to emotions, would have an effect on our decisions *only* when these signals become conscious by functional interoceptive ability, hinting that they conduct on two different levels (Palser et al., 2018). These two levels are independent and a deficiency in one does not mean a defect in the other one necessarily. In fact, different studies have showed that interoception and alexithymia are independent constructs (Bird et al., 2011; Marchesi et al., 2000; Palser et al., 2018), as also backed by our correlational results. Thus, we can assume that they are two independent aspects that must coincide for a person to be more aware of their emotional responses.

These results can be explained by the somatic marker hypothesis (Bechara and Damasio, 2005; Poppa and Bechara, 2017) which takes into account how emotions derived from external stimuli affect our decision-making process. It assumes, contrary to the assumption that human decision-making is fully rational and systematic, that emotions play a determining role in decision-making. It posits that when encountered with a decision, different stimuli trigger somatic states (changes in heartbeat, SCRs, sweating, respiration changes, etc.) and depending on either these states are considered positive or negative by the individual, the behavioral outcome will be affected (Bechara and Damasio, 2005; Finucane et al., 2000; Slovic et al., 2004).

Taking the above description into account, just like we described before, it is a two-phase process: the first phase is the production and awareness of the somatic states triggered by a stimulus and *only* when these changes come into our awareness, the way we attribute them, correctly or not, to different emotions (second phase) will have an impact on our decisions. The first phase is dependent on our interoceptive abilities while the second one is subject to how effectively we recognize these changes and "label" them as different emotions; it means the level of alexithymia. However, for alexithymia to have a significant influence on our decisions, we first must be aware of the sensations coming from our body, if not, it means little, just like backed by our results.

Our findings can have important implications for decision-making and decision-making dysfunctions that have been reported in many psychiatric disorders resulting in excessive risk-taking or impulsivity in some disorders (e.g. Dom et al., 2005; Moeller et al., 2001; Swann et al., 2005) or excessive risk-aversion or demotivation in others (e.g. Epstein, 2006). These patients could benefit from the intervention programs involving interoception and emotional regulation training since it is been shown that decision-making process is highly influenced by somatic states awareness and emotional integration, promoting an adaptive decision-making in addition to a better learning of advantageous decision-making strategies (Bechara et al., 1997; Chiu et al., 2018; Dunn et al., 2010; Kano et al., 2011). In line with the somatic marker hypothesis (explained above), this occurs because decision-making is a complex process, which is constantly influenced by the feedback coming from the outside and from our own body. Hence, a good understanding of owns body reactions in certain situations and correct attribution and regulation of emotions can ease this feedback system in order to promote more responsible decisions avoiding excessive risk-taking or risk-aversion.

All in all, interoception accuracy and emotional regulation and expression training, such as with biofeedback or mindfulness, can promote a better acceptance and communication of own bodily feelings and self-control of the physiological processes (e.g. Nanke and Rief, 2004) and like this contributing to a more conscious decision-making.

Despite the interesting results, our study is not exempt from limitations. One of the main limitations is the sociodemographic homogeneity of our sample. Majority of our participants were young middle class healthy university students making the generalization of our results difficult to people of different ages and with different socioeconomic statuses. Another limitation is the use of the experimental financial paradigm and not real-life decision-making. In the future it would be interesting to contrast these results with real-life dilemmas since research has showed preference differences depending on what we are playing with (human lives vs money or objects) (RÖnnlund et al., 2005). Another thing to consider in the future is that we only measured interoceptive accuracy, how well one is *objectively* able to detect bodily sensation, in our case, counting heartbeats. In future research interoceptive sensibility, *subjective* perception of how accurate one is in perceiving bodily states, would be desirable since previous studies have showed mixed results regarding its relationship with alexithymia (Herbert et al., 2011; Shah et al., 2016). Finally, we would like to highlight

that our reliability index for the alexithymia was quite low (0.63) and in future studies a higher reliability would be desirable.

Studies coping with the question how alexithymia and interoception, separately and combined, affect the FE are rare and our research provides another evidence of the relationships between these variables, which is in accordance with the previous results. However, our study, to our knowledge, is the first to link the interaction between alexithymia and interoception to the FE and provide the evidence that there might be a two-stage processing of the emotional decision-making.

CRediT authorship contribution statement

Namra Manzoor: experiment design; data acquisition; writing.

Francisco Molins: study design and experiment supervision; data curation; statistical analyses.

Miguel Ángel Serrano: study design, reviewing and editing.

Declaration of competing interest

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this manuscript.

Acknowledgements

FM is a predoctoral research fellow, supported by the Generalitat Valenciana (ACIF/2020/062).

References

Aleman, A., 2005. Feelings you can't imagine: towards a cognitive neuroscience of alexithymia. Trends Cogn. Sci. 9 (12), 553–555.
Bagby, M., Parker, J.D.A., Taylor, G.J., 1994. The twenty-item Tronto alexithymia scale-I. item selection and cross-validation of the factor structure. J. Psychosom. Res. 38 (1), 23–32.
Barrett, L., Quigley, K.S., Bliss-Moreau, E., Aronson, K.R., 2012. Interoceptive sensitivity and self-reports of emotional. J. Pers. Soc. Psychol. 23 (1), 1–7. https://doi.org/10.1038/jid.2014.371.
Bechara, A., Damasio, A.R., 2005. The somatic marker hypothesis: a neural theory of economic decision. Games and Economic Behavior 52, 336–372. https://doi.org/10.1016/j.geb.2004.06.010.
Bechara, A., Damasio, A.R., Damasio, H., Anderson, S.W., 1994. Insensitivity to future consequences following damage to human prefrontal cortex. Cognition 50, 7–15.
Bechara, A., Damasio, H., Tranel, D., Damasio, A.R., 1997. Deciding advantageously before knowing the advantageous strategy. Science 275 (February), 1293–1295.
Bird, G., Press, C., Richardson, D.C., 2011. The role of alexithymia in reduced eye-fixation in autism spectrum conditions. J. Autism Dev. Disord. 41 (11), 1556–1564. https://doi.org/10.1007/s10803-011-1183-3.
Chakravarthy, V.S., Chakravarthy, V.S., 2019. Circuits of emotion. Demystifying the Brain 285–319. https://doi.org/10.1007/978-981-13-3320-0_10.
Chiu, Y.C., Huang, J.T., Duann, J.R., Lin, C.H., 2018. Editorial: twenty years after the Iowa gambling task: rationality, emotion, and decision-making. Frontiers in Psychology 8 (JAN), 1–5. https://doi.org/10.3389/fpsyg.2017.02353.
Craig, A.D., Craig, A.D., 2009. How do you feel –now? The anterior insula and human awareness recent findings of AIC activation. Nat. Rev. Neurosci. 10 (1), 1–31. Retrieved from. http://allmanlab.caltech.edu/McDonnellPDFs/CraigInPress.pdf.
Critchley, H.D., Wiens, S., Rotshtein, P., Öhman, A., Dolan, R.J., 2004. Neural systems supporting interoceptive awareness. Nat. Neurosci. 7 (2), 189–195. https://doi.org/10.1038/nn1176.
da Silva, A.N., Vasco, A.B., Watson, J.C., 2017. Alexithymia and emotional processing: a mediation model. J. Clin. Psychol. 73 (9), 1196–1205. https://doi.org/10.1002/jclp.22422.
De Martino, B., Kumaran, D., Seymour, B., Dolan, R.J., 2006. Frames, biases and rational decision-making in the human brain. Science 313 (5787), 684–687. https://doi.org/10.1126/science.1128356.
De Martino, B., Harrison, N.A., Knafo, S., Bird, G., Dolan, R.J., 2008. Explaining enhanced logical consistency during decision making in autism. J. Neurosci. 28 (42), 10746–10750. https://doi.org/10.1523/JNEUROSCI.2895-08.2008.
De Martino, B., Camerer, C.F., Adolphs, R., 2010. Amygdala damage eliminates monetary loss aversion. Proc. Natl. Acad. Sci. U. S. A. 107 (8), 3788–3792. https://doi.org/10.1073/pnas.0910230107.
Dom, G., Sabbe, B., Hulstijn, W., Van Den Brink, W., 2005. Substance use disorders and the orbitofrontal cortex: systematic review of behavioural decision-making and neuroimaging studies. British Journal of Psychiatry 187 (SEPT), 209–220. https://doi.org/10.1192/bjp.187.3.209.
Dunn, B.D., Galton, H.C., Morgan, R., Evans, D., Oliver, C., Meyer, M., Dalgleish, T., 2010. Listening to your heart: How interoception shapes emotion experience and intuitive decision making. Psychological Science 21 (12), 1835–1844. https://doi.org/10.1177/0956797610389191.
Epstein, J., 2006. Lack of ventral striatal response to positive stimuli in depressed versus normal subjects. Am. J. Psychiatr. 163 (10), 1784. https://doi.org/10.1176/appi.ajp.163.10.1784.
Erdfelder, E., Faul, F., Buchner, A., 1996. GPOWER: a general power analysis program. Behavior Research Methods, Instruments & Computers 28 (1), 1–11. https://doi.org/10.3758/BF03203630.
Evans, C.E.Y., Bowman, C.H., Turnbull, O.H., 2005. Subjective awareness on the Iowa gambling task: the key role of emotional experience in schizophrenia. J. Clin. Exp. Neuropsychol. 27 (6), 656–664. https://doi.org/10.1081/13803390490918354.
Finucane, M.L., Alhakami, A., Slovic, P., Johnson, S.M., 2000. The affect heuristic in judgments of risks and benefits. J. Behav. Decis. Mak. 13 (1), 1–17.
Hayes, A.F., 2017. Introduction to Mediation, Moderation and Conditional Process Analysis: A Regression-Based Approach. Guildford Press, Nueva York, EEUU.
Herbert, B.M., Herbert, C., Pollatos, O., 2011. On the relationship between interoceptive awareness and alexithymia: is interoceptive awareness related to emotional awareness? J. Pers. 79 (5), 1149–1175. https://doi.org/10.1111/j.1467-6494.2011.00717.x.
Hsing, C.K., Mohr, A.H., Stansfield, R.B., Preston, S.D., 2013. Alexithymia slows performance but preserves spontaneous semantic decoding of negative expressions in the emostroop task. International Journal of Psychological Research 6 (SPEC. ISSUE), 56–67. https://doi.org/10.21500/20112084.719.
Kacelnik, A., Bateson, M., 1996. Risky theories — the effects of variance on foraging decisions. Am. Zool. 36 (4), 402–434.
Kacelnik, A., Bateson, M., 1997. Risk-sensitivity: crossroads for theories of decision-making. Trends Cogn. Sci. 1 (8), 304–309.
Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. Econometrica 47 (2), 263.
Kano, M., Ito, M., Fukudo, S., 2011. Neural substrates of decision making as measured with the Iowa gambling task in men with alexithymia. Psychosom. Med. 73 (7), 588–597. https://doi.org/10.1097/PSY.0b013e318223c7f8.
Laloyaux, J., Fantini, C., Lemaire, M., Luminet, O., Larøi, F., 2015. Evidence of contrasting patterns for suppression and reappraisal emotion regulation strategies in alexithymia. J. Nerv. Ment. Dis. 203 (9), 709–717. https://doi.org/10.1097/NMD.0000000000000353.
Lane, R.D., Sechrest, L., Riedel, R., Shapiro, D.E., Kaszniak, A.W., 2000. Pervasive emotion recognition deficit common to alexithymia and the repressive coping style. Psychosom. Med. 62 (4), 492–501. https://doi.org/10.1097/00006842-200007000-00007.
Ledoux, J.E., 2000. Emotion circuits in the brain. Annu. Rev. Neurosci. 23 (1), 155–184.
Marchesi, C., Brusamonti, E., Maggini, C., 2000. Are alexithymia, depression, and anxiety distinct constructs in affective disorders? J. Psychosom. Res. 49 (1), 43–49.
Martínez-sánchez, F., 1996. Adaptación española de la escala de Alexitimia de Toronto (TAS-20). Clínica y SAlud 7 (1), 19–32 (January).
Mellers, B.A., Schwartz, A., Cooke, D.J., 1998. Judgment and decision making. Annual Review of Psuchology 49, 447–477.
Moeller, F.G., Dougherty, D.M., Barratt, E.S., Schmitz, J.M., Swann, A.C., Grabowski, J., 2001. The impact of impulsivity on cocaine use and retention in treatment. J. Subst. Abus. Treat. 21 (4), 193–198. https://doi.org/10.1016/S0740-5472(01)00202-1.
Montoya, A.K., 2019. Moderation analysis in two-instance repeated measures designs: probing methods and multiple moderator models. Behav. Res. Methods 51 (1), 61–82. https://doi.org/10.3758/s13428-018-1088-6.
Nanke, A., Rief, W., 2004. Biofeedback in somatoform disorders and related syndromes. Current Opinion in Psychiatry 12 (2), 133–138.
Palser, E.R., Palmer, C.E., Galvez-pol, A., Hannah, R., Fotopoulou, A., Kilner, J.M., 2018. Alexithymia mediates the relationship between interoceptive sensibility and anxiety. PLoS One 13 (9), 1–11. https://doi.org/10.1371/journal.pone.0203212.
Phelps, E.A., 2006. Emotion and cognition: insights from studies of the human amygdala. Annu. Rev. Psychol. 57, 27–53. https://doi.org/10.1146/annurev.psych.56.091103.070234.
Pollatos, O., Herbert, B.M., Matthias, E., Schandry, R., 2007. Heart rate response after emotional picture presentation is modulated by interoceptive awareness. Int. J. Psychophysiol. 63 (1), 117–124. https://doi.org/10.1016/j.ijpsycho.2006.09.003.
Poppa, T., Bechara, A., 2017. The somatic marker hypothesis: revisiting the role of the ' body-loop ' in decision-making. Curr. Opin. Behav. Sci. 19, 61–66. https://doi.org/10.1016/j.cobeha.2017.10.007.
Preuschoff, K., Quartz, S.R., Bossaerts, P., 2008. Human insula activation reflects risk prediction errors as well as risk. J. Neurosci. 28 (11), 2745–2752. https://doi.org/10.1523/JNEUROSCI.4286-07.2008.
Ring, P., 2015. The framing effect and skin conductance responses. Frontiers in Behavioral Neuroscience 9 (AUGUST), 1–7. https://doi.org/10.3389/fnbeh.2015.00188.
Roiser, J.P., De Martino, B., Tan, G.C.Y., Kumaran, D., Seymour, B., Wood, N.W., Dolan, R.J., 2009. A genetically mediated bias in decision making driven by failure of amygdala control. J. Neurosci. 29 (18), 5985–5991. https://doi.org/10.1523/JNEUROSCI.0407-09.2009.
RÖnnlund, M., Karlsson, E., Laggnäs, E., Larsson, L., Lindström, T., 2005. Risky decision making across three arenas of choice: are younger and older adults differently susceptible to framing effects? J. Gen. Psychol. 132 (1), 81–93. https://doi.org/10.3200/GENP.132.1.81-93.
Salminen, J.K., Saarijärvi, S., Äärelä, E., Toikka, T., Kauhanen, J., 1999. Prevalence of alexithymia and its association with sociodemographic variables in the general population of Finland. J. Psychosom. Res. 46 (1), 75–82. https://doi.org/10.1016/S0022-3999(98)00053-1.

Sarlo, M., Lotto, L., Palomba, D., Scozzari, S., Rumiati, R., 2013. Framing the ultimatum game: gender differences and autonomic responses. Int. J. Psychol. 48 (3), 263–271. https://doi.org/10.1080/00207594.2012.656127.

Schandry, R., 1981. Heart beat perception and emotional experience. Psychophisiology 18 (4), 483–488. https://doi.org/10.1111/j.1469-8986.1981.tb02486.x.

Shah, P., Hall, R., Catmur, C., Bird, G., 2016. Alexithymia, not autism, is associated with impaired interoception. Cortex 81, 215–220. https://doi.org/10.1016/j.cortex.2016.03.021.

Sifneos, P.E., 1973. The prevalence of "alexithymic" characteristics in psychosomatic patients. Psychother. Psychosom. 22 (2–6), 255–262.

Slovic, P., Finucane, M.L., Peters, E., Macgregor, D.G., 2004. Risk as analysis and risk as feelings: some thoughts about affect, reason, risk, and rationality. Risk Analysis: An International Journal 24 (2), 311–322.

Sütterlin, S., Schulz, S.M., Stumpf, T., Pauli, P., Vögele, C., 2013. Enhanced cardiac perception is associated with increased susceptibility to framing effects. Cogn. Sci. 37 (5), 922–935. https://doi.org/10.1111/cogs.12036.

Swann, A.C., Dougherty, D.M., Pazzaglia, P.J., Pham, M., Steinberg, J.L., Moeller, F.G., 2005. Increased impulsivity associated with severity of suicide attempt history in patients with bipolar disorder. Am. J. Psychiatr. 162 (9), 1680–1687. https://doi.org/10.1176/appi.ajp.162.9.1680.

Trepel, C., Fox, C.R., Poldrack, R.A., 2005. Prospect theory on the brain ? Toward a cognitive neuroscience of decision under risk. Cogn. Brain Res. 23 (1), 34–50. https://doi.org/10.1016/j.cogbrainres.2005.01.016.

Turnbull, O.H., Bowman, C.H., Shanker, S., Davies, J.L., 2014. Emotion-based learning: insights from the Iowa gambling task. Frontiers in Psychology 5 (MAR), 1–11. https://doi.org/10.3389/fpsyg.2014.00162.

Tversky, A., Kahneman, D., 1981. The framing of decisions and the psychology of choice. Science 211 (4481), 452–458.

Tversky, A., Kahneman, D., 1992. Advances in prospect theory: cumulative representation of uncertainty. J. Risk Uncertain. 5 (4), 297–323.

Vermeer, A.B.L., Sanfey, A.G., 2015. The effect of positive and negative feedback on risk-taking across different contexts. PLoS One 10 (9), 1–13. https://doi.org/10.1371/journal.pone.0139010.

Wiens, S., Mezzacappa, E.S., Katkin, E.S., 2000. Heartbeat detection and the experience of emotions. Cognit. Emot. 14 (3), 417–427.

Xue, G., Lu, Z., Levin, I.P., Bechara, A., 2011. An fMRI study of risk-taking following wins and losses: implications for the gambler's fallacy. Hum. Brain Mapp. 32 (2), 271–281. https://doi.org/10.1002/hbm.21015.

Zaki, J., Davis, J.I., Ochsner, K.N., 2012. Overlapping activity in anterior insula during interoception and emotional experience. Neuroimage 62 (1), 493–499. https://doi.org/10.1016/j.neuroimage.2012.05.012.Overlapping.

Zamariola, G., Vlemincx, E., Luminet, O., Corneille, O., 2018. Relationship between interoceptive accuracy, interoceptive sensibility, and alexithymia. Personal. Individ. Differ. 125 (January 2018), 14–20. https://doi.org/10.1016/j.paid.2017.12.024.

4. Heart rate variability after vigorous physical exercise is positively related to loss aversion

ANXIETY, STRESS, & COPING
https://doi.org/10.1080/10615806.2020.1865531

Routledge
Taylor & Francis Group

Heart rate variability after vigorous physical exercise is positively related to loss aversion

Francisco Molins and Miguel Ángel Serrano

Department of Psychobiology, Universitat de València, Valencia, Spain

ABSTRACT

Background and Objectives of the article: Loss aversion bias, whereby losses loom larger than gains, can be reduced by stress. At the same time, vigorous physical exercise is a powerful neuroendocrine stressor and heart rate variability (HRV) provides an objective measure of the actual exercise impact, relative to each individual physical condition. Our aim was to study whether vigorous exercise can influence loss aversion, considering HRV in this relation. We hypothesized that the lower HRV derived from vigorous exercise (i.e., when stressor produced the most impact) would predict a lower loss aversion.

Methods: Two groups (Experimental, $N = 37$; Control, $N = 39$) completed a loss aversion task, but the experimental group was exposed to an acute physical stressor before.

Results: Results revealed a significant group x HRV interaction. In the control group, HRV was not associated with loss aversion. Conversely, as hypothesized, the lower HRV levels derived from exercise were associated with a lesser loss aversion in the experimental group.

Conclusions: Results suggest that physiological changes from physical exercise could affect decision-making by reducing loss aversion.

ARTICLE HISTORY
Received 16 May 2020
Revised 5 November 2020
Accepted 18 November 2020

KEYWORDS
Loss aversion; stress; physical exercise; heart rate variability; decision-making

Introduction

Kahneman and Tversky (1979) stated that losses loom larger than gains. In other words, we are more sensitive to losses and our decisions are highly shaped by them: this is known as loss aversion bias. The current view is that loss aversion is variable and depends on the context. Stress can affect its expression, although the direction of this effect is still unclear and could differ depending on the type of stressor. Even though physical exercise is a powerful systemic stressor that is common in our daily lives, its effects on loss aversion have never been explored. This study sheds light on this issue.

Loss aversion is one of the most widely accepted ideas in the social sciences, where it is often considered ubiquitous (Gal et al., 2018). This belief is supported by the fact that this bias has been documented in more than 50 countries (Wang et al., 2017), with different experimental paradigms (e.g., Metz et al., 2020; Viswanathan et al., 2015); outside of the laboratory settings, like in politics (Berejikian & Early, 2013) or playing golf (Pope & Schweitzer, 2011); and even in other species, such as monkeys (Chen et al., 2006) or rats (Constantinople et al., 2019). Loss aversion has also shown a stable neural base, which includes the executive network, the salience network and the reward system (Molins & Serrano, 2019), and whose resting state predicts the behavioral loss aversion (Canessa et al., 2017). All this seems to suggest that loss aversion could be a stable trait that affects everyone, all the time.

CONTACT Miguel Ángel Serrano maserrar@uv.es, m.angel.serrano@uv.es

However, this ubiquity has been challenged. The review of Gal et al. (2018, p. 497) point out that "current evidence does not support that losses, on balance, tend to be any more impactful than gains." In fact, gains could have more impact than losses in some contexts (Gal et al., 2018). Hochman and Yechiam (2011) found that even when the autonomic nervous system is more responsive to losses, this does not necessarily translate into greater behavioral loss aversion. These authors also hold that the influence that losses exert on decisions would be better explained by attention-based and contrast-based processes rather than by an overestimation of losses (Yechiam & Hochman, 2013). Similarly, Ert and Erev (2013) indicate that loss aversion may only appear when experimental manipulation is conducive to it. For example, when large economic amounts are at stake or when faced with long experiments that do not provide feedback after the successive decisions.

Despite these discrepancies, loss aversion continues gathering studies that try to clarify the phenomenon. The current thinking is that loss aversion is not necessarily ubiquitous, but a complex and variable phenomenon subject to contextual and individual influences (Gal et al., 2018; Mrkva et al., 2020). Some authors explore which individual aspects may favor the emergence of the bias (Boyce et al., 2016). And others address contextual aspects, such as culture (Wang et al., 2017), or the influence of stress, among others. The latter is the focus of our study.

Many decisions are made under stress, and accumulating evidence indicates that this factor significantly influences loss aversion (Margittai et al., 2018); nevertheless, it remains unclear the direction of this effect. Two hypotheses coexist. The "salience-of-losses" hypothesis suggests that acute stress reallocates the resources in the brain, producing a suppression of the executive network and higher activation of the salience network; thus, enhancing salience of losses and amplifying loss aversion (Metz et al., 2020). However, the most accepted is the "alignment" hypothesis (Metz et al., 2020), supported by the STARS model (Stress Triggers Additional Reward Salience) (Mather & Lighthall, 2012). According to this approach, under stress, losses will not loom larger than gains given that the latter become more attractive; this is, "reward and threat susceptibility are aligned" (Metz et al., 2020, p. 2).

Although seemingly contradictory, both hypotheses may not be mutually exclusive and may reflect different stress phases, depending on their two main physiological pathways: the fast activation of the sympathetic nervous system (SNS), which triggers catecholamines release; and the slower hypothalamus-pituitary-adrenal axis (HPA-axis) activation, resulting in a secretion of cortisol (Hidalgo et al., 2019). In this line, a positive relationship was found between norepinephrine brain levels and loss aversion (Sokol-Hessner & Rutledge, 2019; Takahashi et al., 2013). Yet, concurrent glucocorticoid and catecholaminergic activity significantly reduced loss aversion (Margittai et al., 2018). So, it seems that depending on the SNS and HPA-axis activity, both hypotheses may be supported. Nevertheless, it is also necessary to consider that different stressors can differ in the expression and the magnitude of their physiological responses (Hidalgo et al., 2019). Thus, it is important not to study stress in the singular, but how different stressors impact on loss aversion. When studying stress and loss aversion, the direct manipulation of catecholamines or cortisol is the most common practice (e.g., Margittai et al., 2018; Metz et al., 2020). Only a few physical or systemic stressors, such as Cold Pressor Test (Sokol-Hessner et al., 2016) or an oxygen-depleted environment (hypoxia) (Pighin et al., 2014) have also been tested, reporting mixed results: no-effects and reduced loss aversion, respectively. However, no other stressors have been studied.

Physical exercise is the gold standard recommendation to improve health and it constitutes a common activity in our daily living. Although healthy, exercise disturbs the homeostasis and forces organism to adapt to these demands. As exercise intensity increases, so does the activation of SNS and HPA-axis, and consequently, the circulating concentrations of catecholamines and cortisol (Hackney, 2006). Thus, exercise is considered a powerful stressor of the neuroendocrine system (Hackney, 2006). It has also been widely reported that exercise can affect cognition. The regular practice is usually related to improvements, but the acute effect from a single bout is variable. While a moderate exercise showed benefits on cognitive functions, a heavy exercise bout was related to

increased perceived stress levels (Hopkins et al., 2012) and impairments on cognitive processing (Shibasaki et al., 2019). Despite the exercise's role as stressor, its influence on decision-making and, more specifically, on loss aversion has never been studied. The aim of the present research is to fill this gap.

Considering the above, we expect that vigorous exercise will reduce loss aversion, as seem to do other stressors that produce the strong activation of both SNS and HPA-axis. However, an issue when studying exercise as stressor is that, even if the intensity exposure is systematized, physical condition can modulate the real impact of the stressor (Hackney, 2006). Recently, heart rate variability (HRV) has been proposed as an objective non-invasive indicator of the exercise impact (Michael et al., 2017). HRV refers to the variation in the time interval between heartbeats, which occurs through the actions of the cardiac sympathetic (cSNA) and parasympathetic (cPNA) neural activity (Grossmann et al., 2016). It can be studied through many indicators, but concretely, markers associated with the cPNA (cPNA-HRV) are systematically reduced as exercise intensity increases (Michael et al., 2017). Therefore, at a constant intensity, measuring cPNA-HRV provides information on the actual exercise impact relative to each individual physical condition. It is important to include this variable in the exercise–loss aversion relation to not consider solely the exercise practice, but how this exercise is really affecting. In this line, we hypothesize that, when measuring loss aversion with an economical decision-making task, the lower cPNA-HRV derived from vigorous exercise (i.e., when stressor produced the most impact) will predict the lower loss aversion levels.

Materials and methods

Participants.

A sample of 61 participants is required to detect medium effect size ($d = 0.50$, power = 80%, $\alpha = 0.05$) in a HRV study (Laborde et al., 2017). Complementarily, previous studies specifically relating HRV and loss aversion obtained medium effect sizes ($d = 0.50$) (Mintoft et al., 2012; Sütterlin et al., 2011). Taking this size as a reference, we carried out an a priori power analysis using G*Power, which indicated a requisite of 74 participants ($d = 0.50$, power = 80%, $\alpha = 0.05$) to perform a general lineal model studying main effect (exercise vs control group), covariate (cPNA-HRV) and their interaction (group × cPNA-HRV) on loss aversion.

We oversampled 16 participants to account for possible exclusions. 90 participants were recruited. 14 were eliminated (4 for drug consumption, 4 for accepting or rejecting bets by default when measuring loss aversion, and 6 for not reaching the intensity preset during exercise). A total of 76 participants (women: $N = 61$; age: $M = 22.29$, $SD = 2.17$) were finally included. All of them met the following inclusion criteria: not having cardiovascular, endocrine, neurological or psychiatric diseases; not having impediments to practice exercise; not consuming more than 5 cigarettes a day; not consuming drugs habitually; not doing more than 10 h of exercise per week; not having experienced a highly stressful event in the last month; not having practiced extenuating exercise nor consumed drugs 24 h before and not having taken stimulant drinks in the 2 h before the experiment. Participants were randomly distributed into two groups, experimental ($N = 37$) and control ($N = 39$).

Procedure

This study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki. All sessions were carried out between 15:30 pm and 19:00 pm and lasted approximately one hour and a half. The procedure was explained, and informed consent was signed. Afterwards, they were connected to the polygraph and had 10 min of rest as habituation. Only experimental group was exposed to stress (exercise), but both groups performed an economical decision-making task to measure loss aversion. The control group directly began this task, without waiting for the time that the stressor lasts to avoid boredom (another type of stressor) or relaxation (different level to the basal). Before and after the stressor,

participants were evaluated for positive and negative mood with the Positive and Negative Affect registry, PANAS (Thompson, 2007).

Vigorous exercise stressor

Participants completed 15 min in a cycloergometer. Adapting the protocol of Frith et al. (2017), first 5 min were used as warm-up. In the following 5, pedaling intensity was progressively increased. Finally, last 5 min had to be performed at 70–80% of maximum heart rate (HR_{max}), i.e., vigorous exercise (Ponce et al., 2019). The specific HR was calculated for each participant, using the classic formula of Karvonen et al. (1957), $((HR_{max} - HR_{resting}) \times \%intensity) + HR_{resting}$, were HR_{max} was estimated with the formula of Tanaka et al. (2001), $HR_{max} = 208 - (0.7 \times age)$; and $HR_{resting}$ was obtained averaging the last 5 min of the habituation period (baseline). On average, our sample had to be between 158.11 (*SD* = *3*.42) and 169.46 (*SD* = 2.61) bpm (70 and 80% HR_{max}, respectively).

Mixed gamble task (MGT)

Both groups performed a short version of MGT (Chandrasekhar Pammi et al., 2015). Each trial entailed a bet with one of the combinations randomly extracted from an 8×8 losses and gains matrix, until the 64 combinations were completed. Following the gamble ranges used by Chandrasekhar Pammi et al. (2015), as well as by Tom et al. (2007) in the original task, gains could range from €100 to €380 in €40 increments, and losses from €50 to €190 in €20 increments. Tom et al. (2007, p. 516) selected these unbalanced ranges because "previous studies indicate that people are, on average, roughly twice as sensitive to losses as to gains; thus (they) expected that, for most participants, this range of gambles would elicit a wide range of attitudes". We decided to retain the original unbalanced approach, presenting larger gains than losses.

This approach could bias and inflate loss aversion, suggesting that it would be better a balanced approach, as other authors have used (e.g., Barkley-Levenson et al., 2013; Canessa et al., 2017). However, given the extensive and recent literature that uses the unbalanced approach (e.g., Chandrasekhar Pammi et al., 2015, 2017; Charpentier et al., 2016; Duke et al., 2018), which, in addition, shows loss aversion values close to those originally indicated in the classic literature (Kahneman et al., 1991; Kahneman & Tversky, 1979, 1984), it seems appropriated to use this approach to measure loss aversion. Moreover, given the experimental nature of our study, choosing a balanced or unbalanced approach seems less relevant. Both groups were submitted to the same task, which still allows us to study if stress affects the differential expression of this phenomenon. Nevertheless, results must be interpreted according to the approach used.

In each trial there was a 50% chance of gaining and 50% chance of losing. Participants had to decide whether to accept or reject the bet. They were instructed that €200 was their initial amount and each bet had to be done with that reference. Betting results were not presented immediately, however, they had to choose carefully in each trial since, at the end, four bets would be randomly picked and played heads or tails, affecting the initial amount. Logistic regressions were performed with each participant using possible gains and losses as independent variables, and acceptance or rejection as dependent. Thus, β of gains and β of losses were obtained, being able to apply the formula of Tom et al. (2007): $\lambda = (-\beta_{loss}/\beta_{gain})$, to calculate λ parameter, which represents loss aversion. $\lambda \geq 0.5$ signals the presence of loss aversion.

Heart rate variability (HRV)

Electrocardiogram was recorded using Einthoven's third derivation with 3 reusable electrodes, BIOPAC MP150, an ECG-100C transducer and AcqKnowledge software. Sampling frequency was 1000 Hz. Following Task Force guidelines (1996), five-minute records were standardized. Thus, the 5 baseline minutes and the central 5 of MGT were exported to Kubios software to extract cPNA-HRV. Previously, ECG signals were visually analyzed to detect ectopic beats and other artifacts. 7 participants showed ectopic beats which were corrected using the Heart Timing Signal method (Mateo & Laguna, 2003), and thus, they were included in the posterior analysis. In Kubios, each participant

was also analyzed individually and the threshold-based artefact correction algorithm (Tarvainen et al., 2014), which removes artefacts without distorting normal RR intervals, was applied. According to the recommendations of Tarvainen et al. (2014), since HRV is highly individual, the threshold value, which can range from very low to very strong, was adjusted individually. Finally, as a detrending method, it is, in order to control the possibly slow changes in mean HR during the recording, the smooth prior's filter (Tarvainen et al., 2014) was also applied.

According to Michael et al. (2017), the most reliable cPNA-HRV markers against exercise would be the following: for time domain, the root mean square of successive differences of R-R intervals (RMSSD) in milliseconds. For frequency domain, by means of Fast Fourier Transformation, the high-frequency band (0.15–0.40 Hz) in absolute units (ms^2/Hz; HF_{powfft}).

In short, the cPNA-HRV markers included in our study were: RMSSD and HF_{powfft}, both in a tonic and a phasic level. Phasic level was computed subtracting baseline HRV to MGT HRV (i.e., reactivity). Finally, following Grossmann et al. (2016), to minimize the chance of α-inflation due to multiple testing, and to avoid cherry-picking a marker yielding desirable results from those included, we performed a principal component analysis (PCA) on cPNA-HRV markers and performed primary statistical analyses on the retained factor scores. PCA yielded a one-component solution (HRV-factor): variance explained: 97.58%; loadings: RMSSD = .98, HF_{powfft} = .98. PCA was also performed in the phasic level with similar results (HRV_{phasic}-factor): variance explained: 95.68%; loadings: $RMSSD_{phasic}$- = .97, $HF_{powfft\text{-}phasic}$ = .97.

Respiratory frequency (RF)

Laborde et al. (2017) recommend not to engage in routine correction of HRV for respiration, while still monitoring RF, especially after exercise, to check if it remains between 9 and 24 cycles per minute, needed for the proper interpretation of HF power band. Post-exercise RF (i.e., during MGT) was measured with a sampling frequency of 1000 Hz, using a breathing band under the chest muscles and the RSP-100C transducer. Signal was re-sampled at 50 Hz and filtered by digital Band Pass FIR filter (low cut-off frequency: 0.05 Hz; high cut-off frequency: 1 Hz). Visual inspection was performed to detect artefacts and correct them if needed. To extract RF, positive peaks were detected without removing the baseline and threshold was set at 0 ppm.

Statistical analyses

Outliers were detected with the 2.5 standard deviations method and Mahalanobis distance. Kolmogorov-Smirnoff with Lilliefors correction was used to check normality. RMSSD and HF_{powfft} both in baseline and during MGT, were log10 normalized (Field, 2009). Analyses included Pearson's correlations and multivariate general linear models for cPNA-HRV and loss aversion. The α significance level was set at .05. Partial eta square (η_p^2) symbolizes the effect size and β-1 (power) represents power. All analyses were performed with IBM SPSS Statistics 23, except for the extraction of λ which was done with R i386.

Results

Preliminary analysis

As can be seen in Table 1, experimental and control groups were homogeneously distributed, with no significant differences in age, BMI, exercise hours per week nor in positive/negative mood. There were more women than men, but both groups maintained the same proportion. It can also be checked that the experimental group's heart rate during last 5 min of exercise (HR 15') was within the expected range (between $M = 158.11$, $SD = 3.42$ y $M = 169.46$, $SD = 2.61$). In addition, extra analysis for the experimental group showed that positive and negative mood pre- and post-exercise did not differ significantly ($p = .32$ and $p = .52$, respectively).

Table 1. Homogeneity between groups and heart rate during stressor.

	Experimental (N = 37)	Control (N = 39)	*F*	df between	df within	*p*-value
Age	*M* = 22.62 ± 2.67	*M* = 21.97 ± 1.54	1.69	1	74	.19
Sex						
Men	16.2%	23.1%	0.6†	1	15†	.43
Women	83.8%	76.9%	0.02†	1	61†	.89
BMI	*M* = 22.32 ± 2.97	*M* = 22.45 ± 2.79	0.03	1	74	.87
Exercise hours per week	*M* = 3.28 ± 2.61	*M* = 3.01 ± 2.39	1.1	1	74	.65
PANAS						
Positive mood	*M* = 27.54 ± 4.69	*M* = 28.1 ± 3.89	0.32	1	74	.57
Negative mood	*M* = 21.54 ± 4.53	*M* = 22.64 ± 4.54	1.11	1	74	.29
Vigorous exercise (bpm)						
HR 5′	*M* = 130.47 ± 12.94	–	–	–	–	–
HR 10′	*M* = 155.73 ± 9.21	–	–	–	–	–
HR 15′	*M* = 164.14 ± 4.8	–	–	–	–	–

M, mean; ±, *SD*; BMI, weight(kg) / height(m)^2; Positive mood, 10 items of positive mood added; Negative mood, 10 items of negative mood added; Vigorous exercise (bpm), beats per minute in 5-minute intervals. † these values correspond to χ2 and not to *F*, as well as to *N* and not to gl intra.

Impact of exercise on HRV

First, multivariate general lineal model on HRV showed a significant main effect of the moment (baseline vs. MGT), $F(3, 72) = 81.40$, $p < .001$, $\eta_p^2 = .70$, power = 1; and a significant condition (experimental vs. control) x moment interaction, $F(3, 72) = 37.28$, $p < .001$, $\eta_p^2 = .53$, power = 1. We explored this effect further. When contrasting by groups for differences in cPNA-HRV markers between the baseline and the MGT, the experimental group variables were significantly lower in the MGT than in the baseline: RMSSD, $F(1, 36) = 168.1$, $p < .001$, $\eta_p^2 = .82$, power = 1; HF_{powfft}, $F(1, 36) = 96.48$, $p < .001$, $\eta_p^2 = .73$, power = 1. Similarly, the control group also revealed differences in HF_{powfft}, $F(1, 38) = 7.54$, $p = .009$, $\eta_p^2 = .17$, power = .76; and RMSSD, $F(1, 38) = 14.95$, $p < .001$, $\eta_p^2 = .31$, power = .96; showing higher levels in the baseline than in the MGT. Means and SD can be consulted in Table 2. However, intergroup analysis revealed that, although both groups did not differ in cPNA-HRV markers in the baseline (see Table 2), they showed statistically significant differences when these variables were contrasted after exercise (i.e., during the MGT). As we see in Table 2, the experimental group had lower RMSSD and HF_{powfft} values with respect to the control group. Figure 1 summarizes the results for an easy interpretation.

Checking for normal respiratory frequency (RF)

The experimental group RF during MGT ($M = 18.12$, $SD = 2.47$) did not significantly differ from control group RF ($M = 17.15$, $SD = 2.64$), $F(1, 74) = 2.68$, $p = .11$. In addition, both groups showed a normal breathing (between 9 and 24 bpm), making our results interpretable.

Table 2. HRV intergroup differences during baseline and Mixed Gamble Task (MGT).

		Experimental (*N* = 37)	Control (*N* = 39)	*F*	df between	df within	*p*-value	η_p^2	β-1
Baseline	RMSSD	*M* = 45.53 ± 19.70	*M* = 44.25 ± 21.25	0.12	1	74	.72	.02	.064
	HFpowfft	*M* = 1030.22 ± 936.51	*M* = 831.72 ± 728.05	0.49	1	74	.48	.07	.107
MGT	RMSSD	*M* = 19.9 ± 12.35	*M* = 32.92 ± 12.4	25.65**	1	74	< .001	.26	.99
	HFpowfft	*M* = 299.05 ± 472.54	*M* = 580.78 ± 497.74	22.19**	1	74	< .001	.23	.99

Note: Although contrasts were made with variables transformed with log10, original means are shown to facilitate interpretation.
** Significant contrast at the .01 level. M, mean; ±, SD;

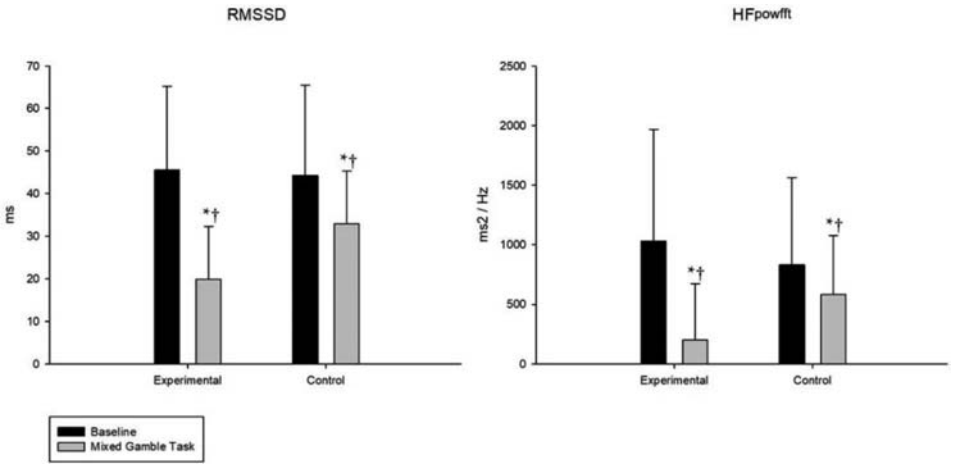


Figure 1. Heart rate variability markers by groups during baseline (pre-exercise) and Mixed Gamble Task (post-exercise). From left to right, RMSSD and HFpowfft compared by condition (experimental vs. control) and by time (baseline vs. MGT). M + SD. * intergroup significant differences; † intragroup significant differences.

Loss aversion and HRV

First, we checked if our sample was loss averse (i.e., $\lambda \geq 0.5$). Both, experimental ($M_{\lambda} = 3.11$, $SD = 1.5$), and control group ($M_{\lambda} = 2.98$, $SD = 1.59$), showed behavioral loss aversion. Moreover, we examined how condition (experimental vs. control), tonic HRV-factor, and their interaction predict λ parameter. BMI, exercise hours per week and respiration rate were included as covariates; results without covariates were very similar. We observed no significant main effects, p's > .05, but, as expected, a significant condition x HRV-factor interaction, $B = 1.48$, $SE = 0.39$, $t = 3.82$, $p < .001$, $\eta_p^2 = .18.8$, power = .96. The same interaction was also found at the phasic level, $B = 1.27$, $SE = 0.55$, $t = 2.31$, $p = .025$, $\eta_p^2 = .081$, power = .62. As Figure 2 and Table 3 indicate, in the experimental group, each HRV marker was positively associated with loss aversion. In contrast, there was no significant HRV-factor associations in the control group.

Discussion

The present work provides the first direct test of the physical exercise as a stressor influencing loss aversion. As was expected, after a vigorous exercise bout, the lower cPNA-HRV, which would indicate the greater exercise impact, was associated with lower loss aversion levels. This relationship was robust across both time-method- and frequency-method-based markers of tonic and phasic cPNA-HRV. Therefore, we could think that exercise constitutes a stressor capable of influencing decision-making. These results will be discussed in depth below. Nevertheless, since this is the first evidence linking physical stress and loss aversion, caution is recommended in their interpretation until further research replicates these findings.

First, it is important to address whether the stress manipulation was effective. As we see, both groups showed lower cPNA-HRV during the betting task (MGT) respecting to their baseline. HRV is susceptible to many kinds of stressors and can be reduced against them (Ciabattoni et al., 2017). MGT itself could constitute an acute cognitive stressor since it is cognitively demanding (Ciabattoni et al., 2017) and, therefore, the decrease found may be attributable to the task itself. However, intergroup analysis during the MGT revealed that, in average, this decrement was significantly higher in the experimental group. Thus, reflecting the expected exercise influence.

Attending now to loss aversion, the values in our study (near to 3) were higher than 2-2.5, which is usually what is stated in the literature (Duke et al., 2018; Kahneman & Tversky, 1979; Tom et al., 2007).

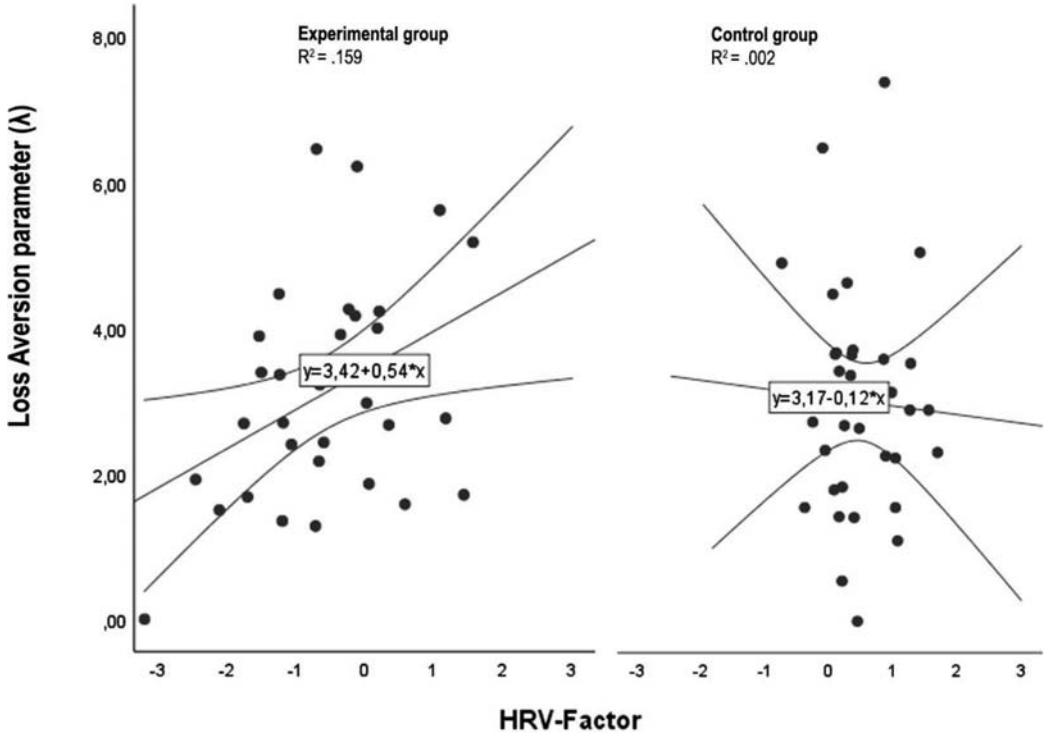


Figure 2. Relationship between heart rate variability composite factor and loss aversion by condition (experimental vs. group).

Table 3. Correlations between λ and heart rate variability markers (tonic and phasic) during MGT (by group).

		Loss aversion parameter (λ)		
		r	*N*	*p*-value
Experimental	RMSSD	.362*	36	.042
	HF_{powfft}	.424*	36	.016
	HRV-factor	.398*	36	.024
	Phasic RMSSD	.391*	36	.029
	Phasic HF_{powfft}	.363*	36	.045
	Phasic HRV-factor	.377*	36	.04
Control	RMSSD	−.105	38	.54
	HF_{powfft}	−.122	38	.47
	HRV-factor	−.044	38	.80
	Phasic RMSSD	−.06	38	.73
	Phasic HF_{powfft}	.008	38	.96
	Phasic HRV-factor	.013	38	.94

p-values were calculated with Pearson correlations. *significant at the .05 level.

These values could be due to the use of a task with unbalanced gain/loss ranges, which may artificially inflate loss aversion. However, as example, Barkley-Levenson et al. (2013) used a balanced approach and found loss aversion values even larger for both teenagers and adults, which would indicate that there may be other factors, and not the task itself, that explain the high value. Moreover, the literature also accepted as valid values close to 3 and higher, both with balanced and unbalanced approaches (e.g., Barkley-Levenson et al., 2013; Chandrasekhar Pammi et al., 2017; Gelskov et al., 2015); therefore, it seems that our results would be generalizable to the rest of the field of study.

Regarding the influence of stress on loss aversion, our data suggest that each group needs to be discussed separately. Focusing on the control group, no HRV marker was associated with loss

aversion. This result seems to contradict previous studies that reported negative correlations between HRV and the framing effect (Sütterlin et al., 2011) or the disposition effect (Mintoft et al., 2012), phenomena that are closely linked to loss aversion. Nevertheless, the results of both studies were extracted with HRV indicators that are now being widely questioned (e.g., LF/HF ratio or HF in normalized units) and its use is not encouraged (Reyes del Paso et al., 2013; Shaffer & Ginsberg, 2017). None of the markers that we used yielded significant results in the above-mentioned studies. Thus, in future it will be necessary to further explore with robust HRV markers to clarify whether the data found to date can be replicated or, conversely, HRV is not related to loss aversion, in line with our results.

By the other side, all cPNA-HRV markers, both at tonic and phasic level, were positively associated with loss aversion in the experimental group. Experimental group was affected by the exercise. Given the constant intensity (70–80% HR_{max}), a steeper reduction in cPNA-HRV markers within the experimental group would indicate a greater exercise impact (Michael et al., 2017). These variations in HRV reflect mechanical changes in the heart and do not necessarily wider changes in the organism, but as Michael et al. (2017) suggest, since these variations are produced by exposure to vigorous exercise, it would be expected that they also reflect the known autonomous heart regulation during exercise, i.e., a PNS withdrawal and a SNS increase (White & Raven, 2014). Thus, as was hypothesized, a higher exercise stressor impact would be linked to lesser loss aversion levels.

Our result seems to be consistent with the alignment hypothesis (Margittai et al., 2018), whereby stress leads to a loss aversion decrease due to the reward system activity increasing. However, present findings do not necessarily support such a mechanism. Exercise could be increasing the attractiveness of gains, but also reducing the aversion to losses, or doing both. In fact, there may be an alternative explanation that has not been considered to date. Stress in general, and also physical exercise in particular, can induce endogenous analgesia, reducing the perceived pain (Butler & Finn, 2009; St-Aubin et al., 2019). SNS and HPA-axis are also involved in this mechanism, but other substances such as endogenous opioids play a key role (Butler & Finn, 2009). In addition, pain and aversion have overlapping characteristics, both at their neural pathways and substrate level (Butler & Finn, 2009); indeed, some authors even talk about "pain of losses" when defining loss aversion (e.g., Hintze et al., 2015, p. 2). Therefore, these results could be also explained by another mechanism, such as an endogenous analgesia induction. Nevertheless, this is only speculation and more research are needed, addressing complementary physiological and neural data.

Limitations and future research directions

In fact, the absence of such measures is the main limitation of our work. We can infer that participants were physiologically stressed, but we cannot explore the role of other factors such as catecholamines, cortisol or opioids since their exact levels were unknown. It is also important to stress that the control group did not engage in a placebo-like task. This design was chosen to avoid any physiological stress, boredom, or relaxation. However, these decisions could threat the internal validity of our finding. Moreover, our results were found 5 min after the exercise, i.e., the recovery phase. As was explained, different results could be found depending on the stress phase and, therefore, further research is necessary to explore if our findings are replicated, for example, performing MGT still on the cycloergometer (i.e., the acute phase). It has to be also mentioned that exercise was not producing unpleasant emotions on our sample; that is, it was stressful but not distressful (Hackney, 2006). Subjective perception is not usually addressed when studying stress and loss aversion, being necessary its consideration since it could modify the results. Finally, previous data have reported age and sex differences when taking risk and facing stress (Hidalgo et al., 2019; van den Bos et al., 2009), but our study was made only with young people and the sample was predominantly female, preventing a thorough exploration of these issues.

Conclusion

Many debates remain about loss aversion, but it seems to be a phenomenon that could affect many of our decisions. At the same time, physical exercise is a common activity in our daily living which can be stressful for our organism. However, their relation had not been addressed to date. Although further research is necessary to investigate whether the reported results can be replicated and if they are behaviorally meaningful when facing a real-world decision, the present research provides a first step. Our work suggests that physiological changes derived from a high-intensity exercise could affect decision-making by reducing loss aversion. If future studies support this, these results could be relevant and should be considered when predicting risky decisions. Physical exercise may push individuals to take less biased decisions, but also to be less cautious when deciding.

Credit author statement:

Francisco Molins: Study design; data collecting and curation; Writing- Original draft preparation
Miguel Ángel Serrano: Study design, writing- Reviewing and Editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was supported by a grant from Ministerio de Economía y Competitividad [grant number: PSI2016-78763-P]. FM is a predoctoral research fellow, supported by the Generalitat Valenciana (ACIF/2020/062); Secretaría de Estado de Investigación, Desarrollo e Innovación.

ORCID

Francisco Molins http://orcid.org/0000-0002-0211-9182
Miguel Ángel Serrano http://orcid.org/0000-0002-6574-4532

References

Barkley-Levenson, E. E., Van Leijenhorst, L., & Galván, A. (2013). Behavioral and neural correlates of loss aversion and risk avoidance in adolescents and adults. *Developmental Cognitive Neuroscience*, *3*(1), 72–83. https://doi.org/10.1016/j.dcn.2012.09.007

Berejikian, J. D., & Early, B. R. (2013). Loss aversion and foreign policy resolve. *Political Psychology*, *34*(5), 649–671. https://doi.org/10.1111/pops.12012

Boyce, C. J., Wood, A. M., & Ferguson, E. (2016). Individual differences in loss aversion: Conscientiousness predicts how life satisfaction responds to losses versus gains in income. *Personality and Social Psychology Bulletin*, *42*(4), 471–484. https://doi.org/10.1177/0146167216634060

Butler, R. K., & Finn, D. P. (2009). Stress-induced analgesia. *Progress in Neurobiology*, *88*(3), 184–202. https://doi.org/10.1016/j.pneurobio.2009.04.003

Canessa, N., Crespi, C., Baud-Bovy, G., Dodich, A., Falini, A., Antonellis, G., & Cappa, S. F. (2017). Neural markers of loss aversion in resting-state brain activity. *NeuroImage*, *146*(September 2016), 257–265. https://doi.org/10.1016/j.neuroimage.2016.11.050

Chandrasekhar Pammi, V. S., Pillai Geethabhavan Rajesh, P., Kesavadas, C., Rappai Mary, P., Seema, S., Radhakrishnan, A., Sitaram, R., Rajesh, P. P. G., Kesavadas, C., Mary, P. R., Seema, S., Radhakrishnan, A., & Sitaram, R. (2015). Neural loss aversion differences between depression patients and healthy individuals: A functional MRI investigation. *The Neuroradiology Journal*, *28*(2), 97–105. https://doi.org/10.1177/1971400915576670

Chandrasekhar Pammi, V. S., Ruiz, S., Lee, S., Noussair, C. N., & Sitaram, R. (2017). The effect of wealth shocks on loss aversion: Behavior and neural correlates. *Frontiers in Neuroscience*, *11*(APR), 1–10. https://doi.org/10.3389/fnins.2017.00237

Charpentier, C. J., De Martino, B., Sim, A. L., Sharot, T., & Roiser, J. P. (2016). Emotion-induced loss aversion and striatal-amygdala coupling in low-anxious individuals. *Social Cognitive and Affective Neuroscience*, *11*(4), 569–579. https://doi.org/10.1093/scan/nsv139

Chen, M. K., Lakshminarayanan, V., & Santos, L. R. (2006). How basic are behavioral biases? Evidence from Capuchin Monkey trading behavior. *Journal of Political Economy*, *114*(3), 517–537. https://doi.org/10.1086/503550

Ciabattoni, L., Ferracuti, F., Longhi, S., Pepa, L., Romeo, L., & Verdini, F. (2017). Real-time mental stress detection based on smartwatch. *2017 IEEE International Conference on Consumer Electronics, ICCE 2017*, 110–111. https://doi.org/10.1109/ICCE.2017.7889247

Constantinople, C. M., Piet, A. T., & Brody, C. D. (2019). An analysis of decision under risk in rats. *Current Biology*, *29*(12), 2066–2074.e5. https://doi.org/10.1016/j.cub.2019.05.013

Duke, É, Schnuerch, R., Heeren, G., Reuter, M., Montag, C., & Markett, S. (2018). Cortical alpha asymmetry at central and posterior – but not anterior – sites is associated with individual differences in behavioural loss aversion. *Personality and Individual Differences*, *121*, 206–212. https://doi.org/10.1016/J.PAID.2017.04.056

Ert, E., & Erev, I. (2013). On the descriptive value of loss aversion in decisions under risk: Six clarifications. *Judgment and Decision Making*, *8*(3), 214–235. https://doi.org/10.2139/ssrn.1012022nsunde

Field, A. (2009). *Discovering statistics using SPSS*. Sage publications (ed.).

Frith, E., Sng, E., & Loprinzi, P. D. (2017). Randomized controlled trial evaluating the temporal effects of high-intensity exercise on learning, short-term and long-term memory, and prospective memory. *European Journal of Neuroscience*, *46*(10), 2557–2564. https://doi.org/10.1111/ejn.13719

Gal, D., Rucker, D. D., & Shavitt, S. (2018). The loss of loss aversion: Will it loom larger than its gain? *Journal of Consumer Psychology*, *28*(3), 497–516. https://doi.org/10.1002/jcpy.1047

Gelskov, S. V., Henningsson, S., Madsen, K. H., Siebner, H. R., & Ramsøy, T. Z. (2015). Amygdala signals subjective appetitiveness and aversiveness of mixed gambles. *Cortex*, *66*, 81–90. https://doi.org/10.1016/J.CORTEX.2015.02.016

Grossmann, I., Sahdra, B. K., & Ciarrochi, J. (2016). A heart and a mind: Self-distancing facilitates the association between heart rate variability, and wise reasoning. *Frontiers in Behavioral Neuroscience*, *10*(April), 1–10. https://doi.org/10.3389/fnbeh.2016.00068

Hackney, A. C. (2006). Stress and the neuroendocrine system: The role of exercise as a stressor and modifier of stress. *Expert Review of Endocrinology & Metabolism*, *1*(6), 783–792. https://doi.org/10.1586/17446651.1.6.783

Hidalgo, V., Pulopulos, M. M., & Salvador, A. (2019). Acute psychosocial stress effects on memory performance: Relevance of age and sex. *Neurobiology of Learning and Memory*, *157*, 48–60. https://doi.org/10.1016/j.nlm.2018.11.013

Hintze, A., Olson, R. S., Adami, C., & Hertwig, R. (2015). Risk sensitivity as an evolutionary adaptation. *Scientific Reports*, *5*(1), 1–7. https://doi.org/10.1038/srep08242

Hochman, G., & Yechiam, E. (2011). Loss aversion in the eye and in the heart: The autonomic nervous system's responses to losses. *Journal of Behavioral Decision Making*, *24*(2), 140–156. https://doi.org/10.1002/bdm.692

Hopkins, M. E., Davis, F. C., VanTieghem, M. R., Whalen, P. J., & Bucci, D. J. (2012). Differential effects of acute and regular physical exercise on cognition and affect. *Neuroscience*, *215*, 59–68. https://doi.org/10.1016/j.neuroscience.2012.04.056

Kahneman, D., Knetsch, J. L., & Thaler, R. H. (1991). Anomalies: The endowment effect, loss aversion, and status quo bias. *Journal of Economic Perspectives*, *5*(1), 193–206. https://doi.org/10.1257/jep.5.1.193

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, *47*(2), 263. https://doi.org/10.2307/1914185

Kahneman, D., & Tversky, A. (1984). Choices, values, and frames. *American Psychologist*, *39*(4), 341–350. https://doi.org/10.1037/0003-066X.39.4.341

Karvonen, M., Kentala, K., & Mustala, O. (1957). The effects of training heart rate: A longitudinal study. *Annales Medicinae Experimentalis Et Biologiae Fenniae*, *35*, 307–315.

Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research - recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology*, *8*(FEB), 1–18. https://doi.org/10.3389/fpsyg.2017.00213

Margittai, Z., Nave, G., Van Wingerden, M., Schnitzler, A., Schwabe, L., & Kalenscher, T. (2018). Combined effects of glucocorticoid and Noradrenergic activity on loss aversion. *Neuropsychopharmacology : Official Publication of the American College of Neuropsychopharmacology*, *43*(2), 334–341. https://doi.org/10.1038/npp.2017.75

Mateo, J., & Laguna, P. (2003). Analysis of heart rate variability in the presence of ectopic beats using the heart timing signal. *IEEE Transactions on Biomedical Engineering*, *50*(3), 334–343. https://doi.org/10.1109/TBME.2003.808831

Mather, M., & Lighthall, N. (2012). Both risk and reward are processed differently in decisions made under stress. *Current Directions in Psychological Science*, *21*(2), 36–41. https://doi.org/10.1038/jid.2014.371

Metz, S., Waiblinger-Grigull, T., Schulreich, S., Chae, W. R., Otte, C., Heekeren, H. R., & Wingenfeld, K. (2020). Effects of hydrocortisone and yohimbine on decision-making under risk. *Psychoneuroendocrinology*, *114*(January), 104589. https://doi.org/10.1016/j.psyneuen.2020.104589

Michael, S., Graham, K. S., & Oam, G. M. D. (2017). Cardiac autonomic responses during exercise and post-exercise recovery using heart rate variability and systolic time intervals-a review. *Frontiers in Physiology*, *8*(MAY), 1–19. https://doi.org/10.3389/fphys.2017.00301

Mintoft, B., Callaghan, K., Buetow, S., Kydd, R., & Sollers, J. J. (2012). Money, sex, and self control: predicting the disposition effect? *SSRN Electronic Journal*, 1–14. https://doi.org/10.2139/ssrn.2136922

Molins, F., & Serrano, M. A. (2019). Bases neurales de la aversión a las pérdidas en contextos económicos: Revisión sistemática según las directrices PRISMA. *Revista de Neurología*, *68*(02), 47. https://doi.org/10.33588/rn.6802.2018276

Mrkva, K., Johnson, E. J., Gächter, S., & Herrmann, A. (2020). Moderating loss aversion: Loss aversion has moderators, but reports of its death are greatly exaggerated. *Journal of Consumer Psychology*, *30*(3), 407–428. https://doi.org/10.1002/jcpy.1156

Pighin, S., Bonini, N., Savadori, L., Hadjichristidis, C., & Schena, F. (2014). Loss aversion and hypoxia: Less loss aversion in oxygen-depleted environment. *Stress*, *17*(2), 204–210. https://doi.org/10.3109/10253890.2014.891103

Ponce, P., del Arco, A., & Loprinzi, P. (2019). Physical activity versus psychological stress: Effects on salivary cortisol and working memory performance. *Medicina*, *55*(5), 119. https://doi.org/10.3390/medicina55050119

Pope, D., & Schweitzer, M. (2011). Is Tiger Woods loss averse ? Persistent bias in the face of experience, competition, and high stakes. *American Economic Review*, *101*(February), 129–157. https://doi.org/10.1257/aer.101.1.129

Reyes del Paso, G. A., Langewitz, W., Mulder, L. J. M., van Roon, A., & Duschek, S. (2013). The utility of low frequency heart rate variability as an index of sympathetic cardiac tone: A review with emphasis on a reanalysis of previous studies. *Psychophysiology*, *50*(5), 477–487. https://doi.org/10.1111/psyp.12027

Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, *5*(September), 1–17. https://doi.org/10.3389/fpubh.2017.00258

Shibasaki, M., Namba, M., Kamijo, Y. I., Ito, T., Kakigi, R., & Nakata, H. (2019). Effects of repetitive exercise and thermal stress on human cognitive processing. *Physiological Reports*, *7*(4), e14003–12. https://doi.org/10.14814/phy2.14003

Sokol-Hessner, P., Raio, C. M., Gottesman, S. P., Lackovic, S. F., & Phelps, E. A. (2016). Acute stress does not affect risky monetary decision-making. *Neurobiology of Stress*, *5*, 19–25. https://doi.org/10.1016/j.ynstr.2016.10.003

Sokol-Hessner, P., & Rutledge, R. B. (2019). The psychological and neural basis of loss aversion. *Current Directions in Psychological Science*, *28*(1), 20–27. https://doi.org/10.1177/0963721418806510

St-Aubin, M.-O., Chalaye, P., Counil, F.-P., & Lafrenaye, S. (2019). Beneficial effects of regular physical activity on exercise-induced analgesia in adolescent males. *Pediatric Exercise Science*, *31*(4), 425–431. https://doi.org/10.1123/pes.2018-0089

Sütterlin, S., Herbert, C., Schmitt, M., Kübler, A., & Vögele, C. (2011). Frames, decisions, and cardiac-autonomic control. *Social Neuroscience*, *6*(2), 169–177. https://doi.org/10.1080/17470919.2010.495883

Takahashi, H., Fujie, S., Camerer, C., Arakawa, R., Takano, H., Kodaka, F., Matsui, H., Ideno, T., Okubo, S., Takemura, K., Yamada, M., Eguchi, Y., Murai, T., Okubo, Y., Kato, M., Ito, H., & Suhara, T. (2013). Norepinephrine in the brain is associated with aversion to financial loss. *Molecular Psychiatry*, *18*(1), 3–4. https://doi.org/10.1038/mp.2012.7

Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, *37*(1), 153–156. https://doi.org/10.1016/S0735-1097(00)01054-8

Tarvainen, M. P., Niskanen, J. P., Lipponen, J. A., Ranta-aho, P. O., & Karjalainen, P. A. (2014). Kubios HRV - heart rate variability analysis software. *Computer Methods and Programs in Biomedicine*, *113*(1), 210–220. https://doi.org/10.1016/j.cmpb.2013.07.024

Task Force of The European Society of Cardiology and The North American Electrophysiology Society of Pacing and Electrophysiology. (1996). Guidelines heart rate variability. *European Heart Journal*, *93*(5), 1043–1065. https://doi.org/10.1161/01.CIR.93.5.1043

Thompson, E. R. (2007). Development and validation of an internationally reliable short-form of the positive and negative affect schedule (PANAS). *Journal of Cross-Cultural Psychology*, *38*(2), 227–242. https://doi.org/10.1177/0022022106297301

Tom, S. M., Fox, C. R., Trepel, C., & Poldrack, R. a. (2007). The neural basis of loss aversion in decision-making under risk-Supporting Material. *Science (New York, N.Y.)*, *315*(5811), 515–518. https://doi.org/10.1126/science.1134239

van den Bos, R., Harteveld, M., & Stoop, H. (2009). Stress and decision-making in humans: Performance is related to cortisol reactivity, albeit differently in men and women. *Psychoneuroendocrinology*, *34*(10), 1449–1458. https://doi.org/10.1016/j.psyneuen.2009.04.016

Viswanathan, V., Lee, S., Gilman, J. M., Kim, B. W., Lee, N., Chamberlain, L., Livengood, S. L., Raman, K., Lee, M. J., Kuster, J., Stern, D. B., Calder, B., Mulhern, F. J., Blood, A. J., & Breiter, H. C. (2015). Age-related striatal BOLD changes without changes in behavioral loss aversion. *Frontiers in Human Neuroscience*, *9*(April), 1–12. https://doi.org/10.3389/fnhum.2015.00176

Wang, M., Rieger, M. O., & Hens, T. (2017). The impact of culture on loss aversion. *Journal of Behavioral Decision Making*, *30*(2), 270–281. https://doi.org/10.1002/bdm.1941

White, D. W., & Raven, P. B. (2014). Autonomic neural control of heart rate during dynamic exercise: Revisited. *The Journal of Physiology*, *592*(12), 2491–2500. https://doi.org/10.1113/jphysiol.2014.271858

Yechiam, E., & Hochman, G. (2013). Loss-aversion or loss-attention: The impact of losses on cognitive performance. *Cognitive Psychology*, *66*(2), 212–231. https://doi.org/10.1016/j.cogpsych.2012.12.001

5. Emotional stress & decision-making: an emotional stressor significantly reduces loss aversion

STRESS
https://doi.org/10.1080/10253890.2021.1919617

Taylor & Francis
Taylor & Francis Group

ORIGINAL RESEARCH REPORT

Emotional stress & decision-making: an emotional stressor significantly reduces loss aversion

Francisco Molins, Carla Ayuso and Miguel Ángel Serrano

Department of Psychobiology, Universitat de València, Valencia, Spain

ABSTRACT

Stress influences loss aversion, the principle that losses loom larger than gains, although the nature of this relationship is unclear. Studies show that stress reduces loss aversion; however, stress response has been only studied by means of physiological measures, but the stressor emotional impact remained unclear. Since emotions can modify stress response and increase the activity of the loss aversion neural substrates, it could be expected that an emotional stressor may produce the opposite effect, i.e. loss aversion increase. 69 participants were divided into experimental and control group. The first one was exposed to emotional stress through a 5-minutes video, and control group viewed a match-length distractor video. Physiological stress response was assessed by means of electrodermal activity (EDA), and both perceived stress, and negative affect (i.e. psychological stress response) were registered through questionnaires. Both groups performed a mixed gamble task, which allowed the extraction of loss aversion through a Bayesian-computational model. During and after video, experimental group had higher electrodermal activity, perceived stress, and negative affect than controls, suggesting that emotional stress induction was effective. However, rather than increasing, loss aversion of stressed participants was lower. These results constitute a new evidence of emotional stress influencing loss aversion and highlight that stress, regardless of its emotional impact, can reduce this phenomenon. These results should be considered when predicting risky decisions.

ARTICLE HISTORY
Received 22 December 2020
Accepted 15 April 2021

KEYWORDS
Stress; decision-making; loss aversion; emotion; emotional stress computational model

Introduction

One of the most accepted phenomena in the social sciences is loss aversion (Gal & Rucker, 2018), the principle that losses loom larger than gains (Kahneman & Tversky, 1979); in other words, "losses are experienced with greater psychological impact" (Gal & Rucker, 2018, p. 497) in comparison to proportional gains, and our judgments and decisions are highly shaped by them. Loss aversion is often considered a fundamental and generalizable principle (Gal & Rucker, 2018), or even a stable behavioral trait (Hadlaczky et al., 2018). However, the current position is that a more contextualized view of this phenomenon would be advisable (Gal & Rucker, 2018; Mrkva et al., 2020). In last years, efforts have been made to identify which factors modulate loss aversion expression, and with it, our decisions. Since many decisions are made under stress, this is one of the most studied factors and the focus of our study.

Stress can significantly influence decision-making (Starcke & Brand, 2012), and specifically loss aversion (Margittai et al., 2018), although the directionality remains unclear. In fact, currently two opposing hypotheses coexist. The "salience-of-losses" hypothesis proposes that acute stress reallocates resources in the brain, favoring the activation of the salience-network (Metz et al., 2020). This network contains regions such as the amygdala, which also constitutes one of the main neural bases of loss aversion (Molins & Serrano, 2019). Hence, it is obvious to expect that stress would enhance loss aversion (Metz et al., 2020). However, the most accepted is the "alignment" hypothesis (Metz et al., 2020), supported by the STARS model (Stress Triggers Additional Reward Salience) (Mather & Lighthall, 2012). It is derived by the findings that in rats, acute stress increases nucleus accumbens extracellular levels of dopamine and firing rates in their midbrain dopamine neurons (Anstrom & Woodward, 2005; Kalivas & Duffy, 1995). In addition, positron emission tomography (PET) studies suggested similar results in humans, where stress enhances striatal dopamine (Scott et al., 2006; Wood et al., 2007), pointing toward thatthese regions may play a key role in representing reward value (Mather & Lighthall, 2012; Rangel et al., 2008). So, with their STARS model, Mather and Lighthall (2012, p. 2) proposed that "stress enhances reward salience via modulation of the dopamine system, resulting in reward-biased learning"; i.e. stress could bias in weighing positive over negative aspects during the decision-making process. Therefore, the alignment hypothesis suggests that stress would balance the susceptibility to gains and losses, the former seeming more attractive, thereby reducing loss aversion (Metz et al., 2020).

Although seemingly contradictory, both hypotheses may not be mutually exclusive and may reflect responses to

CONTACT Miguel Ángel Serrano m.angel.serrano@uv.es Department of Psychobiology, Universitat de València, Av. Blasco Ibáñez, 13, Valencia 46010, Spain

different stressors. Depending on their nature, stressors can vary in the expression and magnitude of their physiological and psychological responses (Hidalgo et al., 2019). For example, it is known that physical or systemic stressors produce a robust Sympathetic Nervous System (SNS) response, whereas psychosocial stressors elicit the activation of both the SNS and the Hypothalamic-Pituitary-Adrenal (HPA) axis (Hidalgo et al., 2019). Thus, it is important not to study stress in the singular, but how different stressors impact loss aversion. When studying stress and loss aversion, the direct manipulation of catecholamines or cortisol is the most common practice (e.g. Margittai et al., 2018; Metz et al., 2020). However, only a few systemic or physical stressors, such as oxygen-depleted environment (hypoxia) (Pighin et al., 2014) or vigorous physical exercise (Molins & Serrano, 2020) have also been tested. When using these types of stressors, a reduction in loss aversion was observed. However, although these stressors produced physiological responses, they did not have an impact on an emotional level. Neither physical exercise nor hypoxia changed the emotional state (Molins & Serrano, 2020; Pighin et al., 2014). In fact, hypoxia acted unconsciously, without the participants being aware of this context (Pighin et al., 2014). Some studies even ignored measuring whether the stressor had an impact beyond on our physiology (e.g. Sokol-Hessner et al., 2016). Yet, an stressor can produce different biological and behavioral responses depending on its emotional impact (Compton et al., 2013; Goldfarb et al., 2019). Thus, the increase of the negative affect during an emotional stressor exposure was positively associated with the salience-network interconnectivity and the noradrenergic activity (Hermans et al., 2011). In parallel, both norepinephrine brain levels (Sokol-Hessner & Rutledge, 2019), and the activity of the regions that compose the salience-network (Molins & Serrano, 2019) have been closely linked to behavioral loss aversion.

Therefore, we hypothesized that an emotional stressor would produce the opposite effect to that found with other non-emotional stressors, leading to increased loss aversion. In fact, as Pabst et al. (2013) found, an stressor that increased negative affect also led to less risk-taking during decision-making. Nevertheless, to our knowledge, it has never been directly explored whether emotional stress could increase loss aversion. Thus, by exposing an experimental group to an emotional stressor, it is expected that this group would show greater physiological activation and more negative emotional state than the control group. Moreover, after the stressor, both groups would differ in loss aversion. This work aimed to shed light on the question of whether emotional stress would support the salience-of-losses hypothesis or, on the contrary, it will reduce loss aversion regardless of its emotional impact.

Material and methods

Participants

Based on the effect size found in a previous work on stress and loss aversion (Molins & Serrano, 2020), an a priori power analysis using G*Power indicated a requisite of 48 participants ($\eta^2_p = .18$, power = 80%, $\alpha = .05$) to perform an ANOVA and compare loss aversion between groups (emotional stress vs control group). We oversampled 22 participants to account for possible exclusions. 70 participants were recruited. One was eliminated for drug consumption. A total of 69 participants (age: $M = 22.33$, $SD = 2.29$; women: $N = 52$, 75.4%) were finally included. They met the following inclusion criteria: not having cardiovascular, endocrine, neurological or psychiatric diseases; not consuming more than 5 cigarettes a day; not consuming drugs habitually; not doing more than 10 hours of exercise per week and not having experienced a highly stressful event in the last month. In addition, participants were asked to not perform extenuating exercise or to take drugs or alcohol in the last 24 h, and to not smoke or take stimulant drinks in the 2 h before the experimental session. Participants were randomly distributed into two groups, experimental ($N = 37$) and control ($N = 32$).

Procedure

This study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki. Experimental session was carried out between 15:00 pm and 20:00 pm and lasted approximately an hour. Participants were asked to wait in the University hall and were accompanied in an elevator to the laboratory, avoiding the use of stairs, to prevent any disruption in their physiological state. The general procedure was explained, and informed consent was signed. Participants were connected to the electrodermal activity (EDA) sensor and had 10 minutes of rest as habituation. Then, experimental group was exposed to emotional stress (stressful video), while the control group was submitted to a distractor (non-stressful video). Before and after the emotional stressor/distractor, participants were evaluated for positive and negative mood with the Positive and Negative Affect registry, PANAS (Watson et al., 1988) and were asked about the subjective stress they felt. After that, both groups performed an economical decision-making task to measure loss aversion.

Emotional stressor

Following Shields et al. (2016), emotional stress was induced through a video with unpleasant content: a 2-day-old crying infant being circumcised. This video had a length of 5 minutes. In contrast, participants in the control condition watched a length-matched, non-emotional video about how marbles are made. Both groups watched the video with headphones to avoid any possible distraction. To prove that the emotional stress manipulation was effective, we also obtained EDA of each group before and during the video, as well as during the economical task. In addition, before and after the emotional stressor/distractor, participants were asked about the stress they felt (perceived stress), and positive and negative mood was assessed with PANAS.

Electrodermal activity (EDA)

EDA is one of the most used physiological signals for detecting stress (Liu & Du, 2018). It has been consistently demonstrated that when the stress induction is effective, it is accompanied by the pronounced increase in EDA (Reinhardt et al., 2012). EDA was recorded and analyzed following recommendations for electrodermal measurements (Boucsein et al., 2012). Two electrodes were placed on non-dominant hand (index and middle finger distal phalanges), using isotonic gel to amplify the signal. BIOPAC, with EDA-100C transducer, 1000 Hz sampling frequency and AcqKnowledge software were also used. The electrodermal registry was resampled with the linear interpolation method at 250 Hz and filtered by smoothing factor with a median value of 5. The average of skin conductance level (SCL) in microsiemens (μS) was extracted from three different periods of 5 minute: (1) baseline (last five minutes of the habituation period), (2) stressor/distractor and (3) economical task.

Perceived stress

Before and after the video (stressor/distractor), participants were asked about the subjective stress they felt. This question, designed *ad hoc* for the study, asked: "How much stress do you feel right now?" The answer was given on a Likert scale where 0 is "no stress," and 10 is "a lot of stress."

Positive and negative affect registry (PANAS)

PANAS (Watson et al., 1988) is a 20 Likert-type items scale (from 1, more than usual, to 4, much less than usual) that evaluates positive and negative mood. Each dimension contains 10 items that must be added. The higher the score, the more positive or negative the mood. PANAS was evaluated before and after the stressor/distractor.

Mixed gamble task (MGT)

Both groups performed a short version of MGT (Chandrasekhar Pammi et al., 2015). Each trial entailed a bet with one of the combinations randomly extracted from an 8×8 losses and gains matrix, until the 64 combinations were completed (see Figure 1). Following gamble ranges used by Chandrasekhar Pammi et al. (2015), as well as by Tom et al. (2007) in the original task, gains could range from €100 to €380 in €40 increments, and losses from €50 to €190 in €20 increments. In each trial there was a 50% chance of gaining and 50% chance of losing. Participants had to decide whether to accept or reject the bet. They were instructed that €200 was their initial amount and each bet had to be encountered with that reference. Betting results were not presented immediately, however, they had to choose carefully in each trial since, at the end, four bets would be randomly picked and played heads or tails, affecting the initial amount. Loss aversion parameter was extracted through the Prospect-Theory computational model (Sokol-Hessner et al., 2009).

Prospect-Theory computational model

The Prospect-Theory model (Sokol-Hessner et al., 2009) follows the classical approach of the Prospect Theory (Kahneman & Tversky, 1979) where a bet would be accepted or rejected as a function of its expected utility. Following the original paper of Sokol-Hessner et al. (2009), the utility for gains was estimated through the equation $u(x^{gain}) = x^{\rho}$, and the utility for losses through the equation $u(x^{loss}) = -\lambda \times (-x)^{\rho}$. Finally, the probability of accepting a gamble was estimated through the SoftMax function, $P_{(Accept)} = 1/(1 + e^{-\mu(U(Accept)-U(Reject))})$. As can be seen, three parameters are derived from this model: λ (loss aversion coefficient), ρ (the curvature of the utility function or risk aversion), and μ (the logit parameter). However, as we were interested in specifically addressing loss aversion, following Ahn et al. (2017), we set the risk aversion parameter to 1 and using the Maximum likelihood estimation method, λ and μ were obtained. $\lambda = 1$ indicates that gains and losses were valued equally, however, when $\lambda > 1$, losses were overvalued relative to gains (loss aversion). The logit parameter (μ) represents the amount of "randomness" in the subject's choices or, in other words, consistency over choices. Higher levels of the parameter would represent that participants rely more on "rule-based" decision-making (Sokol-Hessner et al., 2009).

These parameters were estimated for each participant through Hierarchical Bayesian Analyses (HBA; see Anh, 2008 for more details), performed with the hBayesDM package (Ahn et al., 2017) for the R software. The hBayesDM uses Stan 2.1.1 (Stan Development Team, 2017) with the Hamiltonian Monte Carlo (HMC) algorithm as MCMC for sampling the posterior distributions. Following Alacreu-Crespo et al. (2020), we drawn 40.000 samples, after burn-in of 23.333 samples, in three different chains (in sum, a total of 120.000 samples and 70.000 burn-in). The Gelman-Rubin test (Gelman & Rubin, 1992) was used to study if the chains converged ($\hat{R}$) to the target distribution. $\hat{R}$ values were 1, which means that convergence was achieved. In addition, to confirm this convergence, the MCMC chains were visually inspected.

Statistical analyses

Outliers were detected with the 2.5 standard deviations method and Mahalanobis distance for repeatedly measured variables (e.g. electrodermal activity). Kolmogorov-Smirnoff with Lilliefors correction was used to check normality. Post-video negative affect had to be normalized with log10. The pre-video measure was also transformed to allow the comparison. Analyses included repeated-measures ANOVAs, with the group (experimental vs control) as a between-participants factor, to test the emotional stress induction effectiveness, both at the physiological (EDA) and at the subjective level (stress level, positive affect and negative affect). In addition, loss aversion and the logit parameter were compared between groups through one-way ANOVA. The α significance level was set at .05. Partial eta square (η^2_p) symbolizes the effect size and β-1 (power) represents power. All analyses

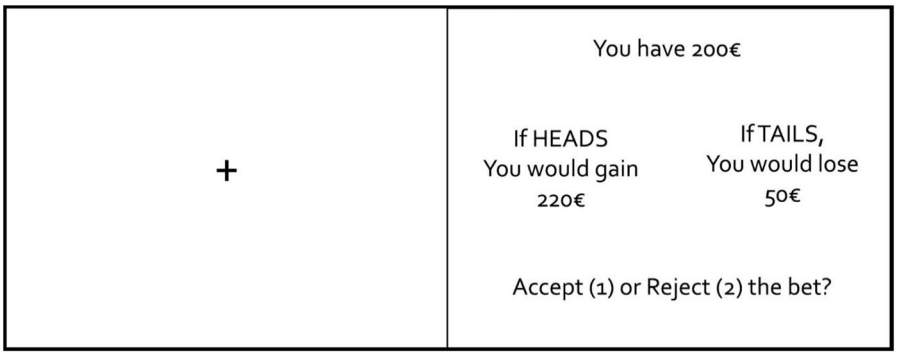


Figure 1. A Mixed gamble task trial. Each of the 64 trials in the task consists of (A) 5 seconds of fixation point and (B) a bet. The bet offers a possible gain and a possible loss, both with a probability of 50% (heads or tails). The participant must decide whether to play or reject that bet.

were performed with IBM SPSS Statistics 25, except for the extraction of λ which was done with R.

Results

Preliminary analyses

Experimental and control groups were homogeneously distributed with no significant differences in age (experimental: $M = 22.27$, $SD = 2.21$; control: $M = 22.41$, $SD = 2.42$), $p = .80$; nor in BMI (experimental: $M = 23.72$, $SD = 3.42$; control: $M = 23.88$, $SD = 2.44$), $p = .92$. Moreover, there were more women than men, but the chi-square test revealed that both women (experimental: 73%; control: 78.1%), $p = .78$; and men (experimental: 27%; control: 21.9%), $p = .47$; maintained similar proportions in both groups.

Emotional stress induction

Physiological stress

A repeated-measures ANOVA including group (experimental vs control) as a between-factor was performed to test whether the emotional stress induction was effective at the physiological level. Analyses revealed a significant main effect of the moment (EDA-baseline vs. EDA-video vs. EDA-MGT), $F(2, 66) = 12.44$, $p < .001$, $\eta^2_p = .29$; and a significant group-$\times$moment interaction, $F(2, 66) = 7.39$, $p < .001$, $\eta^2_p = .19$, which indicates that EDA evolution was different for both groups (see Figure 2). We explored this effect further.

When contrasting by groups, the experimental group's EDA was significantly higher during the video than during the baseline, $F(1, 36) = 24.38$, $p < .001$, $\eta^2_p = .43$. This level was significantly reduced during MGT, $F(1, 36) = 10.09$, $p = .003$, $\eta^2_p = .23$; but even so this level remained higher than the baseline, $F(1, 36) = 14.08$, $p = .001$, $\eta^2_p = .31$. On the other hand, the control group did not show differences between any of the EDA measurement levels (p's $> .05$). All means can be consulted in Table 1. Finally, intergroup analysis controlling for basal levels (see Table 1) revealed that, although both groups did not differ in their EDA at the baseline, the experimental group showed significantly higher activity than the control group during video and MGT.

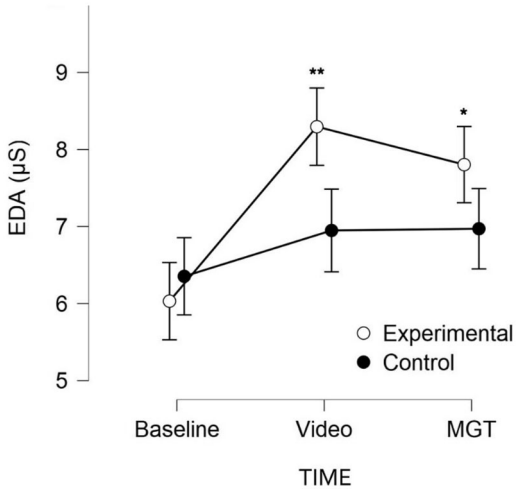


Figure 2. Electrodermal activity during baseline, video, and Mixed Gamble Task (MGT) by group. Experimental and control group significantly differed in their EDA level during the video and the MGT. *Significant contrast at the .05 level; **Significant contrast at the .01 level; $M \pm SE$.

Emotional stress

Regarding the emotional impact of the stress, repeated measures ANOVAs (including group as between-factor) were carried out to study differences pre- and post-video in the subjective-perceived stress and both the positive and the negative affect. Focusing on the perceived stress, it was found a significant group $\times$ moment interaction, $F(1, 67) = 70.06$, $p < .001$, $\eta^2_p = .52$. So, while the control group did not show differences between pre- ($M = 4.28$, $SD = 2.05$) and post-video ($M = 4.45$, $SD = 2.39$) levels, $F(1, 31) = 1.87$, $p = .12$, $\eta^2_p = .02$; the experimental group experienced an increase in perceived stress after being submitted to emotional stress ($M = 5.87$, $SD = 2.20$), compared to their pre-video level ($M = 3.41$, $SD = 2.31$), $F(1, 36) = 45.66$, $p < .001$, $\eta^2_p = .58$. In addition, both groups did not differ at their basal level, $F(1, 67) = 2.60$, $p = .112$, $\eta^2_p = .03$; but the perceived stress level of the experimental group was significantly higher than the level reported by the control group after video, $F(1, 67) = 39.29$, $p < .001$, $\eta^2_p = .38$.

On the other side, regarding positive affect assessed with PANAS, no pre-post changes or differences between groups were found (p's $> .05$). However, regarding negative affect, analyses also revealed a significant group $\times$ moment interaction, $F(1, 67) = 39.91$, $p < .001$, $\eta^2_p = .37$. Experimental

Table 1. Intergroup differences in electrodermal activity (EDA) during baseline, video, and Mixed Gamble Task (MGT).

	Experimental (N = 37)	Control (N = 32)	F	gl between	gl intra	p-value	η^2_p
EDA							
Baseline	M = 5.95 ± 2.81	M = 6.35 ± 2.78	0.34	1	67	.56	.005
Video	M = 8.29 ± 2.88	M = 6.94 ± 2.99	6.41	1	66	.01**	.09
MGT	M = 7.70 ± 2.79	M = 6.91 ± 2.87	4.80	1	66	.03*	.07

M: mean; ± SD; *Significant contrast at the .05 level; **Significant contrast at the .01 level.

(M = 21.68, SD = 4.32) and control (M = 21.59, SD = 2.78) group did not present differences pre-video, $F(1, 67) = .008$, $p = .93$, $\eta^2_p = .00$. Yet, the experimental group suffered a significant increase in negative affect after video (M = 25.11, SD = 6.24), $F(1, 36) = 21.34$, $p < .001$, $\eta^2_p = .37$; while the control group kept a similar level (M = 20.94, SD = 3.17), $F(1, 31) = .007$, $p = .97$, $\eta^2_p = .00$. Levels post-video significantly differed between groups, $F(1, 67) = 26.29$, $p < .001$, $\eta^2_p = .28$.

Loss aversion

First, it was checked if our sample was loss averse. Both control (M = 2.11, SD = .41) and experimental (M = 1.43, SD = .31) groups showed an average λ (loss aversion) value higher than 1, indicating that both groups expressed loss aversion during MGT. However, the group submitted to emotional stress (experimental group) manifested a significantly lower level of loss aversion than the control group, $F(1, 67) = 60.09$, $p < .001$, $\eta^2_p = .47$.

As we saw, applying the computational model also yielded a second parameter, the logit parameter (μ), which informs us about the consistency of participants' choices. Experimental group showed a higher logit parameter or consistency (M = 2.62, SD = .16) than the control group (M = 0.17, SD = .02), $F(1, 67) = 69.86$, $p < .001$, $\eta^2_p = .99$.

Discussion

The present study examined the impact of an emotional stressor on loss aversion (Kahneman & Tversky, 1979). Both physiological and psychological measures suggest that our manipulation worked: compared to the control group, participants exposed to emotional stress exhibited significant increase in electrodermal activity, but also in their perceived stress and negative affect. As expected, both groups differed in their loss aversion level post-stressor, which suggests that the emotional stress was influencing decision-making. However, despite its emotional impact, stressor was followed by a reduction in loss aversion rather than its increase. These results do not support the salience-of-losses hypothesis that was supposed to produce the emotional stress.

Loss aversion values usually described in the literature are between 2 and 2.5 (Duke et al., 2018; Kahneman & Tversky, 1979; Tom et al., 2007). This means that participants accepted gambles if gains were at least 2 times as large as losses. In this study, control participants exhibited loss aversion values compatible with previous evidence. Yet, participants submitted to emotional stress accepted gambles when gains were just 1.43 times as large as losses, which indicates that this group was less loss averse. In addition, the logit parameter of the experimental group indicates that they made more consistent choices. This would be in line with the lower loss aversion as this bias is an emotional phenomenon which, when manifested, tends to lead to more impulsive and less rule-driven decisions. According to the salience-of-losses hypothesis (Metz et al., 2020), since emotional stress enhances the salience-network activity (Hermans et al., 2011), it should exacerbate the impact of losses on our perception and, therefore, behavioral loss aversion should increase. Our results do not support this.

However, the neural bases of loss aversion highlights that this bias does not only depend on the losses processing. Neural loss aversion is composed by two systems: the appetitive and the aversive one (Molins & Serrano, 2019). Faced with a gamble, both systems work together, being activated at different intensities in response to potential gains and losses, respectively. Then, they would send signals to prefrontal regions where a cost-benefit analysis would be carried out, leading to a decision (Canessa et al., 2017; Croxson et al., 2009; Molins & Serrano, 2019).

Attending to the STARS model (Mather & Lighthall, 2012), as was introduced, stress would trigger additional reward salience by enhancing dopamine activity in dopaminergic reward-processing brain regions (Metz et al., 2020; Pighin et al., 2014), which would bias our decisions by weighing positive over negative aspects during the decision-making process; i.e. stress could be also enhancing the loss aversion appetitive-system activity. Therefore, emotional stress may increase the aversive-system activity, but this may not be enough to overcome the greater activity of the appetitive-system. Thus, the balance would shift toward the search for gains, leading to less behavioral loss aversion. This would be in line with our results and multiple previous evidence where stress also reduced loss aversion (Margittai et al., 2018; Molins & Serrano, 2020; Pighin et al., 2014). Moreover, all this seems to support the reward-alignment hypothesis (Metz et al., 2020), whereby stress may lead to a loss aversion decrease due to the reward-system activity increment. Nevertheless, since our study has no measures to explore brain activity, we cannot be sure that this hypothesis is being fulfilled. Our emotional stressor could be increasing the attractiveness of gains, but also reducing the aversion to losses, or both. For all these reasons, our explanation is only speculation and future research addressing complementary physiological and neural data is needed to shed light on these issues.

In fact, the absence of such measures is the main limitation of our work. EDA indicates that participants showed greater physiological arousal, but we did not explore the role

of other factors such as catecholamines or cortisol. In addition, PANAS (Watson et al., 1988) was used to measure the emotional impact. This questionnaire addresses whether the negative affect increased but does not provide information about the specific negative emotion felt. Different negative emotions (e.g. fear or anger) do not affect decision-making in the same way (Lerner et al., 2015). So, it will be necessary to explore whether different stressors that produce different emotions also lead to other results. In fact, because specific stress responses (e.g. an increase in cortisol or proinflammatory cytokines) was not assessed, and because people are bad at distinguishing or reporting stress from other forms of negative affects without training, we cannot confirm that the manipulation is producing a stress response. This may also be another reason why results differ from previous studies using validated experimental paradigms to induce stress, for example using the Trier Social Stress Test (Kirschbaum et al., 1993). Our paradigm is based in Shields et al. (2016) who found that the emotional video produces specific stress responses (i.e. pro-inflammatory cytokine reactivity), but this is not a validated paradigm and we did not include such measures to test this. Finally, previous data have reported age and sex differences when taking risk and facing stress (Hidalgo et al., 2019; van den Bos et al., 2009), but our study was conducted only with young people and the sample was predominantly female (none of them were taking contraceptives, but their ovulatory cycle period was not monitored), preventing a thorough exploration of these issues. Future research should also address the influence of these variables.

Nevertheless, this study constitutes a direct test of an emotional stress influencing loss aversion. Although mechanisms by which this happens need to be further explored, it seems that stress, regardless of its emotional impact, can reduce loss aversion. These results could be relevant and should be considered when predicting risky decisions. Emotional stress may push individuals to take less biased decisions, but also to be less cautious when deciding.

Disclosure statement

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this manuscript.

Funding

This work was supported by the Generalitat Valenciana under Grant ACIF/2020/062.

Notes on contributors

Francisco Molins is a pre-doctoral researcher in the neurosciences PhD programme at the University of Valencia. His thesis is focused on the study of decision-making and how emotions and various physiological states (such as stress) influence this cognitive ability.

Carla Ayuso is a Psychologist and has a postgrade of Neuroscience. Her research interest if focused on the psychophysiology of emotions and stress.

Miguel Ángel Serrano is a PhD in the department of Psychobiology in the University of Valencia. His research is related to psychophysiology of stress and its relaton to emotions and cognition.

ORCID

Francisco Molins http://orcid.org/0000-0002-0211-9182
Miguel Ángel Serrano http://orcid.org/0000-0002-6574-4532

References

Ahn, W. Y., Busemeyer, J. R., Wagenmakers, E. J., & Stout, J. C. (2008). Comparison of decision learning models using the generalization criterion method. Cognitive Science, 32(8), 1376–1402.

Ahn, W., Haines, N., & Zhang, L. (2017). *Revealing neurocomputational mechanisms of reinforcement learning and decision-making with the hBayesDM Package. Figure 1*.

Alacreu-Crespo, A., Guillaume, S., Sénèque, M., Olié, E., & Courtet, P. (2020). Cognitive modelling to assess decision-making impairments in patients with current depression and with/without. *European Neuropsychopharmacology*, *36*, 10–50. https://doi.org/10.1016/j.euroneuro.2020.04.006

Anstrom, K. K., & Woodward, D. J. (2005). Restraint increases dopaminergic burst firing in awake rats. *Neuropsychopharmacology*, *30*(10), 1832–1840. https://doi.org/10.1038/sj.npp.1300730

Boucsein, W., Fowles, D. C., Grimnes, S., Ben-Shakhar, G., Roth, W. T., Dawson, M. E., & Filion, D. L. (2012). Publication recommendations for electrodermal measurements. *Psychophysiology*, *49*(8), 1017–1034. https://doi.org/10.1111/j.1469-8986.2012.01384.x

Canessa, N., Crespi, C., Baud-Bovy, G., Dodich, A., Falini, A., Antonellis, G., & Cappa, S. F. (2017). Neural markers of loss aversion in resting-state brain activity. *NeuroImage*, *146*(September 2016), 257–265. https://doi.org/10.1016/j.neuroimage.2016.11.050

Chandrasekhar Pammi, V. S., Pillai Geethabhavan Rajesh, P., Kesavadas, C., Rappai Mary, P., Seema, S., Radhakrishnan, A., Sitaram, R., Rajesh, P. P. G., Kesavadas, C., Mary, P. R., Seema, S., Radhakrishnan, A., & Sitaram, R. (2015). Neural loss aversion differences between depression patients and healthy individuals: A functional MRI investigation. *The Neuroradiology Journal*, *28*(2), 97–105. https://doi.org/10.1177/1971400915576670

Compton, R. J., Hofheimer, J., & Kazinka, R. (2013). Stress regulation and cognitive control: Evidence relating cortisol reactivity and neural responses to errors. *Cognitive, Affective, & Behavioral Neuroscience*, *13*(1), 152–163. https://doi.org/10.3758/s13415-012-0126-6

Croxson, P. L., Walton, M. E., O'Reilly, J. X., Behrens, T. E. J., & Rushworth, M. F. S. (2009). Effort-based cost–benefit valuation and the human brain. *Journal of Neuroscience*, *29*(14), 4531–4541. https://doi.org/10.1523/JNEUROSCI.4515-08.2009

Duke, É., Schnuerch, R., Heeren, G., Reuter, M., Montag, C., & Markett, S. (2018). Cortical alpha asymmetry at central and posterior – but not anterior – sites is associated with individual differences in behavioural loss aversion. *Personality and Individual Differences*, *121*, 206–212. https://doi.org/10.1016/j.paid.2017.04.056

Gal, D., & Rucker, D. D. (2018). The loss of loss aversion: Will it loom larger than its gain? *Journal of Consumer Psychology*, *28*(3), 497–516. https://doi.org/10.1002/jcpy.1047

Gelman, A., & Rubin, D. (1992). Inference from iterative simulation using multiple sequences. *Statistical Science*, *7*(4), 457–511. https://doi.org/10.1214/ss/1177011136

Goldfarb, E. V., Seo, D., & Sinha, R. (2019). Sex differences in neural stress responses and correlation with subjective stress and stress regulation. *Neurobiology of Stress*, *11*(May), 100177. https://doi.org/10.1016/j.ynstr.2019.100177

Hadlaczky, G., Hökby, S., Mkrtchian, A., Wasserman, D., Balazs, J., Machín, N., Sarchiapone, M., Sisask, M., & Carli, V. (2018). Decision-making in suicidal behavior: The protective role of loss aversion. *Frontiers in Psychiatry*, *9*(APR), 1–9. https://doi.org/10.3389/fpsyt.2018.00116

Hermans, E. J., Van Marle, H. J. F., Ossewaarde, L., Henckens, M. J. A. G., Qin, S., Van Kesteren, M. T. R., Schoots, V. C., Cousijn, H., Rijpkema, M., Oostenveld, R., & Fernández, G. (2011). Stress-related noradrenergic activity prompts large-scale neural network reconfiguration. *Science*, *334*(6059), 1151–1153. https://doi.org/10.1126/science.1209603

Hidalgo, V., Pulopulos, M. M., & Salvador, A. (2019). Acute psychosocial stress effects on memory performance: Relevance of age and sex. *Neurobiology of Learning and Memory*, *157*(July 2018), 48–60. https://doi.org/10.1016/j.nlm.2018.11.013

Kahneman, D., & Tversky, A. (1979). Prospect Theory: An analysis of decision under risk. *Econometrica*, *47*(2), 263. https://doi.org/10.2307/1914185

Kalivas, P. W., & Duffy, P. (1995). Selective activation of dopamine transmission in the shell of the nucleus accumbens by stress. *Brain Research*, *675*(1–2), 325–328. https://doi.org/10.1016/0006-8993(95)00013-G

Kirschbaum, C., Pirke, K. M., & Hellhammer, D. H. (1993). The "Trier social stress test" – A tool for investigating psychobiological stress responses in a laboratory setting. *Neuropsychobiology*, *28*(1–2), 76–81. https://doi.org/10.1159/000119004

Lerner, J. S., Li, Y., Valdesolo, P., & Kassam, K. S. (2015). Emotion and decision making. *Annual Review of Psychology*, *66*(1), 799–823. https://doi.org/10.1146/annurev-psych-010213-115043

Liu, Y., & Du, S. (2018). Psychological stress level detection based on electrodermal activity. *Behavioural Brain Research*, *341*, 50–53. https://doi.org/10.1016/j.bbr.2017.12.021

Margittai, Z., Nave, G., Van Wingerden, M., Schnitzler, A., Schwabe, L., & Kalenscher, T. (2018). Combined effects of glucocorticoid and noradrenergic activity on loss aversion. *Neuropsychopharmacology*, *43*(2), 334–341. https://doi.org/10.1038/npp.2017.75

Mather, M., & Lighthall, N. (2012). Both risk and reward are processed differently in decisions made under stress. *Current Directions in Psychological Science*, *21*(1), 36–41. https://doi.org/10.1038/jid.2014.371 https://doi.org/10.1177/0963721411429452

Metz, S., Waiblinger-Grigull, T., Schulreich, S., Chae, W. R., Otte, C., Heekeren, H. R., & Wingenfeld, K. (2020). Effects of hydrocortisone and yohimbine on decision-making under risk. *Psychoneuroendocrinology*, *114*(January), 104589. https://doi.org/10.1016/j.psyneuen.2020.104589

Molins, F., & Serrano, M. A. (2019). Bases neurales de la aversión a las pérdidas en contextos económicos: revisión sistemática según las directrices PRISMA. *Revista de Neurología*, *68*(02), 47. https://doi.org/10.33588/rn.6802.2018276

Molins, F., & Serrano, M. Á. (2020). Heart rate variability after vigorous physical exercise is positively related to loss aversion. *Anxiety, Stress and Coping*, *2020*, 1–12. https://doi.org/10.1080/10615806.2020.1865531

Mrkva, K., Johnson, E. J., Gächter, S., & Herrmann, A. (2020). Moderating loss aversion: Loss aversion has moderators, but reports of its death are greatly exaggerated. *Journal of Consumer Psychology*, *30*(3), 407–428. https://doi.org/10.1002/jcpy.1156

Pabst, S., Brand, M., & Wolf, O. T. (2013). Stress and decision making: A few minutes make all the difference. *Behavioural Brain Research*, *250*, 39–45. https://doi.org/10.1016/j.bbr.2013.04.046

Pighin, S., Bonini, N., Savadori, L., Hadjichristidis, C., & Schena, F. (2014). Loss aversion and hypoxia: Less loss aversion in oxygen-depleted environment. *Stress*, *17*(2), 204–210. https://doi.org/10.3109/10253890.2014.891103

Rangel, A., Camerer, C., & Montague, P. R. (2008). A framework for studying the neurobiology of value-based decision making. *Nature Reviews Neuroscience*, *9*(7), 545–556. https://doi.org/10.1038/nrn2357

Reinhardt, T., Schmahl, C., Wüst, S., & Bohus, M. (2012). Salivary cortisol, heart rate, electrodermal activity and subjective stress responses to the Mannheim Multicomponent Stress Test (MMST). *Psychiatry Research*, *198*(1), 106–111. https://doi.org/10.1016/j.psychres.2011.12.009

Scott, D. J., Heitzeg, M. M., Koeppe, R. A., Stohler, C. S., & Zubieta, J.-K. (2006). Variations in the human pain stress experience mediated by ventral and dorsal basal ganglia dopamine activity. *Journal of Neuroscience*, *26*(42), 10789–10795. https://doi.org/10.1523/JNEUROSCI.2577-06.2006

Shields, G. S., Kuchenbecker, S. Y., Pressman, S. D., Sumida, K. D., & Slavich, G. M. (2016). Better cognitive control of emotional information is associated with reduced pro-inflammatory cytokine reactivity to emotional stress. *Stress*, *19*(1), 63–68. https://doi.org/10.3109/10253890.2015.1121983

Sokol-Hessner, P., Hsu, M., Curley, N. G., Delgado, M. R., Camerer, C. F., & Phelps, E. A. (2009). Thinking like a trader selectively reduces individuals' loss aversion. *Proceedings of the National Academy of Sciences*, *106*(13), 5035–5040. https://doi.org/10.1073/pnas.0806761106

Sokol-Hessner, P., Raio, C. M., Gottesman, S. P., Lackovic, S. F., & Phelps, E. A. (2016). Neurobiology of Stress Acute stress does not affect risky monetary decision-making. *Neurobiology of Stress*, *5*, 19–25. https://doi.org/10.1016/j.ynstr.2016.10.003

Sokol-Hessner, P., & Rutledge, R. B. (2019). The psychological and neural basis of loss aversion. *Current Directions in Psychological Science*, *28*(1), 20–27. https://doi.org/10.1177/0963721418806510

Stan Development Team. (2017). *Stan Modeling Language User's Guide and Reference Manual*. Version 2.17.0.

Starcke, K., & Brand, M. (2012). Decision making under stress: A selective review. *Neuroscience & Biobehavioral Reviews*, *36*(4), 1228–1248. https://doi.org/10.1016/j.neubiorev.2012.02.003

Tom, S. M., Fox, C. R., Trepel, C., & Poldrack, R. a. (2007). The neural basis of loss aversion in decision-making under risk–Supporting Material. *Science*, *315*(5811), 515–518. https://doi.org/10.1126/science.1134239

van den Bos, R., Harteveld, M., & Stoop, H. (2009). Stress and decision-making in humans: Performance is related to cortisol reactivity, albeit differently in men and women. *Psychoneuroendocrinology*, *34*(10), 1449–1458. https://doi.org/10.1016/j.psyneuen.2009.04.016

Watson, D., Clark, L., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*(6), 1063–1070. [Database] https://doi.org/10.1037/0022-3514.54.6.1063

Wood, P. B., Schweinhardt, P., Jaeger, E., Dagher, A., Hakyemez, H., Rabiner, E. A., Bushnell, M. C., & Chizh, B. A. (2007). Fibromyalgia patients show an abnormal dopamine response to pain. *European Journal of Neuroscience*, *25*(12), 3576–3582. https://doi.org/10.1111/j.1460-9568.2007.05623.x

6. Logical decisions after a psychosocial stressor: The late phase of acute stress reduces loss aversion

Physiology & Behavior 268 (2023) 114232

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Logical decisions after a psychosocial stressor: The late phase of acute stress reduces loss aversion

Francisco Molins, Nour Ben Hassen, Mónica Paz, Raquel Costa, Miguel-Ãngel Serrano *

University of Valencia: Universitat de Valencia, Avd. Blasco Ibáñez, 21, 46010, Valencia, España, Spain

ARTICLE INFO

Keywords:
Decision-making
Loss aversion
Acute stress
Trier social stress test

ABSTRACT

Loss aversion, the principle that losses have a greater impact on decision-making than gains, can be modulated by stress. Most findings reported that stress reduces loss aversion, in line with the alignment hypothesis. Yet, decision-making was always assessed at the early stages of the stress response. Instead, the latter phase of the stress response enhances the salience-network and then, it could amplify the salience of losses, thereby increasing loss aversion. To our knowledge, it has never been studied how the latter stress response influences loss aversion and our aim is to fill this gap. 92 participants were divided into experimental and control group. The first one was exposed to the Trier Social Stress Test, and controls viewed a match-length distractor video. Both groups performed a mixed gamble task to measure loss aversion through a Bayesian-computational model. During and after the stressor, experimental group exhibited signs of both physiological and psychological stress which indicated that stress induction was effective. However, rather than increasing, loss aversion of stressed participants was lower. These results constitute a new evidence of stress influencing loss aversion and are discussed within the alignment hypothesis, according to which stress aligns sensitivity to gains and losses.

1. Introduction

Losses have greater psychological impact and influence decision-making than gains of the same magnitude [1]; this phenomenon is called loss aversion [2] and is one of the most accepted judgmental biases in the social sciences. Loss aversion is considered a fundamental and generalizable principle [3], or even a stable behavioral trait [4], although this position is being called into question [5]. Gal & Rucker [3], for example, stressed that there is no firm evidence to support that losses have always more impact than gains and labeled this phenomenon as a fallacy. Moreover, Ert & Erev [6] stated that loss aversion only would emerge under certain very specific experimental manipulations such as when there are large amounts at stake or when people is submitted to long experiments in which no feedback is provided. Nevertheless, the current position is that loss aversion has moderators and a more contextualized view is advisable [3,5]. Many studies are focused on understanding which factors can shape loss aversion's expression. Since the incidence of stress has risen markedly over the past two decades [7], and many decisions are made under stress, this is one of the most studied factors and the focus of our study.

Recent reports state that stress influences loss aversion [8,9], but the specific direction and its mechanisms are still unknown. Most studies highlight that stress significantly reduces loss aversion (e.g., [8–10]), and these results are usually accommodated within the 'alignment' hypothesis postulates [8]. The biological correlates of the stress response are composed of both the immediate catecholamines rising and the latter cortisol release [11,12]. Both components, but specially cortisol, are known to modulate the brain reward-system by enhancing the dopamine striatal levels, then triggering additional reward salience [13,14]. Therefore, the alignment hypothesis suggests that stress would balance the susceptibility to gains and losses, the former being more attractive, thereby reducing loss aversion [8].

However, a common factor in all these studies is that they were carried out at a very early stage after the stressor onset (e.g., at 5 min) and, except for Margittai et al. [8], none provided hormonal measurements (e.g., [9,10]). So, since it cannot be even assured whether cortisol significantly raised at that point —its peak use to be found between 20 and 40 min [11,15]—, the loss aversion reduction could not be firmly attributed to this hormone nor to its influence over the reward-system. In fact, an alternative explanation could also fit. Concretely, early stages of the acute stress response could favor an optimal arousal level for the prefrontal cortex (PFC) functioning since this region is influenced

* Corresponding author.
E-mail address: m.angel.serrano@uv.es (M.-Ã. Serrano).

https://doi.org/10.1016/j.physbeh.2023.114232
Received 22 November 2022; Received in revised form 5 May 2023; Accepted 9 May 2023
Available online 11 May 2023

by an inverted U-shaped curve of catecholamines [16]. The PFC constitutes the main hub for the executive control-network and it is responsible for a logical, rule-based and non-biased decision-making [11,16,15]. Previous studies showed, indeed, that using strategies that enhance PFC over the limbic system reduced loss aversion [17,18]. Therefore, the first mild-to-moderate catecholamines increase could be enhancing the PFC arousal and buffering loss aversion. As seen, this could also explain previous results on stress and loss aversion, instead of the proposed alignment hypothesis.

Following this line, a competing hypothesis on stress and loss aversion emerged. The 'salience-of-losses' hypothesis [8] proposes that, while early stages of stress could be beneficial for the PFC functioning, when both catecholamines and —mainly— cortisol have reached a high level, the executive control-network is suppressed and an alertness state is promoted by enhancing the salience-network [11,19]. As the salience-network shares key nodes with the loss aversion aversive-system —e.g., the amygdala—, the salience of losses would be increased and, loss aversion, amplified [8,19]. Then, by assessing decision-making 20 – 40 min after the stressor onset, when the cortisol peak is supposed to be reached and PFC activity should be diminished [11,15], rather than a decrease, a higher level of loss aversion may be found. Nevertheless, to our knowledge, no studies on loss aversion addressed this delayed point of the stress response and our aim is to fill this gap. Based on the salience-of-losses hypothesis, it was expected that, compared to controls, an experimental group would exhibit higher loss aversion after being submitted to a prominent psychosocial stressor such as the Trier Social Stress Test (TSST; [20]), specifically 30 min after the stressor onset.

2. Methods

2.1. Participants

Based on the large effect size found in previous works on stress and loss aversion [9,21], an a priori power analysis using G*Power indicated a requisite between 12 and 40 participants (η_p^2 = [.18, 0.47], power = 80%, α = 0.05) to perform an ANOVA and compare loss aversion between groups (experimental vs control group). To ensure an adequate statistical power, we recruited 94 participants and randomly distributed them into two groups, experimental (N = 47) and control (N = 47). Yet, two participants of the experimental group did not complete the experimental season, so our sample was finally composed by a total of 92 participants (age: M = 19.11, SD = 1.87; women: N = 77, 83.7%). They met the following inclusion criteria: not having cardiovascular, endocrine, neurological, or psychiatric diseases; not consuming more than 5 cigarettes a day; not consuming drugs habitually; not doing more than 10 h of exercise per week and not having experienced a highly stressful event in the last month. In addition, participants were asked to not perform extenuating exercise or take drugs or alcohol in the last 24 h, and not smoke or take stimulant drinks in the 2 h before the experimental session.

2.2. Procedure

This study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki. Experimental session was carried out between 15:00 pm and 20:00 pm and lasted approximately one and a half hours. Participants were connected to the electrodermal activity (EDA) sensor and had 10 min of habituation. The last 5 min were taken as baseline. Then, experimental group was exposed to the virtual version of the Trier Social Stress Test (TSST-VR), while the control group was submitted to a distractor (watch a length-matched documentary). Before and after the stressor/distractor, participants were evaluated for positive and negative mood with the Positive and Negative Affect Scale (PANAS) and were asked about the subjective stress they felt. 30 min after the stressor/distractor onset, both groups performed an economical decision-making task to measure loss aversion.

2.3. Virtual reality version of the trier social stress test (TSST-VR)

To induce stress we utilized the software of Montero-López et al. [22] which constitutes a virtual-reality adaptation of the traditional TSST [20]. This software designs a 3D audience, which was projected onto a Screen of 27″ at 1 m from the participant. As in the original, the stressor consisted of four phases. First, participants faced the screen showing a 3D image of a stage curtain and were told that they had to give a speech to convince the audience that they were suitable for a position in their dream job. To lend credibility, a microphone and a camera were added, telling them that both the content and formal aspects of their speech would be analyzed in real time and that the virtual audience would react accordingly. The second phase, the anticipatory stress period, lasted 5 min and participants had to prepare the speech. The third phase was the speech itself. During this period, the virtual audience appeared, and participants had to deliver their speeches. They were instructed to speak for the entire 5 min without interruption. The virtual audience remained neutral for 2.5 min but was manipulated to show signs of impatience for the remaining time. Finally, the last phase of the stressful task was an arithmetic task and participants had to repeatedly subtract a fixed amount from a given number —e.g., subtracting 7 from 123 as quickly as possible—. If they completed a series, they were given a new number and started over. Similarly, if they made a mistake they also had to start over.

Comparable to the original TSST, this protocol demonstrated good reliability in inducing stress responses, which were manifested by the increase in EDA, blood pressure, catecholamines and cortisol levels, as well as in the negative mood [22]. To ensure that our stress induction was also effective, we assessed EDA, negative and positive mood, and subjective stress perception.

2.4. Electrodermal activity (EDA)

EDA is one of the most important physiological signals for detecting stress [23]. It has been consistently demonstrated that when the stress induction is effective, it is accompanied by the pronounced increase in EDA [24]. It was recorded and analyzed following recommendations for electrodermal measurements [25]. Two electrodes were placed on non-dominant hand —index and middle finger distal phalanges—, using isotonic gel to amplify the signal. BIOPAC, with EDA-100C transducer, 1000 Hz sampling frequency and AcqKnowledge software were also used. The electrodermal registry was re-sampled with the linear interpolation method at 250 Hz and filtered by smoothing factor with a median value of 5. The average of skin conductance level (SCL) in microsiemens (μS) was extracted from three different periods of 5 min: (1) baseline —last five min of the habituation period—, (2) stressor/-distractor —middle part— and (3) economical task.

2.5. Positive and negative affect registry (PANAS)

PANAS [26] is a 20 Likert-type items scale —from 1, more than usual, to 4, much less than usual— that evaluates positive and negative mood. Each dimension is composed of the sum of 10 items and ranges from 10 to 40 points. The higher the score, the more positive or negative the mood, respectively. PANAS was evaluated before and after the stressor/distractor.

2.6. Perceived stress

Before and after the stressor/distractor, participants were also asked about the subjective stress they felt. This question, designed *ad hoc* for the study, asked: "How much stress do you feel right now?". The answer was given on a Likert scale where 0 is "no stress", and 10 is "a lot of

stress".

2.7. Mixed gamble task (MGT)

To measure loss aversion, both groups performed a short version of MGT [27]. Each trial entailed a bet with one of the combinations randomly extracted from an 8 × 8 losses and gains matrix, until the 64 combinations were completed (see Fig. 1). Following gamble ranges used by Chandrasekhar Pammi et al. [27], as well as by Tom et al. [28] in the original task, gains could range from €100 to €380 in €40 increments, and losses from €50 to €190 in €20 increments. In each trial there was a 50% chance of gaining and 50% chance of losing. Participants had to decide whether to accept or reject the bet. They were instructed that €200 was their initial amount and each bet had to be done with that reference. Betting results were not presented immediately, however, they had to choose carefully in each trial since, at the end, four bets would be randomly picked and played heads or tails, affecting the initial amount. Loss aversion was obtained through the Prospect-Theory computational model [18].

2.8. Prospect-Theory computational model

The Prospect-Theory model [18] follows the classical approach of the Prospect Theory [1] were a bet would be accepted or rejected as a function of the expected utility that it brings to the individual. Following the original paper of Sokol-Hessner et al. [18], the utility of accepting a bet (U_{Accept}) depends on both the utility of the potential gain, estimated through the equation $u(x^{gain}) = x^{\rho}$; and the utility of the potential loss, estimated through the equation $u(x^{loss}) = - \lambda \times (-x)^{\rho}$. Finally, the probability of accepting a gamble is estimated through the SoftMax function, $P_{(Accept)} = 1/(1 + e^{-\mu(U(Accept) - U(Reject))})$; see Sokol-Hessner et al. [18] for a detailed math description. As can be seen, three parameters are derived from this model: λ —loss aversion coefficient—, ρ —the curvature of the utility function or risk attitude—, and μ —the logit or consistency parameter—. However, as we were interested in specifically addressing loss aversion, following Ahn et al. [29] and Molins et al. [9], we set the risk aversion parameter to 1 and using the Maximum likelihood estimation method, λ and μ were obtained. $\lambda = 1$ indicates that gains and losses were valued equally, however, when $\lambda > 1$, losses were overvalued relative to gains —loss aversion—. The logit parameter (μ) represents the amount of "randomness" in the subject's choices or, in other words, consistency over choices. Higher levels of the parameter would represent that participants rely more on rule-based decision-making [18].

These parameters were estimated for each participant through Hierarchical Bayesian Analyses (HBA; see Anh, 2008 for more details), performed with the hBayesDM package [29] for the R software. The hBayesDM uses Stan 2.1.1 [30] with the Hamiltonian Monte Carlo (HMC) algorithm as MCMC for sampling the posterior distributions. Following Alacreu-Crespo et al. [31], we drawn 40.000 samples, after burn-in of 23.333 samples, in three different chains —in sum, a total of 120.000 samples and 70.000 burn-in—. The Gelman-Rubin test [32] was used to study if the chains converged ($\hat{R}$) to the target distribution. $\hat{R}$ values were 1, which means that convergence was achieved. In addition, to confirm this convergence, the MCMC chains were visually inspected.

2.9. Statistical analyses

Outliers were analyzed with the 2.5 standard deviations method and Mahalanobis distance for repeatedly measured variables —e.g., EDA—. Kolmogorov-Smirnoff with Lilliefors correction was used to check normality. Analyses included repeated-measures ANOVAs, with the group —experimental vs control— as a between-participants factor, to test the stress induction effectiveness, both at the physiological (EDA) and at the subjective level —perceived stress, positive affect, and negative affect—. Moreover, the loss aversion level was compared between groups through one-way ANOVA. The α significance level was set at 0.05 and partial eta square (η_p^2) symbolizes the effect size. All analyses were performed with IBM SPSS Statistics 25.

3. Results

3.1. Preliminary analyses

Experimental and control groups were homogeneously distributed with no significant differences in age (experimental: $M = 19.36$, $SD = 2.14$; control: $M = 18.87$, $SD = 1.56$), $p = 0.21$; in BMI (experimental: $M = 22.01$, $SD = 3.05$; control: $M = 21.75$, $SD = 3.48$), $p = 0.69$; nor in socioeconomic status (experimental: $M = 6.42$, $SD = 1.17$; control: $M = 6.43$, $SD = 0.90$), $p = 0.98$. Moreover, there were more women than men, but the chi-square test revealed that both women (experimental: 84.4%; control: 83%) and men (experimental: 15.6%; control: 17%), $p = 0.84$, maintained similar proportion in both groups.

3.2. Stress induction

3.2.1. Physiological stress

A repeated-measures ANOVA including group —experimental vs. control— as a between-factor was performed to test whether the stress

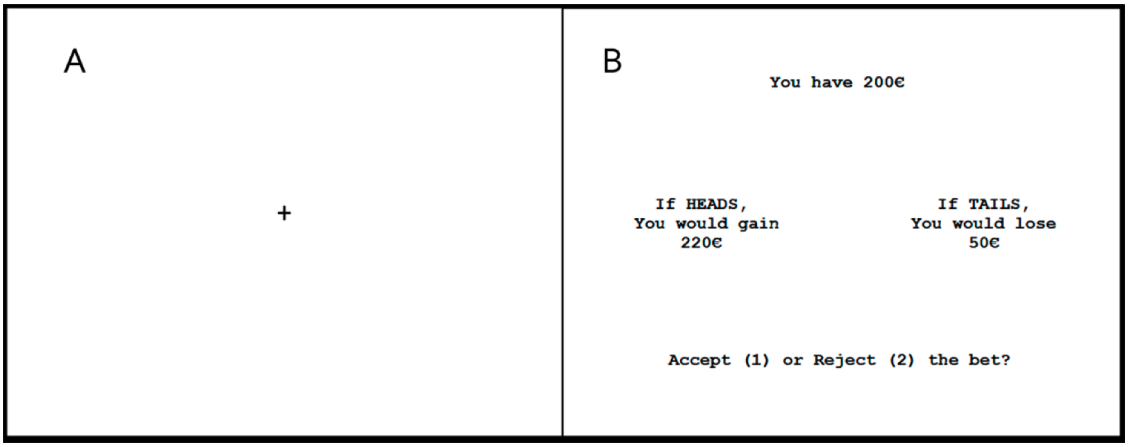


Fig. 1. A representative mixed gamble task trial.
Each of the 64 trials in the task consists of (A) 5 s of fixation point and (B) a bet. The bet offers a possible gain and a possible loss, both with a probability of 50% (heads or tails). The participant must decide whether to play or reject that bet.

induction was effective at the physiological level. Analyses revealed a significant moment (baseline vs. stressor/distractor vs. MGT) × group interaction, $F(2, 180) = 22.19$, $p < 0.001$, $\eta_p^2 = 0.20$, which indicated that the EDA evolution was different for both groups (see Fig. 2). We explored this effect further.

When contrasting by groups, the experimental group's EDA revealed a significant main effect for the moment, $F(1, 88) = 56.05$, $p < 0.001$, $\eta_p^2 = 0.56$, and *posthoc* comparisons indicated that every point of the protocol differed from each other (p's < 0.001); specifically: the highest EDA's level was found during the stressor, followed by the level exhibited during the MGT. The lowest level was found during the baseline. Similar results were found in the control group, where EDA also revealed a significant main effect for the moment, $F(1, 92) = 11.69$, $p < 0.001$, $\eta_p^2 = 0.21$. However, *posthoc* comparisons only revealed significant differences between the baseline EDA's level and both the level during the distractor, $p = 0.009$; and during the MGT, $p < 0.001$; while the latter two points did not differ between them, $p = 0.24$. All means can be consulted in Table 1.

Lastly, the intergroup analysis controlling for basal levels —see Table 1— revealed that, although both groups did not differ in their EDA at the baseline, the experimental group showed significantly higher EDA than the control group during both the stressor /distractor and the MGT.

3.2.2. Psychological stress

Regarding the psychological impact of the stress, repeated measures ANOVAs —including group as between-factor— were carried out to study differences pre- and post-stressor/distractor in the subjective-perceived stress and both the positive and the negative affect measured with PANAS. Focusing on the perceived stress, it was found a significant group × moment interaction, $F(1, 90) = 94.86$, $p < 0.001$, $\eta_p^2 = 0.51$. So, while the control group did not show significant differences between pre- and post-distractor levels, $F(1, 46) = 2.06$, $p = 0.15$, $\eta_p^2 = 0.044$; the experimental group experienced an increase in perceived stress after being submitted to the stressor, compared to their pre-stressor level, $F(1, 44) = 95.48$, $p < 0.001$, $\eta_p^2 = 0.68$ —means can be consulted in Table 1—. Complementarily, both groups did not differ at their basal level, but the perceived stress of the experimental group was significantly higher than the level reported by the control group after the stressor/distractor —see Table 1—.

By the other side, regarding positive affect assessed with PANAS, no pre-post changes or differences between groups were found (p's > 0.05). However, regarding negative affect, analyses also revealed a significant group × moment interaction, $F(1, 90) = 43.54$, $p < 0.001$, $\eta_p^2 = 0.32$. Experimental and control groups did not present differences pre-stressor/distractor —see Table 1—. Yet, the stress group suffered a significant increase in negative affect after the stressor, $F(1, 44) = 11.85$, $p = 0.001$, $\eta_p^2 = 0.21$; while the control group kept a similar level after the distractor, $F(1, 46) = 1.12$, $p = 0.11$, $\eta_p^2 = 0.031$. So, levels post stressor/distractor significantly differed between groups —again, means and statistics can be consulted in Table 1—.

3.3. Loss aversion

First, it was checked if our sample was loss averse. Both control ($M = 2.55$, $SD = 0.61$) and experimental ($M = 2.23$, $SD = 0.56$) groups showed an average λ —loss aversion— value higher than 1, indicating that both groups expressed loss aversion during MGT. However, the ANOVA revealed that the group submitted to stress (experimental group) manifested a significantly lower level of loss aversion than the control group, $F(1, 90) = 6.79$, $p = 0.011$, $\eta_p^2 = 0.07$. Moreover, regarding the second parameter yielded by the Prospect-Theory model, stressed participants showed a higher consistency (μ) in their decisions ($M = 0.064$, $SD = 0.01$) than the control group ($M = 0.038$, $SD = 0.008$), $F(1, 90) = 166.22$, $p < 0.001$, $\eta_p^2 = 0.64$.

4. Discussion

The present study examined how the late phase of the acute stress influences loss aversion. Intergroup analysis revealed that the experimental group's EDA was significantly higher compared to controls, not only during exposure to TSST-VR, but also during MGT. Specifically, with respect to their baseline, the experimental group suffered an increase in EDA of 42.85% during the stressor, comparable to the average increase (45.56%) observed in previous literature also using the TSST-VR [22,33–35]. In addition, the experimental group also showed a higher subjective stress perception, as well as a worse mood after exposure to TSST-VR, while the control group did not show any differences after watching the documentary. Thus, both physiological and psychological measures suggest that our stress manipulation worked. Nevertheless, and despite we addressed the latter stress response, our results showed a loss aversion reduction in the experimental group, contrary to the hypothesized based on the salience-of-losses hypothesis. Once again, stress seems capable of altering decision-making, but on the absence of complementary measures such as cortisol or neural activity, it is difficult to determine whether these results are in line with the alignment hypothesis —as is often proposed in previous literature— or whether other mechanisms are involved in this late phase of stress. The following arguments attempt to shed light on this debate, but caution is advised as this is only speculation that needs to be verified by future research.

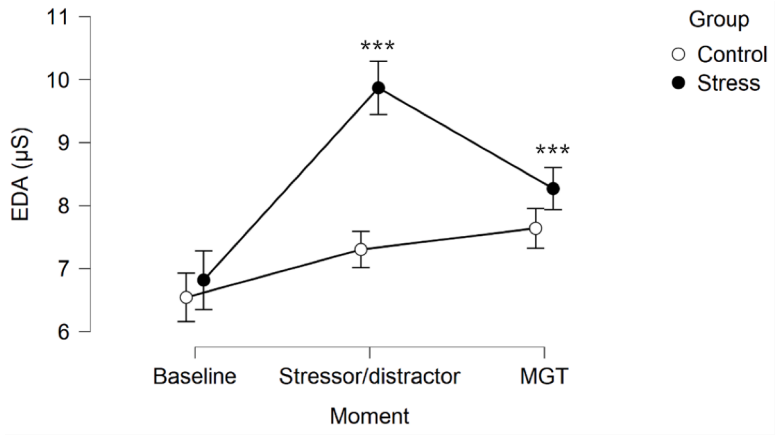


Fig. 2. Electrodermal activity during baseline, stressor/distractor, and MGT by group.
Experimental (stress) and Control groups significantly differed in their EDA level during the stressor/distractor and during the MGT. *** Significant contrast at the 0.001 level; $M \pm$ 95% confidence interval.

Table 1
Intergroup differences in electrodermal activity (EDA) during baseline, stressor/distractor, and MGT; and differences in perceived stress and negative mood with PANAS pre- and post-stressor/distractor.

		Experimental ($N = 45$)	Control ($N = 47$)	F	df between	df intra	p-value	η_p^2
EDA (μS)	Baseline	$M = 6.81 \pm 0.49$	$M = 6.54 \pm 0.42$	0.17	1	90	0.67	0.002
	Stressor / distractor	$M = 9.86 \pm 0.60$	$M = 7.30 \pm 0.42$	31.03	1	90	<0.001***	0.26
	MGT	$M = 8.27 \pm 0.48$	$M = 7.64 \pm 0.40$	23.88	1	90	<0.001***	0.21
Perceived Stress	Pre-Stress	$M = 3.76 \pm 1.92$	$M = 3.96 \pm 1.97$	0.24	1	90	0.62	0.003
	Post-Stress	$M = 6.38 \pm 1.81$	$M = 3.49 \pm 1.79$	116.16	1	90	<0.001***	0.56
PANAS -	Pre-Stress	$M = 20.76 \pm 4.95$	$M = 20.91 \pm 4.20$	0.028	1	90	0.86	0.000
	Post-Stress	$M = 23.47 \pm 6.07$	$M = 20.04 \pm 4.03$	30.56	1	90	<0.001***	0.25

M, mean; ± *SD*; df, degrees of freedom.
*** significant contrast at the 0.001 level.

As mentioned, and in accordance with the main premise of this work, stress influenced loss aversion. Both groups exhibited loss aversion values compatible with previous evidence, which stablished average values between 2 and 2.5 —i.e., that participants accepted gambles if gains were at least twice as large as losses— [1,36,28], yet the experimental group exhibited a significantly lower level of loss aversion. These results contradict our hypothesis and the salience-of-losses hypothesis by which stress would amplify loss aversion [8]. Instead, they may fit better with most previous evidence showing reductions in loss aversion under stress (e.g., [8–10]). Nevertheless, an important difference exists between all this evidence and our work, which may imply different mechanisms as responsible of the loss aversion reduction. As introduced, previous studies addressed decision-making at the very early stage of the stress response. Cortisol is one of the main implicated in the reward-system modulation, enhancing striatal dopamine and being able to balance sensitivity to gains and losses, thereafter, reducing loss aversion —alignment hypothesis— [8,19]; but cortisol peak concentrations in the brain are not reached within 20 min after stressor onset [11,16,37], which implies that 'the role of corticosteroids in the immediate stress response must be limited' ([11], p. 306). Therefore, as suggested Pabst et al. [16], the lower loss aversion found in works addressing early stress stages may be rather attributed to the beneficial role that the initial catecholaminergic release can exert on the PFC activity, which can buffer the manifestation of biases and enhance logical and rule-based decisions [17,38].

In contrast, our work addressed loss aversion 30 min after the stressor onset, focusing on the latter stress response. At this point, acute stress should have promoted an 'off-line' state in the PFC [39,40] and boosted the salience-network —which also includes striatum— by action of both catecholamines and cortisol [11,12]. Therefore, a loss aversion reduction at this point of the stress response may fit better with the alignment hypothesis. In fact, our data could be in line with previous evidence, where people made more conservative decisions until 18 min after the stressor onset, but the tendency was reversed, by making more risky choices, when the cortisol peak was reached 28 min after the stressor onset [16]. Complementarily, concurrent glucocorticoids and catecholamines prompted an alignment of reward- with loss-sensitivity, and thus diminished loss aversion [8]. Accordingly, and rather than into the salience-of-losses hypothesis [8], the effect of the latter, acute stress response on loss aversion may be better suited within the alignment hypothesis postulates [8]. Nevertheless, as stated, since we did not bring complementary neural or hormonal measures, this cannot be firmly assured, and further research is needed to shed light into the specific mechanisms whereby stress is reducing loss aversion. In fact, an alternative explanation to the alignment hypothesis could also fit.

Loss aversion parameter (λ) was computed considering how sensible is someone to losses relative to gains [18]. Then, a reduction in loss aversion could represent a higher sensitivity to gains, but also a lower sensitivity to losses, or even both. Therefore, the 'off-line' state that stress promotes in the PFC [11,40] may also account for our data. So, PFC plays a key role in valuation, stablishing preferences, as well as in reward and threats sensitivity [16,41,42]. In this line, Genauck et al. [43] found that alterations in the connectivity between PFC and limbic regions were associated with lower loss aversion. Thus, our results may also reflect that stressed individuals have difficulties when processing gains and losses and then, emotional influence in decision-making would be reduced. This may also explain why, according to the logit parameter (μ), stressed participants showed a greater reliance on a rule-based decision-making [18]. As seen, these arguments may compete with the alignment hypothesis and further research is needed to determine where they fit best.

Future studies must overcome limitations presented by our work, especially the absence of complementary hormonal or neural measures. Addressing catecholamines, noradrenaline, or opioids, will help to disentangle the specific mechanisms by which stress affects decision-making. It is also necessary to not consider stress in the singular, but rather to address whether its different phases —rapid vs. slow response— differentially influence decision-making, as some studies —including this one— already suggested [9,16]. For this reason, the inclusion in future studies of different groups directly testing the differences between early and late phase stress would be desirable. Additionally, our control situation —watching a documentary— had differences in form from the TSST-VR (e.g., one condition involves talking and the other does not). This could lead to the differences found in the EDA being attributed to movement rather than stress. Although our study also reflects through subjective measures that participants are actually perceiving stress, it would be desirable for future studies to further homogenize the stress and control conditions. On the other hand, previous studies showed sex differences in the psychophysiological response to stress, as well as in the effects of stress on decision-making [37,44]. All analyses were replicated controlling for sex and did not yield significant results. However, our sample was disproportionate and included significantly more women than men, so these analyses could be underpowered, and caution is advisable.

Despite limitations, our work is the first one addressing whether the latter phase of the acute stress response also modulates loss aversion. Specific mechanisms of such modulation remain unclear, and it is necessary further research to confirm whether they can be accounted within the reward alignment hypothesis. Nevertheless, we provide further evidence that stress can influence risky decision-making by reducing such a prominent bias as loss aversion and making decisions more logical. Our data reflect that stress can modulate how people perceives rewards and threats. Therefore, it should be considered when assessing and describing how people make decisions, opening the door to explanations that fit into a biological rationality, instead of the classic economic rationality.

Disclosure statement

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this manuscript, nor do they declare any conflict of interest.

Funding

FM is a predoctoral research fellow, supported by the University of Valencia under Grant AT/2020.

Data availability

Data will be made available on request.

References

[1] D. Kahneman, A. Tversky, Prospect theory: an analysis of decision under risk, Econometrica 47 (2) (1979) 263–291, https://doi.org/10.1017/CBO9780511803475.003.
[2] D. Kahneman, J.L. Knetsch, R.H. Thaler, Anomalies: the endowment effect, loss aversion, and status quo bias, J. Econ. Perspect. 5 (1) (1991) 193–206, https://doi.org/10.1017/CBO9780511803475.009.
[3] D. Gal, D.D. Rucker, The loss of loss aversion: will it loom larger than its gain? J. Consum. Psychol. 28 (3) (2018) 497–516, https://doi.org/10.1002/jcpy.1047.
[4] G. Hadlaczky, S. Hökby, A. Mkrtchian, D. Wasserman, J. Balazs, N. Machín, M. Sarchiapone, M. Sisask, V. Carli, Decision-making in suicidal behavior: the protective role of loss aversion, Front. Psychiatry 9 (APR) (2018) 1–9, https://doi.org/10.3389/fpsyt.2018.00116.
[5] K. Mrkva, E.J. Johnson, S. Gächter, A. Herrmann, Moderating loss aversion: loss aversion has moderators, but reports of its death are greatly exaggerated, J. Consum. Psychol. 30 (3) (2020) 407–428, https://doi.org/10.1002/JCPY.1156.
[6] E. Ert, I. Erev, On the descriptive value of loss aversion in decisions under risk: six clarifications, Judgm. Decis. Mak. 8 (3) (2013) 214–235, https://doi.org/10.2139/ssrn.1012022nsunde. *Judgment and Decision Making, 8*(3), 214–235. http://journal.sjdm.org/12/12712/jdm12712.html.
[7] G. Ward, H. Collins, M.I. Norton, A.V. Whillans, Work Values Shape the Relationship Between Stress and (un) Happiness, Harvard Business School, 2020.
[8] Z. Margittai, G. Nave, M. Van Wingerden, A. Schnitzler, L. Schwabe, T. Kalenscher, Combined effects of glucocorticoid and noradrenergic activity on loss aversion, Neuropsychopharmacology 43 (2) (2018) 334–341, https://doi.org/10.1038/npp.2017.75.
[9] F. Molins, C. Ayuso, M.Á. Serrano, Emotional stress & decision-making: an emotional stressor significantly reduces loss aversion, Stress 24 (6) (2021) 780–786, https://doi.org/10.1080/10253890.2021.1919617.
[10] S. Pighin, N. Bonini, L. Savadori, C. Hadjichristidis, F. Schena, Loss aversion and hypoxia: less loss aversion in oxygen-depleted environment, Stress 17 (2) (2014) 204–210, https://doi.org/10.3109/10253890.2014.891103.
[11] E.J. Hermans, M.J.A.G. Henckens, M. Joëls, G. Fernández, Dynamic adaptation of large-scale brain networks in response to acute stressors, Trends Neurosci. 37 (6) (2014) 304–314, https://doi.org/10.1016/j.tins.2014.03.006.
[12] E.J. Hermans, H.J.F. Van Marle, L. Ossewaarde, M.J.A.G. Henckens, S. Qin, M.T. R. Van Kesteren, V.C. Schoots, H. Cousijn, M. Rijpkema, R. Oostenveld, G. Fernández, Stress-related noradrenergic activity prompts large-scale neural network reconfiguration, Science 334 (6059) (2011) 1151–1153, https://doi.org/10.1126/science.1209603.
[13] M. Mather, N.R. Lighthall, Risk and reward are processed differently in decisions made under stress, Curr. Dir. Psychol. Sci. 21 (1) (2012) 36–41, https://doi.org/10.1177/0963721411429452.
[14] K. Starcke, M. Brand, Decision making under stress: a selective review, Neurosci. Biobehav. Rev. 36 (4) (2012) 1228–1248, https://doi.org/10.1016/j.neubiorev.2012.02.003.
[15] K. Starcke, M. Brand, Effects of stress on decisions under uncertainty: a meta-analysis, Psychol. Bull. 142 (9) (2016) 909–933, https://doi.org/10.1037/bul0000060.
[16] S. Pabst, M. Brand, O.T. Wolf, Stress and decision making: a few minutes make all the difference, Behav. Brain Res. 250 (2013) 39–45, https://doi.org/10.1016/j.bbr.2013.04.046.
[17] P. Sokol-Hessner, C.F. Camerer, E.A. Phelps, Emotion regulation reduces loss aversion and decreases amygdala responses to losses, Soc. Cogn. Affect. Neurosci. 8 (3) (2013) 341–350, https://doi.org/10.1093/scan/nss002.
[18] P. Sokol-Hessner, M. Hsu, N.G. Curley, M.R. Delgado, C.F. Camerer, E.A. Phelps, Thinking like a trader selectively reduces individuals' loss aversion, Proc. Natl. Acad. Sci. U.S.A. 106 (13) (2009) 5035–5040, https://doi.org/10.1073/pnas.0806761106.
[19] S. Metz, T. Waiblinger-Grigull, S. Schulreich, W.R. Chae, C. Otte, H.R. Heekeren, K. Wingenfeld, Effects of hydrocortisone and yohimbine on decision-making under risk, Psychoneuroendocrinology 114 (August 2019) (2020), 104589, https://doi.org/10.1016/j.psyneuen.2020.104589.
[20] C. Kirschbaum, K.M. Pirke, D.H. Hellhammer, The "Trier social stress test" - a tool for investigating psychobiological stress responses in a laboratory setting, Neuropsychobiology 28 (1–2) (1993) 76–81, https://doi.org/10.1159/000119004.
[21] F. Molins, M.Á. Serrano, Heart rate variability after vigorous physical exercise is positively related to loss aversion, Anxiety, Stress Coping 34 (3) (2020) 308–319, https://doi.org/10.1080/10615806.2020.1865531.
[22] E. Montero-López, A. Santos-Ruiz, M.C. García-Ríos, R. Rodríguez-Blázquez, M. Pérez-García, M.I. Peralta-Ramírez, A virtual reality approach to the trier social stress test: contrasting two distinct protocols, Behav. Res. Methods 48 (1) (2016) 223–232, https://doi.org/10.3758/s13428-015-0565-4.
[23] Y. Liu, S. Du, Psychological stress level detection based on electrodermal activity, Behav. Brain Res. 341 (2018) 50–53.
[24] T. Reinhardt, C. Schmahl, S. Wüst, M. Bohus, Salivary cortisol, heart rate, electrodermal activity and subjective stress responses to the Mannheim multicomponent stress test (MMST), Psychiatry Res. 198 (1) (2012) 106–111.
[25] W. Boucsein, D.C. Fowles, S. Grimnes, G. Ben-Shakhar, W.T. Roth, M.E. Dawson, D. L. Filion, Publication recommendations for electrodermal measurements, Psychophysiology 49 (8) (2012) 1017–1034, https://doi.org/10.1111/j.1469-8986.2012.01384.x.
[26] D. Watson, L. Clark, A. Tellegen, Development and validation of brief measures of positive and negative affect: the PANAS scales, J. Pers. Soc. Psychol. 54 (1988) 1063–1070.
[27] V.C.C. Pammi, P.P.G. Rajesh, C. Kesavadas, P.R. Mary, S. Seema, A. Radhakrishnan, R. Sitaram, Neural loss aversion differences between depression patients and healthy individuals: a functional MRI investigation, Neuroradiol. J. 28 (2) (2015) 97–105, https://doi.org/10.1177/1971400915576670.
[28] S.M. Tom, C.R. Fox, C. Trepel, R.A. Poldrack, The neural basis of loss aversion in decision-making under risk, Science 315 (5811) (2007) 515–518, https://doi.org/10.1126/science.1134239.
[29] W.Y. Ahn, N. Haines, L. Zhang, Revealing neurocomputational mechanisms of reinforcement learning and decision-making with the hBayesDM package, Comput. Psychiatry 1 (0) (2017), 24, https://doi.org/10.1162/cpsy_a_00002.
[30] Stan Development Team. (2017). *Stan Modeling Language User ' s Guide and Reference Manual*. Version 2.17.0.
[31] A. Alacreu-Crespo, S. Guillaume, M. Sénèque, E. Olié, P. Courtet, Cognitive modelling to assess decision-making impairments in patients with current depression and with/without suicide history, Eur. Neuropsychopharmacol. 36 (2020) 50–59, https://doi.org/10.1016/j.euroneuro.2020.04.006.
[32] A. Gelman, D. Rubin, Inference from iterative simulation using multiple sequences, Stat. Sci. 7 (4) (1992) 457–511.
[33] Q. Liu, W. Zhang, Sex differences in stress reactivity to the trier social stress test in virtual reality, Psychol. Res. Behav. Manag. 13 (2020) 859–869, https://doi.org/10.2147/PRBM.S268039.
[34] J. Santl, Y. Shiban, A. Plab, S. Wüst, B.M. Kudielka, A. Mühlberger, Gender differences in stress responses during a virtual reality trier social stress test, Int. J. Virtual Reality 19 (2) (2019) 2–15, https://doi.org/10.20870/ijvr.2019.19.2.2912.
[35] Y. Shiban, J. Diemer, S. Brandl, R. Zack, A. Mühlberger, S. Wüst, Trier social stress test in vivo and in virtual reality: dissociation of response domains, Int. J. Psychophysiol. 110 (2016) 47–55, https://doi.org/10.1016/j.ijpsycho.2016.10.008.
[36] É. Duke, R. Schnuerch, G. Heeren, M. Reuter, C. Montag, S. Markett, Cortical alpha asymmetry at central and posterior – but not anterior – sites is associated with individual differences in behavioural loss aversion, Pers. Individ. Dif. 121 (2018) 206–212, https://doi.org/10.1016/j.paid.2017.04.056.
[37] V. Hidalgo, M.M. Pulopulos, A. Salvador, Acute psychosocial stress effects on memory performance: relevance of age and sex, Neurobiol. Learn. Mem. 157 (November 2018) (2019) 48–60, https://doi.org/10.1016/j.nlm.2018.11.013.
[38] G. Park, J.F. Thayer, From the heart to the mind: cardiac vagal tone modulates top-down and bottom-up visual perception and attention to emotional stimuli, Front. Psychol. 5 (MAY) (2014) 1–8, https://doi.org/10.3389/fpsyg.2014.00278.
[39] S. Laborde, E. Mosley, J.F. Thayer, Heart rate variability and cardiac vagal tone in psychophysiological research - recommendations for experiment planning, data analysis, and data reporting, Front. Psychol. 8 (FEB) (2017) 1–18, https://doi.org/10.3389/fpsyg.2017.00213.
[40] J.F. Thayer, R.D. Lane, Claude Bernard and the heart-brain connection: further elaboration of a model of neurovisceral integration, Neurosci. Biobehav. Rev. 33 (2) (2009) 81–88, https://doi.org/10.1016/j.neubiorev.2008.08.004.
[41] X. Gu, X. Wang, X. Hula, S. Wang, S. Xu, T.M. Lohrenz, R.T. Knight, Z. Gao, P. Dayan, P.R. Montague, Necessary, yet dissociable contributions of the insular and ventromedial prefrontal cortices to norm adaptation: computational and lesion evidence in humans, J. Neurosci. 35 (2) (2015) 467–473, https://doi.org/10.1523/JNEUROSCI.2906-14.2015.
[42] E.T. Rolls, Y. Zhou, W. Cheng, M. Gilson, G. Deco, J. Feng, Effective connectivity in autism, Autism Res. 13 (1) (2020) 32–44, https://doi.org/10.1002/AUR.2235.
[43] A. Genauck, S. Quester, T. Wüstenberg, C. Mörsen, A. Heinz, N. Romanczuk-Seiferth, Reduced loss aversion in pathological gambling and alcohol dependence is associated with differential alterations in amygdala and prefrontal functioning, Sci. Rep. 7 (1) (2017) 1–11, https://doi.org/10.1038/s41598-017-16433-y.
[44] R. van den Bos, M. Harteveld, H. Stoop, Stress and decision-making in humans: performance is related to cortisol reactivity, albeit differently in men and women, Psychoneuroendocrinology 34 (10) (2009) 1449–1458, https://doi.org/10.1016/j.psyneuen.2009.04.016.

7. The relationship between the psychological distress derived from COVID-19 and the loss aversion is modulated by the alexithymia trait

Retos
Revista de Ciencias de Administración y Economía

April-September 2023
pp.35-46
https://doi.org/10.17163/ret.n25.2023.03

The relationship between the psychological distress derived from COVID-19 and the loss aversion is modulated by the alexithymia trait

La relación entre el distrés psicológico derivado del COVID-19 y la aversión a las pérdidas es modulada por el rasgo de alexitimia

Francisco Molins
Researcher at Universitat de València, España
francisco.molins@uv.es
https://orcid.org/0000-0002-0211-9182

Miguel Ángel Serrano
Professor and researcher at Universitat de València, España
m.angel.serrano@uv.es
https://orcid.org/0000-0002-6574-4532

Received on: 19/01/2023 **Revised on:** 20/02/2023 **Approved on:** 22/02/2023 **Published on:** 01/04/2023

Abstract: studies on stress and decision-making usually address acute and artificial stressors. However, COVID-19 outbreak set the perfect scenario to address how decision-making, and specifically loss aversion, could be affected by a real and persistent stressor, able to promote a significant psychological distress. In parallel, alexithymia has been identified as a potential moderator of the loss aversion expression, since it could impair the incorporation of emotional information when making a decision, leading to "cold" decisions. Through a within-subjects design (N = 70), our aim was to study the relationship between the psychological distress caused by the pandemic context and the loss aversion changes, considering alexithymia as a moderating factor. Our results show a significant increment in both psychological distress and loss aversion, merely one month after the confinement's onset. Moreover, both variables were positively associated only when alexithymia was low, i.e., the alexithymia buffered the effect of psychological distress on decision-making: a higher alexithymia implied a lower loss aversion increase.

Keywords: decision-making, cognitive bias, loss aversion, alexithymia, psychological distress, COVID-19, confinement, stress.

Resumen: los estudios sobre estrés y toma de decisiones suelen abordar estresores agudos y artificiales. Sin embargo, el brote de COVID-19 creó el escenario perfecto para abordar cómo la toma de decisiones, y específicamente la aversión a las pérdidas, podría verse afectada por un estresor real y persistente, capaz de promover un distrés psicológico significativo. Paralelamente, la alexitimia ha sido identificada como un potencial moderador de la expresión de la aversión a las pérdidas, ya que podría perjudicar la incorporación de información emocional a la hora de decidir, conduciendo a decisiones "frías". Mediante un diseño intrasujeto (N = 70), nuestro objetivo fue estudiar la relación entre el malestar psicológico derivado del contexto pandémico y los cambios en la aversión a las pérdidas, considerando la alexitimia como factor moderador. Nuestros resultados muestran un incremento significativo tanto del malestar psicológico como de la aversión a las pérdidas, tan solo un mes después del inicio del confinamiento. Además, ambas variables se asociaron positivamente solamente cuando la alexitimia era baja; es decir, la alexitimia amortiguaba el efecto del distrés psicológico en la toma de decisiones: cuanto mayor era la alexitimia, menor era el aumento de la aversión a las pérdidas.

Palabras clave: toma de decisiones, sesgo cognitivo, aversión a las pérdidas, alexitimia, distrés psicológico, COVID-19, confinamiento, estrés.

Suggested citation: Molins, F. and Serrano, M. Á. (2023). The relationship between the psychological distress derived from COVID-19 and the loss aversion is modulated by the alexithymia trait. *Retos Revista de Ciencias de la Administración y Economía, 13*(25), 35-46. https://doi.org/10.17163/ret.n25.2023.03

Introduction

Decision-making is a complex and heterogeneous executive function, which is often studied within different contexts and conditions, breaking it down into more analyzable pieces (Starcke and Brand, 2012, 2016). One of the most studied scenarios are risky contexts, where the decision options or prospects are well defined, and the outcomes' probabilities are known (Volz and Gigerenzer, 2012). Here, it can be assessed whether people use more logical and rule-based strategies, such as utility maximization (Camerer, 2003; Starcke and Brand, 2016), or conversely, they are more prone to be affected by emotional phenomena, such as loss aversion (Kahneman, 2003; Kahneman *et al.*, 1991; Sokol-Hessner and Rutledge, 2019).

Loss aversion, the principle that "losses loom larger than gains" (Kahneman and Tversky, 1979, p. 279), is one of the most studied biases in decision-making, because of its important influence in shifting the balance in favor of risk avoidance. So, for example, potential gains should be at least twice as large as potential losses for someone to risk on a bet (Sokol-Hessner and Rutledge, 2019). It is often considered a generalizable and fundamental principle (Gal and Rucker, 2018), or even a stable behavioral trait (Hadlaczky *et al.*, 2018). However, the current position is that a more contextualized view of loss aversion should be considered, since it could be moderated by several factors (Gal and Rucker, 2018; Mrkva *et al.*, 2020).

Many studies are focusing on the contextual factors that could influence loss aversion, from the most stable, such as culture (Wang *et al.*, 2017); to the more situational, such as repulsive odors (Stancak *et al.*, 2015) or even oxygen saturation in the environment (Pighin *et al.*, 2014). Since stress has increased alarmingly in the last two decades (Ward *et al.*, 2020) and many of our decisions are made under stress, this factor is receiving substantial attention (Starcke and Brand, 2012, 2016).

Although a few evidence did not show significant effects on loss aversion (Metz *et al.*, 2020; Sokol-*Hessner et al.*, 2016), most studies report that stress reduce its manifestation (Margittai *et al.*, 2018; Molins *et al.*, 2021; Pighin *et al.*, 2014). These results could be supported by the 'alignment hypothesis' (Margittai *et al.*, 2018), i.e., stress triggers additional reward salience by enhancing the firing rate of dopaminergic neurons in key centers of the reward system, such as the ventral striatum (Mather and Lighthall, 2012), thereby balancing the weight of losses and gains and reducing loss aversion (Margittai *et al.*, 2018; Metz *et al.*, 2020). Nevertheless, the stress response is heterogenous, and it could depend on the nature, duration and intensity of the stressor (Hidalgo *et al.*, 2019). A frequent feature in most studies is that they involve acute and artificial laboratory stressors (e.g., stressful video; Molins *et al.*, 2021) ranging from 5 to 15 minutes, and loss aversion is usually assessed when the stressor is already gone or, at most, during an unconscious stressful condition (e.g., hypoxia; Pighin *et al.*, 2014). In fact, some stressors only affected at a physiological level, without inducing subjective stress or changes in the mood (Margittai *et al.*, 2018; Pighin *et al.*, 2014). Rarely, however, it can be studied how loss aversion is influenced by a real, persistent stressor (still present during the decision-making assessment), which promotes significant psychological distress. This opportunity was provided by the COVID-19 pandemic context.

On 30 January 2020, COVID-19 outbreak was proclaimed a public health emergency of international concern by the World Health Organization (Mahase, 2020), and several countries, such as Spain, were responding through confinement strategies. Confinement involves loss of freedom, social isolation, boredom, routine detriment, sleep disturbances, among many other factors which, along with the fear or concern about the virus contagion itself, were disrupting normal psychosocial life and promoting an important psychological distress, characterized by poorer mood and symptoms of anxiety and depression (Brooks *et al.*, 2020; Ingram *et al.*, 2020; Liang *et al.*, 2020; Pierce *et al.*, 2020; Shuja *et al.*, 2020).

Other fear-related stressors which led to psychological distress have been associated with the salience-network interconnectivity (Hermans *et al.*, 2014; Hermans *et al.*, 2011), enhancing key nodes of the loss aversion neural bases, such as the amygdala (Sokol-Hessner and Rutledge, 2019). Thus, in line with the 'salience-of-losses

Print ISSN: 1390-6291; electronic ISSN:1390-8618

hypothesis' (Margittai *et al.*, 2018), hypervigilance to losses could be increased and, with it, behavioral loss aversion. Complementarily, survivors of other catastrophes such as the Fukushima Daiichi Nuclear Disaster, who also experienced severe psychological distress, reported higher levels of loss aversion (Iwasaki and Sawada, 2015). Finally, an elevated level of this phenomenon is usually observed in patients with anxiety and depression (Baek *et al.*, 2017; Sip *et al.*, 2018). Based on the above, it could be expected that the distressing situation arisen from COVID-19 context were increasing loss aversion.

However, it should be noted that loss aversion is an emotional response to the 'pain of losses' (Hintze *et al.*, 2015; Sokol-Hessner and Rutledge, 2019). From an intrapersonal level, therefore, how sensitive a person is to his or her own emotions should also be considered, as this variable could moderate the degree to which emotions such as loss aversion influence decision-making. In this line, recent studies underline the important role of alexithymia, which is considered a personality trait characterized by difficulties identifying, describing and regulating one's emotions (Patwardhan *et al.*, 2019; Shah *et al.*, 2016; Walker *et al.*, 2011). In the decision-making field, it has been found that alexithymia impairs the incorporation of emotional information when deciding, leading to "cold" decisions (Kano *et al.*, 2011; Shah *et al.*, 2016). Indeed, other emotional phenomena closely linked to loss aversion, such as framing effect, were diminished when the alexithymia was high (Manzoor *et al.*, 2021; Shah *et al.*, 2016). Consequently, the influence of COVID-19-derived stress on loss aversion might be moderated by alexithymia, although this has not been tested to date.

In this study, we were able to assess the loss aversion level of a Spanish population sample one month after the confinement onset and compare it to the level they had before this safety measure was implemented. We hypothesize that, in comparison to pre-confinement measurements, individuals will display a higher psychological distress with increased symptoms of depression and anxiety, as well as higher loss aversion during the confinement. Moreover, considering the moderating role that alexithymia could play on the loss aversion expression, we also hypothesize that alexithymia will buffer the expected increase in loss aversion during confinement. So, the higher alexithymia, the lower increment in loss aversion will be found. Finally, we hypothesize that psychological distress will be associated with the loss aversion increase, but this relation will also depend on the alexithymia level. With this study we aim to contribute to a better understanding of COVID-19 pandemic's impact on mental health and behavior, specifically on decision-making.

Material and methods

Participants

An *a priori* power analysis using G*Power indicated a pre-requisite of 15-20 participants to find a medium effect size (d = 0.50, power = 80 %, α = 0.05) when performing a repeated-measures ANOVA testing for differences in loss aversion, pre- and during-confinement, including the alexithymia's interaction. 85 Spanish participants, all of them students of Psychology from the University of Valencia, were recruited pre-confinement by asking them if they wanted to participate in exchange for academic credits. However, 15 participants did not answer during-confinement and could not be compared. So, a total of 70 participants (women: 71.4 %, and men: 28.6 %) were finally included in the study. They filled out a self-administered questionnaire to confirm they met the following inclusion criteria when first contacted: not having neurological or psychiatric diseases; not consuming drugs regularly; not consuming more than 5 cigarettes a day and not having experienced a highly stressful event in the last month.

Procedure

This research was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki. Participants were first recruited in February 2020 to participate in another study not reported here. They read and

signed informed consent and completed the first battery of questionnaires, which included biometric and socio-economic questions, as well as the pre-confinement measurements of psychological distress and loss aversion. We contacted the participants telematically for the second assessment one month after the declaration of the state of alarm in Spain. Participants were informed about the study's objectives, signed a new consent, and completed a new battery of questionnaires. It was focused on their current level of psychological distress and loss aversion, but also addressed their alexithymia trait and several informative variables about confinement.

Questionnaires

Socio-economic questions were developed *ad hoc* for the research purpose and gathered information about age, gender, and socio-economic status. The latter using a 10-point Likert scale where 0 is the worst socioeconomic situation and 100 the best, taking as a reference the socioeconomic situation in Spain.

For psychological distress, pre- and during-confinement, we used the Spanish version of the General Health Questionnaire (GHQ, $\alpha = .86$) (Rocha *et al.*, 2011). GHQ is a self-report measure extensively recommended and administered in epidemiological surveys (Gnambs and Staufenbiel, 2018). Its short form with 12 items (in a Likert-scale ranging from 0 - not at all, to 3 - much more than usual), allows a screening of psychological distress during the last month and the risk of developing psychiatric disorders (Gnambs and Staufenbiel, 2018; Puustinen *et al.*, 2011). GHQ-12 has a two-dimensional structure: 8 items corresponding to depression symptoms and 4 to anxiety symptoms, where higher scores indicate the manifestation of more symptoms. In our sample the Cronbach's alpha pre-confinement was .88, and during-confinement .85, i.e. GHQ had a high reliability.

An *ad hoc* Spanish translation of the Lottery Choice Task (Gächter *et al.*, 2007) was employed to measure loss aversion pre- and during-confinement. In this task, participants had to decide along six lotteries whether they would accept or reject the bet. In each lottery the gain was fixed at 6 € and the loss varied through bets (ranging from 2 to 7 €), yielding a successively decreasing expected value for each lottery. Following Hadlaczky *et al.* (2018), loss aversion is defined as the inverse of the highest accepted gamble, thus providing a continuous variable ranging from 0 to 6, where higher scores indicate higher loss aversion, since the ratio gains/losses would be higher. This ratio would show how big the potential gain must be in relation to the potential loss for the bet to be accepted.

For alexithymia, the Spanish version of the Toronto Alexithymia Scale (TAS-20, $\alpha = .78$) (Martínez, 1996) allowed the extraction of a general alexithymia factor by adding the scores of all items together. The higher the total score, the greater the alexithymia trait. Nevertheless, only scores above 60 indicate clinical alexithymia. The questionnaire is composed by 20 items in a Likert-scale, ranging from 1 – total agreement, to 5 – total disagreement. In our sample, the Cronbach's alfa was .80, indicating a high reliability of the questionnaire.

Finally, during confinement, we also asked whether the participants or their families had been infected, as well as with whom they lived during this situation.

Statistical analyses

Kolmogorov-Smirnov test with Lilliefors correction and Q-Q plots were used to check for normality. Psychological distress and loss aversion measurements were contrasted in a within-subjects design (pre- vs during-confinement) through repeated-measures ANOVAs (controlling for the alexithymia interaction when addressing loss aversion). In addition, to further explore how alexithymia was moderating the evolution of loss aversion, we carried out a moderation analysis for Two-Instance Repeated-Measures designs and followed the Johnson-Neyman procedure and the simple-slopes method with the recently developed MEMORE macro for SPSS (Montoya, 2019). Johnson-Neyman method selects a continuum of hypothetical values for the moderator variable (in this case, alexithymia) and identifies impor-

Print ISSN: 1390-6291; electronic ISSN:1390-8618

tant transition or critical points (JN) where this moderator's effect over Y (changes in loss aversion), shifts from significant to non-significant, or vice versa (see Montoya, 2019 for a detailed explanation). The simple-slopes method is similar to the previous one, but instead of selecting a continuum of values for the moderator variable, it chooses three of them that represent, regarding this variable, a low, intermediate and high level based on the mean (M) and plus/minus one SD from the mean. Thus, it is possible to see the conditional change of "Y" at each of the three levels of one or more moderators (again, see Montoya, 2019 for more details). In every analysis, the α significance level was set at .05 and partial eta square (η2p) represents the effect size. They were carried out with IBM SPSS Statistics 25.

Results

Sample description

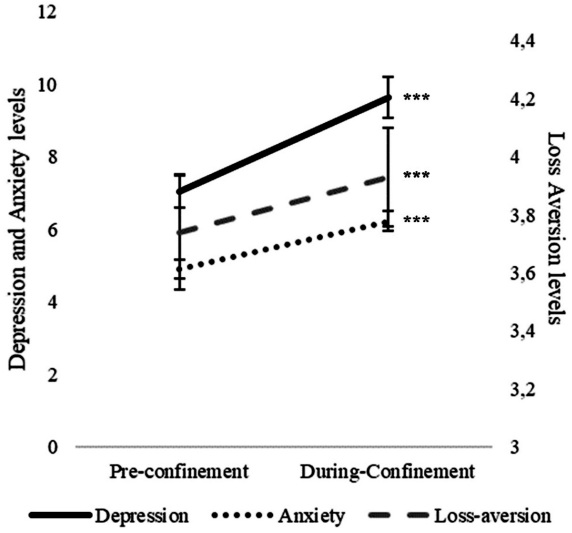
A description of the sample and its status during confinement is shown below. Participants were young people (age: M = 22.56, SD = 2.58), all of them psychology students at the University of Valencia (Spain), with a BMI (M = 23.14, SD = 3.39) within normal range (18.5-24.9), and with an intermediate socio-economic status (M = 60.30, SD = 10.15). Moreover, their alexithymia level (M = 42.50, SD = 8.94) significantly differed from the established score (60 points) that identifies clinical alexithymia, t (69) = -19.33, p < .001. Besides, it must be noted that neither of the participants, nor their loved ones were infected by COVID-19, plus they were not alone during confinement: 75.7 % of them were living with their family; 12.9 % with their (romantic) partner; and 11.4 % with friends or flatmates.

Psychological distress

To test whether the COVID-19 context was increasing psychological distress, pre- and post-confinement symptoms of anxiety and depression assessed with GHQ-12 were compared through repeated-measures ANOVAs. Significant differences were found in both variables, showing higher levels during confinement (see Figure 1). So, the pre-confinement depressive symptoms average was 7.05 (SD = 3.7), and during-confinement 9.69 (SD = 4.7), F(1.68) = 9.01, p = .004, η2p = .12; while the pre-confinement anxiety symptoms average was 4.89 (SD = 2.21), and during-confinement 6.23 (SD = 2.28), F(1.68) = 8.03, p = .006, η2p = .17.

Figure 1

Depression symptoms, anxiety symptoms (with GHQ-12) and loss aversion levels, pre-confinement, and one-month after the confinement onset



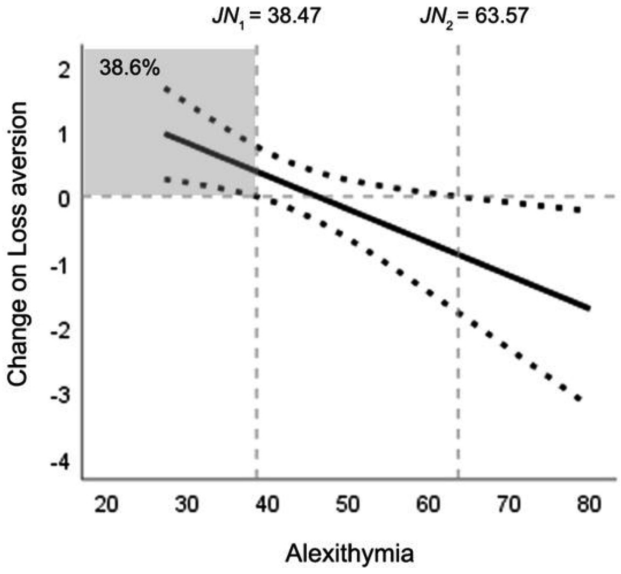
Loss aversion and the moderating role of alexithymia

The aim of this study was to test whether loss aversion grew during the distressful context, as well as whether alexithymia was moderating this increase. Hence, we performed a repeated-measures ANOVA controlling for alexithymia. A significant increment was found during-confinement (see Figure 1). Loss aversion average pre-confinement was 3.74 (SD = 1.6), whereas during-confinement it was 3.91 (SD = 1.4), $F(1.68) = 7.52$, $p = .008$, $\eta 2p = .10$. Moreover, a significant alexithymia*moment interaction was also found, $F(1.68) = 6.72$, $p = .012$, $\eta 2p = .10$, which highlighted that alexithymia was influencing the evolution of loss aversion.

To further explore the direction of these results, we carried out a moderation analysis on repeated-measures. The resulting regression equation was $\hat{Y}_{post}$-$\hat{Y}_{pre}$=$\hat{Y}_{D}$= 2.33 - .05W_i, indicating that during-confinement, it was expected an increment of 2.33 units on loss aversion since pre-confinement, $t(69) = 2.7$, $p = .007$. However, for each unit of alexithymia (W_i), there was a .05 unit decrease in the difference in loss aversion, $t(69) = –2.5$, $p = .01$. Following the Johnson-Neyman procedure, we found two critical points in alexithymia levels (see Figure 2). Alexithymia scores lower than 38.47 suffered a significant increase in loss aversion during-confinement, but scores greater than 63.57, which indicate clinical alexithymia, experienced the opposite. Nevertheless, the latter point is outside of our data's range and methodologists do not recommend interpreting those results (Montoya, 2019). Finally, scores ranging between both critical points did not show a significant change in their loss aversion level. Therefore, the increase in loss aversion was only significant when alexithymia level was low (below 38.47 points).

Figure 2

Graph of the conditional change on Loss aversion as a function of Alexithymia



Note: A JN point is where the confidence interval around the condition effect intersects zero on the y-axis. Thus, the shaded quadrant is the region of significance, i.e., those values of alexithymia for which the change in loss aversion is significant. As can be seen, these changes are only significant for low values of alexithymia. This quadrant includes the actual percentage of participants who fall within these alexithymia scores. Finally, another region of significance is observed that has not been shaded (for high values of alexithymia), this is because none of our participants have such high alexithymia scores and methodologist recommend to not interpret these results.

Print ISSN: 1390-6291; electronic ISSN:1390-8618

Complementarily, to explore whether changes in psychological distress were associated with significant changes in loss aversion, and whether alexithymia moderated this association, we conducted a repeated-measures moderation analysis that included as outcome ($\hat{Y}_{post}$-$\hat{Y}_{pre}$=$\hat{Y}_{D}$) the change in loss aversion and, as moderators, both the level of alexithymia and the change in anxiety/depression symptoms (i.e. the level during-confinement minus pre-confinement level). To our knowledge, and as the MEMORE macro specifies, "Johnson-Neyman procedure is not available for models with more than one moderator", nonetheless, the simple-slopes method is. Using this method, three levels of each moderator (lower, medium, and high) were selected based on the mean value and plus/minus one SD from the mean. Results from this analysis revealed that the increase on anxiety symptoms was only associated with a significant increase on loss aversion when the alexithymia was low and the anxiety increase was either medium ($t(67) = 2.47$, $p = .016$) or high ($t(67) = 2.24$, $p = .02$). For lower levels of anxiety increase and medium or high alexithymia levels, no significant changes in loss aversion were observed. However, the increase on depression symptoms was associated with the significant increase on loss aversion at all levels of change in depression: low ($t(67) = 2.25$, $p = .02$), moderate ($t(67) = 2.59$, $p = .011$) and high ($t(67) = 1.94$, $p = .04$), as long as alexithymia level was low. Otherwise, no significant changes in loss aversion were found for any level of change in depression symptoms.

To sum up, psychological distress (anxiety and depression symptoms) was associated with significant increments on loss aversion when the level of alexithymia was low. Contrarily, for moderate or higher alexithymia levels, even if psychological distress worsened, no significant changes in loss aversion were found.

Conclusions and discussion

Previous studies addressed how stress influences decision-making and, specifically, the psychological impact of losses or loss aversion. However, most utilized acute and artificial stressors, many of which only affected at the physiological level but did not produce psychological distress (Margittai *et al.*, 2018; Pighin *et al.*, 2014). In our study, however, we had the opportunity to address a real and persistent stressor, derived from the pandemic situation experienced with COVID-19. Our results, obtained through a within-subjects design, indicated that this stressful context produced a significant increase in psychological distress, and, as expected, a higher level of loss aversion only one month after the confinement onset. Moreover, alexithymia played an important moderating role by buffering the increase in loss aversion. These results will be discussed in depth below.

First, psychological distress was assessed using the GHQ-12 questionnaire, which provides information on symptoms of anxiety and depression. As expected, both depression and anxiety symptoms increased significantly from their pre-confinement measurement, which would evidence that the stressful pandemic context was producing a significant psychological distress. Thresholds for determining the symptomatology's significance can vary (Goldberg *et al.*, 1998), but a reference adapted from the original GHQ Manual (Goldberg and Williams, 1988) indicates 8 points for depressive symptoms, and 4 points for anxiety symptoms. On average, during confinement, our sample showed scores above these thresholds in both depression ($M = 9.69$, $SD = 4.7$) and anxiety ($M = 6.23$, $SD = 2.28$). But the most concerning aspect is that these levels were reached in just one month. Since GHQ-12 is a good predictor of developing psychiatric disorders (Gnambs and Staufenbiel, 2018), it is not surprising that, months later, various systematic reviews and meta-analyses highlighted that the prevalence of all forms of depression, anxiety, stress, sleep problems, and psychological distress in general population was higher during COVID-19 pandemic (Lakhan *et al.*, 2020; Salari *et al.*, 2020).

However, the main objective of this study was to analyze how this psychological distress affected the perception of economic losses and, therefore, decision-making. As hypothesized, and in line with previous evidence on survivors of other

distressing contexts (Iwasaki and Sawada, 2015), loss aversion increased during the COVID-19 outbreak. This would fit with the enhancing role that psychological distress is thought to exert on the salience network (Hermans *et al.*, 2014, 2011). So, this would promote increased activity in regions such as the amygdala or insula, which, in turn, constitute the main nodes of the neural loss aversion (Sokol-Hessner and Rutledge, 2019). Therefore, this context would promote an alert state that provides greater salience to losses and behavioral loss aversion (Margittai *et al.*, 2018).

It should be noted that greater loss aversion is not good or bad *per se* (Sokol-Hessner *et al.*, 2016). From the classical approach of economic rationality (Camerer, 2003), loss aversion is an emotional phenomenon that would hinder logical or rule-based decision-making. However, in line with the ecological rationality approach (Gigerenzer and Gaissmaier, 2011), loss aversion must be analyzed in terms of its context. So, given the concerning situation, an increase in loss aversion could be considered adaptive, leading to more cautious decisions. In fact, Presti *et al.* (2022) found that confinement adherence was mostly predicted by loss-averse attitudes. Nevertheless, since anxiety and depressive disorders use to be associated with higher levels of loss aversion (Baek *et al.*, 2017; Sip *et al.*, 2018), our results could also constitute further evidence of the mental health worsening. Thus, rather than cautious decisions, increments in loss aversion could represent the maladaptive decision-making commonly found on mood and anxiety disorders (Alexander *et al.*, 2017; Bishop and Gagne, 2018). Therefore, it would be important to deeper study whether loss aversion continued growing, as well as to obtain additional behavioral measurements, in order to explore whether this phenomenon was related only to risk avoidance or, on the contrary, was leading to procrastination, indecisiveness, and other maladaptive ways of deciding, typical in anxiety and depression (Alexander *et al.*, 2017; Bishop and Gagne, 2018; Pushkarskaya *et al.*, 2017).

One possible explanation is that the increase in loss aversion may be adaptive in the early stages of this pandemic context, but if psychological distress deteriorates over time, loss aversion may eventually become very high and lead to maladaptive decisions. In fact, our data support that increased psychological distress at least partially predicted loss aversion increments. Consequently, higher levels of loss aversion could be found when mental health worsens even more. However, an important finding in our study is that alexithymia seems to play a key role in the evolution of loss aversion. The lower alexithymia was associated with the higher increment in loss aversion. Indeed, for levels of alexithymia greater than 38 points, no significant changes in loss aversion were found. This result would be in line with evidence that point out that alexithymia could difficult the incorporation of emotional states (such as the negative affect derived from the psychological distress) into the decisional process, leading to "cold" or rational decisions (Manzoor *et al.*, 2021; Shah *et al.*, 2016; Zhang *et al.*, 2017). Complementarily, our moderation analyses also showed that increased symptoms of anxiety and depression were only associated with a significant increase in loss aversion when levels of alexithymia were low.

An explanation could be drawn from neuroimaging studies. As explained before, the neural bases of loss aversion (Sokol-Hessner and Rutledge, 2019) involve an aversive system (mainly the amygdala and the insula) which reacts disproportionately to losses and sends the information to prefrontal cortex (mainly dorsolateral and ventromedial regions), where it would be synthetized and decisions would be determined. Under conditions of anxiety or depression (even subclinical), several studies showed an increased amygdala and insula reactivity (e.g. Klumpp *et al.*, 2012; Laeger *et al.*, 2012; Stein *et al.*, 2007). As these regions are the main hubs for loss aversion, this may explain why this phenomenon use to be high in these disorders (Alexander *et al.*, 2017; Bishop and Gagne, 2018). Yet, it has also been seen that alexithymia is characterized by hypoactivity of the ventromedial prefrontal cortex, as well as reduced connectivity between the latter region and the insula (Sutherland *et al.*, 2013). This has been proposed as the mechanism by which emotional responses are not adequately incorporated into the decisional process (Kano *et al.*, 2011; Zhang *et al.*, 2017). In this line, although symptoms of

Print ISSN: 1390-6291; electronic ISSN:1390-8618

anxiety and depression increase, and with it, the aversive system's activity, loss aversion could remain low since the emotional information may have difficulties reaching the prefrontal cortex when the alexithymia is high. Nonetheless, this is only speculation, and more research is needed to address the specific mechanisms that explain our results. Indeed, it should not be forgotten that the study's nature is correlational and not experimental, so explanations in the opposite direction may also be plausible. For example, it could be that there were increases in loss aversion, but only those with low alexithymia developed more symptoms of anxiety and depression. Thus, using objective neurophysiological or neuropsychological techniques to address these issues would be very helpful.

In fact, since this is a natural study and participants could not come to the laboratory to take that kind of measures, this is one of our main limitations. Moreover, given the abrupt situation, more pre-confinement variables that could have also been important to consider were not evaluated. In addition, our data must be interpreted based on our specific sample: young people, with middle socioeconomic status, and accompanied during confinement. It is likely that other factors, such as loneliness or a precarious economic condition, may show different results. It would be necessary to replicate our study in broader samples to test whether our results can be extrapolated beyond young psychology students. On the other hand, all analyses were replicated including the gender variable. Results were very similar, and the variable gender did not show significant main effects, nor interaction effects. However, the sample was disproportionate, and this conclusion should not be taken firmly, since analyses could be underpowered. In fact, there is evidence for gender influencing emotional responses to stress, being men less likely to develop psychological symptoms (e.g. Liu *et al.*, 2020; Moccia *et al.*, 2020). Thus, it would be necessary to incorporate a bigger and more balanced sample in the future.

Despite limitations, our study was a first step for understanding how the distressing context generated by COVID-19 was influencing decision-making, and specifically loss aversion. As seen, our data shows that the connection between psychological distress, alexithymia and loss aversion exists must be considered, beyond attending to the different variables separately or in pairs. So, psychological distress seems to enhance loss aversion as long as the level of alexithymia is low. Future lines of research should address whether increased loss aversion in a threatening context such as the COVID-19 outbreak should be understood as a protective factor or, on the contrary, as a manifestation of poorer mental health. Furthermore, alexithymia should be considered in future studies on decision-making and stress, as it seems to be an important factor in the decisional process.

References

Alexander, L. F., Oliver, A., Burdine, L. K., Tang, Y. and Dunlop, B. W. (2017). Reported maladaptive decision-making in unipolar and bipolar depression and its change with treatment. *Psychiatry Research, 257*, 386-392. https://doi.org/10.1016/j.psychres.2017.08.004

Baek, K., Kwon, J., Chae, J. H., Chung, Y. A., Kralik, J. D., Min, J. A., Huh, H. J. J., Choi, K. M., Jang, K.-I., Lee N.-B., Kim, S., Peterson, B. S. and Jeong, J. (2017). Heightened aversion to risk and loss in depressed patients with a suicide attempt history. *Scientific Reports, 7*(1), 1-13. https://doi.org/10.1038/s41598-017-10541-5

Bishop, S. J. and Gagne, C. (2018). Anxiety, depression, and decision making: A computational perspective. *Annual Review of Neuroscience, 41*, 371-388. https://doi.org/10.1146/annurev-neuro-080317-062007

Brooks, S. K., Webster, R. K., Smith, L. E., Woodland, L., Wessely, S., Greenberg, N. and Rubin, G. J. (2020). The psychological impact of quarantine and how to reduce it: rapid review of the evidence. *The Lancet, 395*(10227), 912-920. https://doi.org/10.1016/S0140-6736(20)30460-8

Camerer, C. F. (2003). Behavioral game theory: Plausible formal models that predict accurately. *Behavioral and Brain Sciences, 26*(2), 157-158.

Gächter, S., Johnson, E. and Herrmann, A. (2007). Individual-level loss aversion in riskless and risky choices. *CeDEx Discussion Paper Series*, (2010-20), 1-26.

Gal, D. and Rucker, D. D. (2018). The loss of loss aversion: will it loom larger than its gain? *Journal of Consumer Psychology, 28*(3), 497-516. https://doi.org/10.1002/jcpy.1047

Gigerenzer, G. and Gaissmaier, W. (2011). Heuristic decision making. *Annual Review of Psychology, 62*, 451-482. https://doi.org/10.1146/annurev-psych-120709-145346

Gnambs, T. and Staufenbiel, T. (2018). The structure of the General Health Questionnaire (GHQ-12): two meta-analytic factor analyses. *Health Psychology Review, 12*(2), 179-194. https://doi.org/10.1080/17437199.2018.1426484

Goldberg, D. P., Oldehinkel, T. and Ormel, J. (1998). Why GHQ threshold varies from one place to another. *Psychological Medicine, 28*(4), 915-921. https://doi.org/10.1017/S0033291798006874

Goldberg, D. P. and Williams, P. (1988). *A user's guide to the General Health Questionnaire*. nferNelson.

Hadlaczky, G., Hökby, S., Mkrtchian, A., Wasserman, D., Balazs, J., Machín, N., Sarchapione, M., Sisask, M. y Carli, V. (2018). Decision-making in suicidal behavior: The protective role of loss aversion. *Frontiers in Psychiatry, 9*,1-9. https://doi.org/10.3389/fpsyt.2018.00116

Hermans, E. J., Henckens, M. J. A. G., Joëls, M. and Fernández, G. (2014). Dynamic adaptation of large-scale brain networks in response to acute stressors. *Trends in Neurosciences, 37*(6), 304-314. https://doi.org/10.1016/j.tins.2014.03.006

Hermans, E. J., Van Marle, H. J. F., Ossewaarde, L., Henckens, M. J. A. G., Qin, S., Van Kesteren, M. T. R., Schoots, V., Cousijn, H., Rijpkema, M., Oostenveld, R. and Fernández, G. (2011). Stress-related noradrenergic activity prompts large-scale neural network reconfiguration. *Science, 334*(6059), 1151-1153. https://doi.org/10.1126/science.1209603

Hidalgo, V., Pulopulos, M. M. and Salvador, A. (2019). Acute psychosocial stress effects on memory performance: Relevance of age and sex. *Neurobiology of Learning and Memory, 157* 48-60. https://doi.org/10.1016/j.nlm.2018.11.013

Hintze, A., Olson, R. S., Adami, C. and Hertwig, R. (2015). Risk sensitivity as an evolutionary adaptation. *Scientific Reports, 5*, 1-7. https://doi.org/10.1038/srep08242

Ingram, J., Maciejewski, G. and Hand, C. J. (2020). Changes in diet, sleep, and physical activity are associated with differences in negative mood during COVID-19 lockdown. *Frontiers in Psychology, 11*, 2328. https://doi.org/10.3389/FPSYG.2020.588604/BIBTEX

Iwasaki, K. and Sawada, Y. (2015). Evacuation and *psychological distress: new evidence of reference-dependent utility and loss aversion*. 行動経済学, *8*, 77-80. https://doi.org/10.11167/JBEF.8.77

Kahneman, D. (2003). Maps of bounded rationality: Psychology for behavioral economics. *American Economic Review, 93*(5), 1449-1475. https://doi.org/10.1257/000282803322655392

Kahneman, D., Knetsch, J. L. and Thaler, R. H. (1991). Anomalies: The endowment effect, loss aversion, and status quo bias. *Journal of Economic Perspectives, 5*(1), 193-206. https://doi.org/10.1017/CBO9780511803475.009

Kahneman, D. and Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica, 47*(2), 263-291. https://doi.org/10.1017/CBO9780511803475.003

Kano, M., Ito, M. and Fukudo, S. (2011). Neural substrates of decision making as measured with the iowa gambling task in men with alexithymia. *Psychosomatic Medicine, 73*(7), 588-597. https://doi.org/10.1097/PSY.0b013e318223c7f8

Klumpp, H., Angstadt, M. and Phan, K. L. (2012). Insula reactivity and connectivity to anterior cingulate cortex when processing threat in generalized social anxiety disorder. *Biological Psychology, 89*(1), 273-276. https://doi.org/10.1016/j.biopsycho.2011.10.010

Laeger, I., Dobel, C., Dannlowski, U., Kugel, H., Grotegerd, D., Kissler, J., Keuper, K., Eden, A., Zwitserlood, P. and Zwanzger, P. (2012). Amygdala responsiveness to emotional words is modulated by subclinical anxiety and depression. *Behavioural Brain Research, 233*(2), 508-516. https://doi.org/10.1016/j.bbr.2012.05.036

Lakhan, R., Agrawal, A. and Sharma, M. (2020). Prevalence of Depression, Anxiety, and Stress during COVID-19 Pandemic. *Journal of Neurosciences in Rural Practice, 11*(4), 519-525. https://doi.org/10.1055/S-0040-1716442/ID/JR_40

Liang, L., Ren, H., Cao, R., Hu, Y., Qin, Z., Li, C. and Mei, S. (2020). The effect of COVID-19 on youth mental health. *Psychiatric Quarterly, 91*(3), 841-852. https://doi.org/10.1007/S11126-020-09744-3/TABLES/5

Liu, N., Zhang, F., Wei, C., Jia, Y., Shang, Z., Sun, L., Wu, L., Sun, Z, Zhou, Y., Wang, Y. and Liu, W. (2020). Prevalence and predictors of PTSS during COVID-19 outbreak in China hardest-hit areas: Gender differences matter. *Psychiatry Research, 287*, 112921. https://doi.org/10.1016/j.psychres.2020.112921

Mahase, E. (2020). China coronavirus: WHO declares international emergency as death toll exceeds 200. *BMJ (Clinical Research Ed.), 368*(January), m408. https://doi.org/10.1136/bmj.m408

Manzoor, N., Molins, F. and Serrano, M. Á. (2021). Interoception moderates the relation between

Print ISSN: 1390-6291; electronic ISSN:1390-8618

alexithymia and risky-choices in a framing task: A proposal of two-stage model of decision-making. International *Journal of Psychophysiology, 162*, 1-7. https://doi.org/10.1016/j.ijpsycho.2021.01.002

Margittai, Z., Nave, G., Van Wingerden, M., Schnitzler, A., Schwabe, L. and Kalenscher, T. (2018). Combined effects of glucocorticoid and noradrenergic activity on loss aversion. *Neuropsychopharmacology: official publication of the American College of Neuropsychopharmacology, 43*(2), 334-341. https://doi.org/10.1038/npp.2017.75

Martínez, F. (1996). Adaptación española de la escala de Alexitimia de Toronto (TAS-20). *Clínica y Salud, 7*(1), 19-32. http://bit.ly/3JdlbdEv

Mather, M. and Lighthall, N. R. (2012). Risk and reward are processed differently in decisions made under stress. *Current Directions in Psychological Science, 21*(1), 36-41. https://doi.org/10.1177/0963721411429452

Metz, S., Waiblinger-Grigull, T., Schulreich, S., Chae, W. R., Otte, C., Heekeren, H. R. and Wingenfeld, K. (2020). Effects of hydrocortisone and yohimbine on decision-making under risk. *Psychoneuroendocrinology, 114*,104589. https://doi.org/10.1016/j.psyneuen.2020.104589

Moccia, L., Janiri, D., Pepe, M., Dattoli, L., Molinaro, M., De Martin, V., Chieffo, D., Janiri, L., Fiorillo, A., Sani, G. and Di Nicola, M. (2020). Affective temperament, attachment style, and the psychological impact of the COVID-19 outbreak: an early report on the Italian general population. *Brain, Behavior, and Immunity, 87*, 75-79. https://doi.org/10.1016/j.bbi.2020.04.048

Molins, F., Ayuso, C. and Serrano, M. Á. (2021). Emotional stress and decision-making: an emotional stressor significantly reduce loss aversion. *Stress, 24*(6), 780-786. https://doi.org/10.1080/10253890.2021.1919617

Montoya, A. K. (2019). Moderation analysis in two-instance repeated measures designs: Probing methods and multiple moderator models. *Behavior Research Methods, 51*(1), 61-82. https://doi.org/10.3758/s13428-018-1088-6

Mrkva, K., Johnson, E. J., Gächter, S. and Herrmann, A. (2020). Moderating loss aversion: loss aversion has moderators, but reports of its death are greatly exaggerated. *Journal of Consumer Psychology, 30*(3), 407-428. https://doi.org/10.1002/JCPY.1156

Patwardhan, I., Mason, W. A., Chmelka, M. B., Savolainen, J., Miettunen, J. and Järvelin, M. R. (2019). Prospective relations between alexithymia, substance use and depression: findings from a National Birth Cohort. Nordic *Journal of Psychiatry, 73*(6), 340-348. https://doi.org/10.1080/08039488.2019.1634758

Pierce, M., Hope, H., Ford, T., Hatch, S., Hotopf, M., John, A., Kontopantelis, E., Webb, R., Wessely, S., McManius, S. and Abel, K. M. (2020). Mental health before and during the COVID-19 pandemic: a longitudinal probability sample survey of the UK population. *The Lancet Psychiatry, 7*(10), 883-892. https://doi.org/10.1016/S2215-0366(20)30308-4

Pighin, S., Bonini, N., Savadori, L., Hadjichristidis, C. and Schena, F. (2014). Loss aversion and hypoxia: Less loss aversion in oxygen-depleted environment. *Stress, 17*(2), 204-210. https://doi.org/10.3109/10253890.2014.891103

Presti, S. Lo, Mattavelli, G., Canessa, N. and Gianelli, C. (2022). Risk perception and behaviour during the COVID-19 pandemic: Predicting variables of compliance with lockdown measures. *PLOS ONE, 17*(1), e0262319. https://doi.org/10.1371/JOURNAL.PONE.0262319

Pushkarskaya, H., Tolin, D., Ruderman, L., Henick, D., Kelly, J. M. L., Pittenger, C. and Levy, I. (2017). Value-based decision making under uncertainty in hoarding and obsessive- compulsive disorders. *Psychiatry Research, 258*, 305-315. https://doi.org/10.1016/j.psychres.2017.08.058

Puustinen, P. J., Koponen, H. and Kautiainen, H. (2011). Psychological distress measured by the GHQ-12 and mortality: A prospective population-based study. *Scandinavian Journal of Public Health, 39*, 577-581. https://doi.org/10.1177/1403494811414244

Rocha, K. B., Pérez, K., Rodríguez-Sanz, M., Borrell, C. and Obiols, J. E. (2011). Propiedades psicométricas y valores normativos del general health questionnaire (GHQ-12) en población general española. *International Journal of Clinical and Health Psychology, 11*(1), 125-139. https://bit.ly/3mQnr37

Salari, N., Hosseinian-Far, A., Jalali, R., Vaisi-Raygani, A., Rasoulpoor, S., Mohammadi, M., … Khaledi-Paveh, B. (2020). Prevalence of stress, anxiety, depression among the general population during the COVID-19 pandemic: A systematic review and meta-analysis. *Globalization and Health, 16*(1), 1-11. https://doi.org/10.1186/s12992-020-00589-w

Shah, P., Catmur, C. and Bird, G. (2016). Emotional decision-making in autism spectrum disorder: the roles of interoception and alexithymia. *Molecular Autism, 7*, 43. https://doi.org/10.1186/s13229-016-0104-x

Shuja, K. H., Aqeel, M., Jaffar, A. and Ahmed, A. (2020). Covid-19 pandemic and impending global mental health implications. *Psychiatria Danubina, 32*(1), 32-35. https://doi.org/10.24869/psyd.2020.32

Sip, K. E., Gonzalez, R., Taylor, S. F. and Stern, E. R. (2018). Increased loss aversion in unmedicated patients with obsessive-compulsive disorder. *Frontiers in Psychiatry, 8*, 1-10. https://doi.org/10.3389/fpsyt.2017.00309

Sokol-Hessner, P., Raio, C. M., Gottesman, S. P., Lackovic, S. F. and Phelps, E. A. (2016). Acute stress does not affect risky monetary decision-making. *Neurobiology of Stress, 5*, 19-25. https://doi.org/10.1016/j.ynstr.2016.10.003

Sokol-Hessner, P. and Rutledge, R. B. (2019). The psychological and neural basis of loss aversion. Current *Directions in Psychological Science, 28*(1), 20-27. https://doi.org/10.1177/0963721418806510

Stancak, A., Xie, Y., Fallon, N., Bulsing, P., Giesbrecht, T., Thomas, A. and Pantelous, A. A. (2015). Unpleasant odors increase aversion to monetary losses. *Biological Psychology, 107*, 1-9. https://doi.org/10.1016/j.biopsycho.2015.02.006

Starcke, K. and Brand, M. (2012). Decision making under stress: A selective review. Neuroscience and *Biobehavioral Reviews, 36*(4), 1228-1248. https://doi.org/10.1016/j.neubiorev.2012.02.003

Starcke, K. and Brand, M. (2016). Effects of stress on decisions under uncertainty: A meta-analysis. *Psychological Bulletin, 142*(9), 909-933. https://doi.org/10.1037/bul0000060

Stein, M. B., Simmons, A. N., Feinstein, J. S. and Paulus, M. P. (2007). Increased amygdala and insula activation during emotion processing in anxiety-prone subjects. *American Journal of Psychiatry, 164*, 318-327.

Sutherland, M. T., Carroll, A. J., Salmeron, B. J., Ross, T. J. and Stein, E. A. (2013). Insula's functional connectivity with ventromedial prefrontal cortex mediates the impact of trait alexithymia on state tobacco craving. *Psychopharmacology, 228*(1), 143-155. https://doi.org/10.1007/s00213-013-3018-8

Volz, K. G. and Gigerenzer, G. (2012). Cognitive processes in decisions under risk are not the same as in decisions under uncertainty. *Frontiers in Neuroscience, 6*, 1-6. https://doi.org/10.3389/fnins.2012.00105

Walker, S., O'Connor, D. B. and Schaefer, A. (2011). Brain potentials to emotional pictures are modulated by alexithymia during emotion regulation. *Cognitive, Affective and Behavioral Neuroscience, 11*(4), 463-475. https://doi.org/10.3758/s13415-011-0042-1

Wang, M., Rieger, M. O. and Hens, T. (2017). The Impact of Culture on Loss Aversion. *Journal of Behavioral Decision Making, 30*(2), 270-281. https://doi.org/10.1002/bdm.1941

Ward, G., Collins, H., Norton, M. I. and Whillans, A. V. (2020). *Work values shape the relationship between stress and (un) happiness*. Harvard Business School.

Zhang, L., Wang, X., Zhu, Y., Li, H., Zhu, C., Yu, F. and Wang, K. (2017). Selective impairment of decision making under ambiguity in alexithymia. *BMC Psychiatry, 17*(1), 1-8. https://doi.org/10.1186/s12888-017-1537-2

Print ISSN: 1390-6291; electronic ISSN:1390-8618

8. Early stages of the acute physical stress response increase loss aversion and learning on decision making: A Bayesian approach

Physiology & Behavior 237 (2021) 113459

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Early stages of the acute physical stress response increase loss aversion and learning on decision making: A Bayesian approach

Francisco Molins [a], Miguel Ángel Serrano [a,*], Adrian Alacreu-Crespo [b,c,d]

[a] Department of Psychobiology, Universitat de València, Spain
[b] PSNREC, Univ Montpellier, INSERM, CHU de Montpellier, Montpellier, France
[c] Department of Emergency Psychiatry and Acute Care, Lapeyronie Hospital, CHU Montpellier, Montpellier, France
[d] Laboratory of Cognitive Social Neuroscience, Department of Psychobiology and IDOCAL, University of Valencia, Valencia, Spain

ARTICLE INFO

Keywords:
Stress
Vigorous physical activity
Decision-making
Computational model
Loss aversion
Reward-learning

ABSTRACT

When the cortisol peak is reached after a stressor people learn slower and make worse decisions in the Iowa Gambling Task (IGT). However, the effects of the early stress response have not received as much attention. Since physical exercise is an important neuroendocrine stressor, this study aimed to fill this gap using an acute physical stressor. We hypothesized that this stress stage would promote an alertness that may increase feedback-sensitivity and, therefore, reward-learning during IGT, leading to a greater overall decision-making. 90 participants were divided into two groups: 47 were exposed to an acute intense physical stressor (cycloergometer) and 43 to a distractor 5 min before IGT. The Prospect Valence-Learning (PVL) computational model was applied to the IGT to investigate decision-making components (feedback-sensitivity, loss aversion, learning and choice consistency). There were no differences in the overall IGT performance, but physically stressed participants showed greater loss aversion and higher learning than controls. In addition, this loss aversion was linearly related to the learning and the choice consistency. These results would support the potentially beneficial role that early stages of stress could play in decision-making and suggest the need of studying the components that underlie this cognitive skill, rather than addressing it as a single dimension.

1. Introduction

Decision-making refers to the cognitive ability "to choose between competing courses of action based on their relative value of consequences." ([6], p. 8159). Since many decisions are made under stress or elicit stress responses themselves, and brain regions associated with decision-making are sensitive to stress-induced changes [47], stress effects on subsequent decision-making have been widely studied. The general conclusion is that stress affects decision-making, however, whether the effect is beneficial or detrimental depends on the task and the context [47].

Decision contexts can be described on a continuum from complete certainty to complete ignorance, and can trigger specific decision-making mechanisms [47, 53]. Under ambiguity decisions, when uncertainty is high and there exist several outcomes with unknown probabilities [7, 47, 53], people could not be able to follow strategies such as utility maximization [54] and would rely on the reward or punishment experiences after each decision. These experiences produce emotions that are linked to the different decision alternatives and act as somatic markers that guide following decisions [7, 36]. Sensitivity to reward and punishment play a key role in this reinforcement-learning process [47]. A prominent task to measure decision-making under ambiguity is the Iowa Gambling Task (IGT; [7, 8, 10]). In IGT, participants must choose one hundred cards from four decks to get the most benefit. However, they do not know what they will find in those decks, nor that two of them are advantageous and two disadvantageous. They must learn to choose, based on their experiences of reward and punishment, those cards which yield smaller gains but lower losses in the long run, the advantageous decks. Developing this conservative strategy is considered a better decision-making [7, 10].

Regarding the stress effect on IGT performance, Reiman & Bechara [38] highlighted that stress can interrupt the connection between somatic markers and decision-making in healthy population. Stress interferes with the reinforcement-learning process by reducing feedback sensitivity [26] and impeding attentional disengagement from poorer decks [42]. This can lead to a slower learning during IGT [37] and

* Corresponding author at: *Av.* Blasco Ibáñez, 13, 46010 Valencia, Spain
E-mail address: m.angel.serrano@uv.es (M.Á. Serrano).

https://doi.org/10.1016/j.physbeh.2021.113459
Received 21 December 2020; Received in revised form 7 May 2021; Accepted 8 May 2021
Available online 12 May 2021

disadvantageous card selections [3, 37, 41, 42, 46, 51, 56]. Nevertheless, studies on stress and IGT administered the decision-making task at times of approximately cortisol peak, where strongest stress effects are expected [32, 47]; that is, they address the slower response to stress, related to the hypothalamus-pituitary-adrenal axis (HPA-axis). Yet, the rapid stress effects on decision making as evoked by the fast activation of the sympathetic nervous system (SNS) and catecholamine's secretion have not received as much attention.

Pabst et al. [32] addressed this issue on risky decision-making, where decision rules are explicit and outcomes probabilities are known. They reported that 5 min after the stressor onset, participants improved decision-making by taking less risks than both control and cortisol-peak groups. An explanation can be found in the "salience-of-losses" hypothesis [28]. This suggests that acute stress produces a higher activation of the salience network; thus, enhancing sensitivity to the negative feedbacks by amplifying loss aversion; that is, the greater sensitivity to losses than to proportional gains [23]. In this line, the central norepinephrine (NE) blockade by propranolol reduced sensitivity to the magnitude of possible losses [39], and a linear relationship was found between NE brain levels and loss aversion [44, 48]. Additionally, the salience-of-losses hypothesis would find support in the model of Hermans et al. [19] who argue that the exposure to acute stress prompt a redistribution of neural resources to a salience network, promoting fear and vigilance, and reducing executive control. Finally, it has been recently confirmed the essential role of Salience Network in the coordination of stress response [52]. Therefore, given the IGT nature, the salience-of-losses could favor the reinforcement-learning by enhancing the emotions from punishments and, thus, an advantageous decision-making. However, the rapid stress effects on decision making under ambiguity have never been addressed to date. Our aim is to fill this gap.

On the other side, studies on stress and IGT take the overall performance or the learning-curve during the task as an unidimensional construct of decision-making, but do not take into account that this cognitive ability involves multiple components [4]. Decomposing decision-making performance into single components might identify subtle effects of the stress that are not captured by the traditional task scoring. Computational models based on Bayesian logic have been developed to study the underlying processes that guide the reinforcement-learning in the IGT [2]. Busemeyer & Stout [9] proposed the mathematical model Expectancy Valence Learning (EVL), which was subsequently improved with the Prospect Valence Learning (PVL) model by Ahn et al. [1]. PVL redefines the equations for establishing the value of the card and the consistency between choices and expectations, which provides greater explanatory power to the PVL model [14]. Specifically, the PVL model [1] extracts four theorized parameters: feedback sensitivity, loss aversion, learning and consistency. Based on the above and in line with the salience-of-losses hypothesis, it would be logical to expect that acute stress will enhance sensitivity to feedback and loss aversion and, in turn, this will favor learning and following a consistent strategy. This strategy should be shown through the relationship between the different parameters; in other words, the enhancement in sensitivity to feedback and loss aversion should correlate with the learning parameter during the task. In turn, these parameters should be related to the total IGT index.

Finally, regarding the stress induction, studies on stress and IGT used mainly social stressors. However, considering that physical and psychological events that threaten homeostasis are referred to as 'stressors" [12], we choose a common systemic stressor: physical exercise. In this sense, systemic stressors act unconsciously influencing decision-making sub-components, such as loss aversion [33]. Thus, although healthy, exercise is considered a powerful stressor of the neuroendocrine system since it creates the need to recovery the homeostasis [18]. The SNS and HPA-axis activity increase as the intensity of exercise increases [18]. Moreover, while regular practice is associated with better mental health, a heavy exercise single bout was related to increased perceived stress levels [21]. The decision to use this stressor was justified by the fact that its physiological effects are comparable to those of social stressors [34], but also by the fact that physical stressors emphasize a robust and rapid response of the SNS [5, 20] without the need for interpretation by higher-order brain structures [33]. This is particularly relevant if we want to address the early phase of stress. Consistent with this, acute and intense physical activity, regardless of whether it is considered a stressor or not, is being studied in relation to cognitive processes. For example, some studies show that acute aerobic exercise has beneficial effects on memory, favoring the encoding and consolidation of information during learning. Thus, one focus of research is on the temporal effects of acute and intense physical activity on learning and memory processes in young adults [15]. In addition, it has recently been pointed out that the effect of acute bouts of physical activity on cognitive processes (after such activity) needs to be investigated in more depth, as positive results have been found (i.e. moderate to vigorous intensity activities impacts upon inhibitory control after cessation of the activity bout), but with a low effect size given the wide variety of studies with methodological differences [35]. Furthermore, as it is described in their study, decision-making after this type of physical activity has not been studied, so we believe that this is a gap that should be filled.

Therefore, based on the above, this research aims to investigate if acute and vigorous physical activity has immediate effects in an ambiguity decision-making on IGT, focusing on decision-making components extracted with the PVL model. We hypothesize that 5 min after the physical activity, participants will improve decision-making in IGT with respect to the control group. Furthermore, in line with the salience-of-losses hypothesis, the PVL parameters will show that the better performance is related to increased feedback sensitivity and loss aversion, which in turn will lead to improved learning and consistency. Furthermore, we expect the different parameters to be correlated with each other, showing consistency in the strategy of completing the IGT.

2. Material and methods

2.1. Participants

95 students from the University of Valencia were recruited by asking them if they wish to participate in a study in exchange for academic credits. Those interested filled out a self-administered questionnaire to ensure that they met the following inclusion criteria when first contacted: not having cardiovascular, endocrine, neurological or psychiatric diseases; not consuming more than 5 cigarettes a day; not consuming drugs habitually; not doing more than 10 h of exercise per week and not having experienced a highly stressful event in the last month. In addition, participants were asked to not perform extenuating exercise or take drugs or alcohol in the last 24 h, and not smoke or take stimulant drinks in the 2 h before the experimental session. 5 participants were eliminated for not reaching the intensity preset (70 - 80% of maximum heart rate, HR) in the vigorous exercise. A total of 90 participants (age: $M = 22.43$, $SD = 2.5$; women: $N = 67$, (74.4%)) were finally included in the study. These participants were randomly distributed into two groups, experimental ($N = 47$) and control ($N = 43$) using random number assignment in Excel. However, we finally prioritized a larger number of participants in the experimental group, considering possible exclusions in case they did not reach the intended vigorous exercise preset.

2.2. Procedure

The experimental session was carried out between 15:00 pm and 20:00 pm and lasted approximately one and a half hours. Participants were cited in the University hall and accompanied in an elevator to the laboratory, avoiding the use of stairs. The general procedure was explained, and informed consent was signed. Participants were connected to the electrocardiogram (ECG) and had 10 min of rest as habituation. The last 5 min of habituation were taken as baseline. Then,

experimental group was exposed to stress (physical exercise), while the control group was submitted to a distractor task (watch a construction documentary of similar length to the stressor). Before and after the stressor/distractor, participants were evaluated for positive and negative mood with the Positive and Negative Affect registry, PANAS [55]. Five minutes after the stressor or control, both groups performed the Iowa Gambling Task (IGT). This study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki.

2.3. Vigorous physical exercise considered as stressor

As indicated in the introduction, in this study we have used acute high-intensity physical exercise as a stressor. Thus, experimental group was submitted to 15 min of exercise in a cycloergometer. Following Frith et al. [15], the first 5 min were used as warm-up. In the following 5, pedaling intensity was progressively increased. Finally, last 5 min had to be performed at 70 - 80% of maximum heart rate (HR_{max}), that is, vigorous exercise [34]. The specific HR was calculated and adapted for each participant, using the formula of Karvonen et al. [25], $((HR_{max} - HR_{resting}) \times \%intensity) + HR_{resting}$, where HR_{max} was estimated with the formula of Tanaka et al. [49], $HR_{max} = 208 - (0.7 \times age)$; and $HR_{resting}$ was obtained averaging the last 5 min of the habituation period (baseline). On average, our sample had to be between 159.23 ($SD = 2.98$) and 171.16 ($SD = 2.43$) bpm (70 and 80% HR_{max}, respectively).

To prove that stress manipulation was effective, we also obtained the HR during IGT and both groups were compared to each other. This contrast was made with absolute HR_{IGT} values, but also with reactivities (HR_{IGT} - $HR_{baseline}$) to control changes relative to the basal level of each participant. In addition, the positive and negative mood before and after the stressor/distractor was also assessed with PANAS.

2.3.1. Electrocardiogram (ECG)

The ECG was recorded using the third Einthoven derivation with 3 re-usable electrodes, BIOPAC MP150, a transducer ECG-100C and the AcqKnowledge 4.2.0 software. The sampling frequency was 1000 Hz. The ECG was filtered by digital Band Pass FIR filter, with a low cut-off frequency of 1 Hz and a high cut-off frequency of 35 Hz. [13]. 12 participants showed some ectopic beats which were corrected using the Heart Timing Signal method [27]. For each period (Baseline, Stress and IGT), the mean HR (bpm) was extracted.

2.3.2. Positive and negative affect scale (PANAS)

PANAS [55] is a 20 Likert-type items scale (from 1, more than usual, to 4, much less than usual) that evaluates positive mood ($\alpha = 0.61$) and negative ($\alpha = 0.64$). Each dimension contains 10 items that must be added. The higher the score, the more positive or negative the mood. PANAS was evaluated before and after the stressor/distractor.

2.4. Iowa gambling task (IGT)

Decision-making was evaluated through the computerized version of the IGT [8, 10]. Participants should get the maximum benefit possible over 100 consecutive decisions where they can win and lose money. They can choose from four decks of cards: two disadvantageous (A and B) and two advantageous (C and D). A and B provide large immediate gains, but large losses in the long run. C and D provide lower short-term gains, but lower long-term losses, so their choice leads to higher profit. After each decision, participant receives feedback that can be used to adjust future decisions. Performance was assessed by calculating the Iowa Gambling (IG) index: selections of C and D minus selections of A and B. This index was calculated for the entire task (IG_{TOTAL}), and in blocks of 20 trials to study the learning curve. In addition, the PVL model was used to study the underlying processes that guide the reinforcement-learning in the IGT.

2.4.1. Prospect-Valence learning (PVL) model

The PVL model with the Delta learning rule (PVL-Delta) [1] was applied to extract 4 parameters. Feedback sensitivity (α), can range from 0 to 1, where values near to 1 implies that the subjective utility is greater; that is,the execution of the task is controlled by the magnitude of the gains and losses; lower values, however, represent that all gains and losses, regardless of their size, are perceived in the same way, so what is relevant is the frequency of gains and losses, rather than their size. Loss aversion (λ), λ can range from 0 to 5, where 1 implies an equal sensitivity to losses and gains, values below 1 indicate greater sensitivity to gains, and values above 1 indicate greater sensitivity to losses (loss aversion). Learning (A), from 0 to 1, represents the weight the subject gives to previous experiences with a deck of cards compared to the weight given to the last result obtained. A higher value of A indicates a greater influence of the last card on the expectations of the deck and quick forgetting of previous selections. On the other hand, a low value indicates the predominance of previous experiences; that is,higher learning. Finally, the consistency (c) parameter, ranging from 0 to 5, indicates whether the participant tends to choose a deck according to his/her expectations or, on the contrary, makes random choices. A value close to 0 would reflect randomness, and a high value would represent greater consistency with expectations.

Each parameter of the PVL-Delta model was estimated for each participant through Hierarchical Bayesian Analyses (HBA; see Anh, 2008 for more details), performed with the hBayesDM package [2] for the R software. The hBayesDM uses Stan 2.1.1 [45] with the Hamiltonian Monte Carlo (HMC) algorithm as MCMC for sampling the posterior distributions. Following Alacreu-Crespo et al. [4], we drawn 40.000 samples, after burn-in of 23.333 samples, in three different chains (in sum, a total of 120.000 samples and 70.000 burn-in). The Gelman-Rubin test [17] was used to study if the chains converged ($\hat{R}$) to the target distribution. $\hat{R}$ values of all parameters were 1, which means that convergence was achieved. In addition, to confirm this convergence, the MCMC chains were visually inspected.

2.5. Statistical analyses

The results of our study were extracted through Bayesian analyses performed with JASP 0.13.0.0. Bayesian T-Tests for independent samples were used to check homogeneity between control and experimental groups, as well as to study whether there were differences between groups in HR and mood post-stressor, in the PVL-Delta parameters and in the IG_{TOTAL}. A Bayesian repeated measures ANOVA, including group as between-subjects factor, was carried out to study possible differences in the learning curve during the IGT blocks. This analysis compares the null model (without any predictive variables) against three different models: model 1, that contains "Trial Block" factor (the 5 blocks of IGT); model 2, that contains "Trial Block" and "group" (experimental vs control); and model 3, that contains "Trial Block", "group", and their interaction (Trial Block*group). The results report which model obtains the higher evidence. Finally, Bayesian correlations were used to study the possible relationships between the PVL-Delta parameters, as well as between these parameters and the IG_{TOTAL}.

In all analyses the Bayes factor (BF_{10}) was extracted. This is the ratio between the likelihood of certainty of the alternative hypothesis (H_1) and the likelihood of certainty of the null hypothesis (H_0): $P(H_1) / P(H_0)$. The Bayes factor allows us to talk about the degree of certainty of the alternative hypothesis, but also of the null hypothesis [22]. The language used to discuss and interpret the Bayes factor was selected following Jeffreys' terminology, as shown in the guide to computing and reporting Bayes Factors [22]. In Table 1 it can be seen this terminology. As an example, if a Bayes factor of 15 were obtained, this would indicate that the alternative hypothesis is 15 times more likely to be true than the null hypothesis, which according to Jeffreys' terminology is considered strong evidence.

Table 1
Evidence level for both alternative and null hypotheses according to Jeffreys' terminology (seen in [22]).

Bayes Factor	Support for H_1	Bayes Factor	Support for H_0
1–3	Anecdotal	1–0.33	Anecdotal
3–10	Substantial	0.33–0.10	Substantial
10–20	Strong	.10–0.05	Strong
20–30	Strong	.05–0.03	Strong
30–100	Very Strong	.03–0.01	Very Strong
100–150	Decisive	0.01–0.0067	Decisive
>150	Decisive	<0.0067	Decisive

Although our hypotheses were directional, given that there is not enough evidence to rely exclusively on this directionality, in our analysis we used the "difference between groups" as an alternative hypothesis, in favor of exploring different results than those hypothesized. For the T-Tests the priors were described by a Cauchy distribution centered around zero and with a width parameter of 0.707. This corresponds to a probability of 80% that the effect size lies between −2 and 2. For the correlations, the priors were described by a beta-distribution centered around zero and with a width parameter of 1. This corresponds to a probability of 80% that the correlation coefficients lie between −0.750 and 0.750. It should be noted that all analyses were replicated by controlling for sex, with similar results. For this reason, the results presented below do not incorporate this variable.

3. Results

3.1. Preliminary analyses

Through Bayesian T-Tests we checked that the distribution of participants in the experimental and control groups was homogeneous in terms of sociodemographic variables and baseline measures. We also checked if manipulation was effective. As can be seen in Table 2, there was substantial evidence supporting the absence of differences in BMI, pre-stress mood and basal HR, as well as anecdotal evidence for the absence of differences in age. In addition, although there were more women than men, the distribution of both sexes into the two groups maintained substantially the same proportion (see Table 2).

Regarding the stress manipulation effectiveness, it was proved that, during the last 5 min, experimental group HR was within the expected according to the vigorous intensity preset (bpm was between M = 157.86, SD = 2.98 y M = 170.23, SD = 2.43). In addition, we can see that there was decisive evidence supporting the HR differences between groups during the last 5 min of the stressor/distractor, during IGT, as well as in HR reactivity. However, there also was substantial evidence against the differences post-stressor at a subjective level, e.g. in the emotional state assessed with PANAS.

Table 2
Homogeneity between groups, PANAS and Heart Rate (HR).

	Experimental (N = 47)	Control (N = 43)	BF_{10}
Age	M = 22.87 ± 3.11	M = 21.95 ± 1.47	0.85
Sex			
Men	25.5%	25.6%	0.25[†]
Women	74.5%	74.4%	0.16[†]
BMI	M = 22.45 ± 3.22	M = 22.70 ± 2.89	0.23
PANAS (Baseline)			
Positive affect	M = 26.46 ± 4.67	M = 27.09 ± 3.9	0.27
Negative affect	M = 20.76 ± 4.6	M = 21.81 ± 4.47	0.32
PANAS (pre IGT)			
Positive affect	M = 26.93 ± 4.9	M = 27.1 ± 3.89	0.31
Negative affect	M = 21.06 ± 4.51	M = 21.64 ± 4.54	0.30
HR (Baseline)	M = 78.68 ± 10.29	M = 79.81 ± 11.16	0.26
HR (Stress)	M = 162.94 ± 6.62	M = 77.79 ± 13.65	1.002×10^{48}
HR (IGT)	M = 95.33 ± 9.30	M = 78.16 ± 12.49	4238.1
HR (Reactivity)	M = 16.19 ± 12.14	M = 0.70 ± 21.51	166.01

M, mean; ±, SD; BMI, weight(kg) / height(m)^2; Positive mood, sum 10 items of positive mood; Negative mood, sum 10 items of negative mood; HR, Heart Rate (in bpm); HR (Reactivity) HRIGT - HRbaseline; BF_{10}, Bayes Factor from Bayesian T-Test.

[†] These BF were calculated by means of a Bayesian Binomial Test.

3.2. Behavioral results: ig index and the learning curve

Regarding the learning curve, the Bayesian repeated measures ANOVA revealed that the main factor "Trial blocks" (each of the 5 IGT blocks) obtained the highest Bayes factor, with decisive evidence with respect to the main effect "group" (BF_{10} = 293.08) and substantial evidence with respect to the interaction "moment" x "group" (BF_{10} = 7.32). Thus, both groups increased performance throughout the task in a similar way, without differences in their evolution during the IGT (see Fig. 1).

3.3. Decision-making components: PVL-Delta parameters

A Bayesian T-Test for independent samples revealed that there was decisive evidence (BF_{10} = 509.98) in support of the differences between groups in loss aversion (λ). The experimental group showed greater λ (M = 1.38, SD = 0.91) than the control (M = 0.61, SD = 0.6). Moreover, we found decisive evidence (BF_{10} = 710.31) supporting the existence of differences in the learning (A) parameter. Specifically, the experimental group obtained a lower score (M = 0.29, SD = 0.17), with respect to the control group (M = 0.50, SD = 0.27), which means a higher learning in the stressed participants. However, there also was substantial (BF_{10} = 0.22) and anecdotal (BF_{10} = 0.35) evidence in favor of the absence of differences in feedback sensitivity (α) (experimental group, M = 0.22, SD = 0.04; control group, M = 0.22, SD = 0.09) and consistency (C) (experimental group, M = 0.70, SD = 0.49; control group, M = 0.79, SD = 0.27), respectively.

3.4. Correlations between PVL-Delta parameters and ig index

We addressed the possible relation between the general IG index and the parameters of the PVL-Delta model, as well as the internal relations between these parameters. As can be seen in Table 3, the Bayesian correlations provided substantial evidence in support of the absence of correlation between IG_{TOTAL} and PVL-delta parameters. However, decisive evidence of the correlation between loss aversion and both feedback sensitivity and learning were found. In addition, the correlation between loss aversion and consistency received strong evidence. Feedback sensitivity received substantial evidence in support of its negative correlation with learning, and substantial evidence against its correlation with consistency. Finally, substantial evidence against the correlation between learning and consistency was also found.

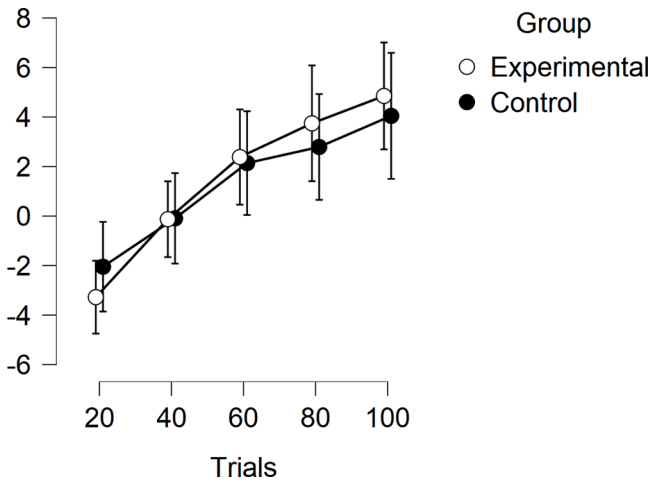


Fig. 1. Between groups comparison of learning curve along the 5 blocks in the Iowa Gambling Task. Means and 95% Confidence intervals.

Table 3
- Bayesian correlations between IG index and PVL-Delta parameters.

Variable		1	2	3	4
1. IG_{TOTAL}	Pearson's r	—			
	BF_{10}	—			
2. Learning	Pearson's r	0.054	—		
	BF_{10}	0.149	—		
3. Feedback sensitivity	Pearson's r	−0.126	−0.308	—	
	BF_{10}	0.262	9.714	—	
4. Constancy	Pearson's r	−0.040	−0.127	0.100	—
	BF_{10}	0.141	0.267	0.202	—
5. Loss aversion	Pearson's r	−0.009	−0.513	0.385	0.320
	BF_{10}	0.132	65,541.006	132.470	13.936

4. Discussion

Previous works studied the delayed psychosocial stress influence on IGT (e.g. when the cortisol-peak was approximately reached) and reported a deleterious effect in the decision-making (e.g. [37, 41, 42, 46, 51, 56]). This research aimed to study whether a vigorous physical activity (named as stressor) could produce the opposite effect, and improving decision-making under ambiguity, as Pabst et al. [32] found in risky contexts. Attending to the IGT classical scoring, our results suggest that physically stressed participants did not perform better than non-stressed participants, but neither did they perform worse. Yet, if we attend to decision-making underlying components, physically stressed participants showed higher sensitivity to punishments (losses) and a greater learning. These results will be discussed in depth below.

First, with regard to stress manipulation, using a vigorous physical activity, all participants in the experimental group reached the pre-set HR level and therefore a vigorous exercise intensity [34]. Furthermore, experimental and control group differed in HR during IGT, both in absolute and relative values. The experimental group showed greater physiological activation, in line with the expected physiological effects of stress influence. By the other side, substantial evidence was found against the differences in post-stress mood. This could indicate that although the stressor affected physiologically, it had no influence on the subjective emotional level, as was the case with most studies using psychosocial stressors (e.g. [3, 32]). Nevertheless, systemic stressors can influence cognition even when they are not interpreted by higher-order brain structures, but only processed in limbic forebrain structures, which are implicated in automatic processing [33, 40].

Regarding decision-making, the total score and the learning curve during the task were similar in both stressed and non-stressed participants. This would support the idea that stress is not necessarily harmful, but also seems to contradict what was observed in Pabst et al. [32], where stress increased overall performance by facilitating conservative choices. An explanation could be, as mentioned, that vigorous physical activity did not generate emotional discomfort. Moreover, Pabst et al. [32] used a decision making task with an uncertainty of risk while we used a task with an uncertainty of ambiguity. Therefore, physiological activation may be enough to affect risky decision making [33], but not decision making under ambiguity. However, it should also be noted that the classic form of scoring IGT assumes decision-making as a single dimension, which could not be reflecting its full complexity [4]. This is especially relevant if we consider that both the experimental and control groups were composed of young, healthy participants. Since both groups should not face difficulties in learning the appropriate strategy in IGT [8], the margin for improvement in the task may not be large enough to be observed with the overall score.

Nevertheless, if we examine the other parameters provided by the PVL-Delta model, relevant information is revealed. In fact, as Pighin et al. [33] reported, systemic stressors that act unconsciously influence decision-making sub-components, such as loss aversion [33]. Results partially supported our hypotheses, evidencing differences in two of the four PVL parameters: loss aversion and learning. The control group exhibited low loss aversion (λ) level (0.61). In fact, based on the PVL-Delta criteria, this value indicates more sensitivity to gains, rather than loss aversion. Recently, Alacreu-Crespo et al. [4] showed that healthy controls also had an average λ of 0.40 in IGT. This might suggest that unlike in risky tasks, where it is usually assumed that losses loom larger than gains [24], people may be more sensitive to gains than losses under ambiguity. Nevertheless, it could also be due to other modulating factors, such as the initial instruction given in IGT: "you must achieve as much money as you can", which could be encouraging the search for gains [11]. More research is needed to answer these questions; however, this result would be in line with the need to contextualize loss aversion rather than consider it as a ubiquitous and generalizable phenomenon [16, 30]. By the other side, after vigorous physical activity participants showed high loss aversion ($\lambda = 1.38$) and, therefore, a higher level than controls. This result supports our hypothesis that stress would increase loss aversion. In turn, this could be in line with the salience of losses hypothesis [28]. This hypothesis states that stress produces a relocation of the brain resources in favor of the amygdala and in detriment of the prefrontal cortex. The amygdala is one of the main neural bases of loss aversion, constituting, with the insula, an aversive system that responds to negative emotional stimuli [29, 44]. Thus, in line with Sokol-Hessner et al. [43], if the amygdala is more responsive, negative stimuli could be more easily detected and rejected, which leads to an increased loss aversion. Additionally, this result is according to the reported impact that vigorous intensity aerobic activities have upon inhibitory control in young adults [35].

Regarding the learning parameter (A), as was hypothesized, physically stressed participants had lower levels of A than controls; they exhibited a greater learning based on their previous decisions during the task [1, 2]. In addition, a close negative correlation was observed between this parameter (A) and loss aversion, which would indicate that loss aversion was somehow implicated in the acquisition of the expectancies about the IGT's decks. It could be seen that the feedback sensitivity (α) parameter also correlated negatively with learning (A). However, as was established by the PVL-Delta model [1, 2], and supported by our results, α indicates the feedback sensitivity and it is directly related to loss aversion. Therefore, we could argue that, ultimately, it was the loss aversion increment who played a fundamental role in the higher learning of the stressed participants. Moreover, loss aversion was also related to a more consistent IGT strategy, e.g., fewer random choices. All these results would support the potentially beneficial role that early stages of stress could play in decision making under ambiguity. These results could explain the lack of results obtained with a similar stressor in short-term memory and learning [15]; that is, loss aversion could be influencing learning processes, although more research is needed. Thus, and contrary to what a later stage seems to produce, the fast stress response could promote an alertness that increases sensitivity to punishments (losses), which helps them to act as somatic markers in following decisions [36, 47]. These markers could warn of which decks provide punishment and facilitate their avoidance. It has been seen in previous works that this negative reinforcement, as opposed to comparable positive reinforcement, would lead to greater learning [31, 50].

Our study is not exempt from limitations. As White & Raven [57] sustained, in an exercise of such intensity, it is expected that the effects would not only be mechanical, e.g. focused on the heart, but of greater magnitude, involving the fast release of catecholamines and the slower HPA-axis activation. Nevertheless, other measures such as cortisol, alpha-amylase or catecholamines would complement our results to better address the extent to which the stressor affected the organism. On the other hand, although the role of sex was considered by adjusting results by sex, the disproportionate sample (most women) makes it difficult to draw conclusions. Further research is needed to conclude whether our results are generalizable to both sexes, including, in the case of women, the control for menstrual cycle and intake of oral

contraceptives. Finally, vigorous physical activity did not produce effects at the emotional level, however, these effects may alter the results. Future research should explore these issues further.

Nevertheless, our work provides a first step in understanding how rapid stress response, obtained using vigorous physical activity, could improve ambiguous decision-making. On the one hand, it highlights the importance of studying the components that underlie this cognitive skill, rather than addressing it as a single dimension. On the other, our results emphasize the need to better contextualize the study of stress and loss aversion, since both phenomena have been usually considered in a negative way but may constitute an advantage depending on the context. They could favor the reinforcement-learning in complex decision-making. Finally, it is also noteworthy that a stressor as common as physical exercise may be affecting our cognition, in line with embodied brain approaches.

Funding

FM is a predoctoral research fellow, supported by the Generalitat Valenciana (ACIF/2020/062). AA-C is a postdoctoral research fellow, supported by the Generalitat Valenciana (APOSTD/2020/104)

Declaration of Competing Interest

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this manuscript.

References

[1] W. Ahn, J. Busemeyer, E. Wagenmakers, J.C. Stout, Comparison of decision learning models using the generalization criterion method, Cogn. Sci. 32 (8) (2008) 1376–1402, https://doi.org/10.1080/03640210802352992.
[2] Ahn, W., Haines, N., & Zhang, L. (2017). Revealing neurocomputational mechanisms of reinforcement learning and decision-making with the hbayesdm package. Figure 1.
[3] A. Alacreu-Crespo, R. Costa, D. Abad-Tortosa, V. Hidalgo, A. Salvador, M.Á. Serrano, Hormonal changes after competition predict sex-differentiated decision-making, J. Behav. Decis. Mak. 32 (5) (2019) 550–563, https://doi.org/10.1002/bdm.2128.
[4] A. Alacreu-Crespo, S. Guillaume, M. Sénèque, Cognitive modelling to assess decision-making impairments in patients with current depression and with /without, Eur. Neuropsychopharmacol. (2020) 1–10, https://doi.org/10.1016/j.euroneuro.2020.04.006.
[5] A.P. Allen, P.J. Kennedy, J.F. Cryan, T.G. Dinan, G. Clarke, Biological and psychological markers of stress in humans: focus on the trier social stress test, Neurosci. Biobehav. Rev. 38 (2014) 94–124, https://doi.org/10.1016/j.neubiorev.2013.11.005.
[6] B.W. Balleine, The neural basis of choice and decision making, J.Neurosci. 27 (31) (2007) 8159–8160, https://doi.org/10.1523/JNEUROSCI.1939-07.2007.
[7] A. Bechara, A.R. Damasio, The somatic marker hypothesis : a neural theory of economic decision, Games Econ. Behav. 52 (2005) 336–372, https://doi.org/10.1016/j.geb.2004.06.010.
[8] A. Bechara, A.R. Damasio, H. Damasio, S.W. Anderson, Insensitivity to future consequences following damage to human prefrontal cortex, Cognition 50 (1994) 7–15.
[9] J.R. Busemeyer, J.C. Stout, A contribution of cognitive decision models to clinical assessment: decomposing performance on the Bechara gambling task, Psychol. Assess. 14 (3) (2002) 253.
[10] Y.C. Chiu, J.T. Huang, J.R. Duann, C.H. Lin, Editorial: twenty years after the Iowa Gambling Task: rationality, emotion, and decision-making, Front. Psychol. 8 (JAN) (2018) 1–5, https://doi.org/10.3389/fpsyg.2017.02353.
[11] W.A. Cunningham, J.J.Van Bavel, I.R Johnsen, Affective flexibility evaluative processing goals shape amygdala activity, Psychol. Sci. 19 (2) (2008) 152–160, https://doi.org/10.1111/j.1467-9280.2008.02061.x.
[12] E.R. de Kloet, M. Joëls, F. Holsboer, Stress and the brain: from adaptation to disease, Nature Rev. Neurosci. 6 (6) (2005) 463–475, https://doi.org/10.1038/nrn1683.
[13] D. Dellacherie, M. Roy, L. Hugueville, I. Peretz, S. Samson, The effect of musical experience on emotional self-reports and psychophysiological responses to dissonance, Psychophysiology 48 (3) (2011) 337–349, https://doi.org/10.1111/j.1469-8986.2010.01075.x.
[14] D.J. Fridberg, S. Queller, W.Y. Ahn, W. Kim, A.J. Bishara, J.R. Busemeyer, L. Porrino, J.C. Stout, Cognitive mechanisms underlying risky decision-making in chronic cannabis users, J. Math. Psychol. 54 (1) (2010) 28–38, https://doi.org/10.1016/j.jmp.2009.10.002.
[15] E. Frith, E. Sng, P.D. Loprinzi, Randomized controlled trial evaluating the temporal effects of high-intensity exercise on learning, short-term and long-term memory, and prospective memory, European J. Neurosci. 46 (10) (2017) 2557–2564, https://doi.org/10.1111/ejn.13719.
[16] D. Gal, D.D. Rucker, The loss of loss aversion: will it loom larger than its gain? J. Consumer Psychol. 28 (3) (2018) 497–516, https://doi.org/10.1002/jcpy.1047.
[17] A. Gelman, D. Rubin, Inference from iterative simulation using multiple sequences, Statistical Sci. 7 (4) (1992) 457–511.
[18] A.C. Hackney, Stress and the neuroendocrine system: the role of exercise as a stressor and modifier of stress, Expert Rev. Endocrinol. Metab. 1 (6) (2006) 783–792.
[19] E.J. Hermans, M.J.A.G. Henckens, M. Joëls, G Fernández, Dynamic adaptation of large-scale brain networks in response to acute stressors, Trends Neurosci. 37 (6) (2014) 304–314, https://doi.org/10.1016/j.tins.2014.03.006.
[20] V. Hidalgo, M.M. Pulopulos, A. Salvador, Acute psychosocial stress effects on memory performance: relevance of age and sex, Neurobiol. Learn. Mem. 157 (July 2018) (2019) 48–60, https://doi.org/10.1016/j.nlm.2018.11.013.
[21] M.E. Hopkins, F.C. Davis, M.R. VanTieghem, P.J. Whalen, D.J. Bucci, Differential effects of acute and regular physical exercise on cognition and affect, Neuroscience 215 (2012) 59–68, https://doi.org/10.1016/j.neuroscience.2012.04.056.
[22] A. Jarosz, J. Wiley, What are the odds? a practical guide to computing and reporting Bayes factors, J. Problem Solving 7 (2014) 2–9.
[23] D. Kahneman, J.L. Knetsch, R.H. Thaler, Anomalies: the endowment effect, loss aversion, and status Quo Bias, J. Economic Perspectives 5 (1) (1991) 193–206, https://doi.org/10.1257/jep.5.1.193.
[24] D. Kahneman, A. Tversky, Prospect Theory: an analysis of decision under risk, Econometrica 47 (2) (1979) 263.
[25] M. Karvonen, K. Kentala, O. Mustala, The effects of training heart rate: a longitudinal study, Ann. Med. Exp. Biol. Fenn. 35 (1957) 307–315.
[26] N. Lighthall, M. Gorlick, A. Schoeke, M. Frank, M. Mather, Stress modulates reinforcement learning in younger and older adults, Psychol. Aging 28 (1) (2013) 35–46.
[27] J. Mateo, P. Laguna, Analysis of heart rate variability in the presence of ectopic beats using the heart timing signal, IEEE Transact. Biomed Eng. 50 (3) (2003) 334–343, https://doi.org/10.1109/TBME.2003.808831.
[28] S. Metz, T. Waiblinger-Grigull, S. Schulreich, W.R. Chae, C. Otte, H.R. Heekeren, K. Wingenfeld, Effects of hydrocortisone and yohimbine on decision-making under risk, Psychoneuroendocrinology 114 (January) (2020), 104589, https://doi.org/10.1016/j.psyneuen.2020.104589.
[29] F. Molins, M.A. Serrano, Bases neurales de la aversión a las pérdidas en contextos económicos: revisión sistemática según las directrices PRISMA, Revista de Neurología 68 (02) (2019) 47, https://doi.org/10.33588/rn.6802.2018276.
[30] K. Mrkva, E.J. Johnson, S. Gächter, A. Herrmann, Moderating loss aversion: loss aversion has moderators, but reports of its death are greatly exaggerated, J. Consumer Psychol. 30 (3) (2020) 407–428, https://doi.org/10.1002/jcpy.1156.
[31] A. Öhman, S. Mineka, Fears, phobias, and preparedness: toward an evolved module of fear and fear learning, Psychol. Rev. 108 (3) (2001) 483–522, https://doi.org/10.1037/0033-295X.108.3.483.
[32] S. Pabst, M. Brand, O.T. Wolf, Stress and decision making: a few minutes make all the difference, Behav. Brain Res. 250 (2013) 39–45, https://doi.org/10.1016/j.bbr.2013.04.046.
[33] S. Pighin, N. Bonini, L. Savadori, C. Hadjichristidis, F. Schena, Loss aversion and hypoxia: less loss aversion in oxygen-depleted environment, Stress 17 (2) (2014) 204–210, https://doi.org/10.3109/10253890.2014.891103.
[34] P. Ponce, A. del Arco, P. Loprinzi, Physical activity versus psychological stress: effects on salivary cortisol and working memory performance, Medicina (B Aires) 55 (5) (2019) 119, https://doi.org/10.3390/medicina55050119.
[35] M.B. Pontifex, A.L. McGowan, M.C. Chandler, K.L. Gwizdala, A.C. Parks, K. Fenn, K. Kamijo, A primer on investigating the after effects of acute bouts of physical activity on cognition, Psychol. Sport Exerc. 40 (July 2018) (2019) 1–22, https://doi.org/10.1016/j.psychsport.2018.08.015.
[36] T. Poppa, A. Bechara, The somatic marker hypothesis: revisiting the role of the 'body-loop' in decision-making, Curr. Opin. Behav. Sci. 19 (2018) 61–66, https://doi.org/10.1016/j.cobeha.2017.10.007.
[37] S.D. Preston, T.W. Buchanan, R.B. Stansfield, A. Bechara, Effects of anticipatory stress on decision making in a gambling task, Behav. Neurosci. 121 (2) (2007) 257–263, https://doi.org/10.1037/0735-7044.121.2.257.
[38] M. Reimann, A. Bechara, The somatic marker framework as a neurological theory of decision-making: review, conceptual comparisons, and future neuroeconomics research, J Econ Psychol 31 (5) (2010) 767–776, https://doi.org/10.1016/j.joep.2010.03.002.
[39] R.D. Rogers, M. Lancaster, J. Wakeley, Z. Bhagwagar, Effects of beta-adrenoceptor blockade on components of human decision-making, Psychopharmacology (Berl.) 172 (2) (2004) 157–164, https://doi.org/10.1007/s00213-003-1641-5.
[40] P.E. Sawchenko, H.Y. Li, A. Ericsson, Circuits and mechanisms governing hypothalamic responses to stress: a tale of two paradigms, Prog. Brain Res. 122 (2000) 61–78, https://doi.org/10.1016/s0079-6123(08)62131-7.
[41] B. Simonovic, E.J.N. Stupple, M. Gale, D Sheffield, Stress and risky decision making: cognitive reflection, emotional learning or both, J Behav Decis. Mak. 30 (2) (2016) 658–665, https://doi.org/10.1002/bdm.1980.
[42] B. Simonovic, E.J.N. Stupple, M. Gale, D Sheffield, Performance under stress: an eye-tracking investigation of the Iowa gambling task (IGT), Front. Behav. Neurosci. 12 (September) (2018) 1–10, https://doi.org/10.3389/fnbeh.2018.00217.
[43] P. Sokol-Hessner, C.F. Camerer, E.A. Phelps, Emotion regulation reduces loss aversion and decreases amygdala responses to losses, Soc. Cogn. Affect. Neurosci. 8 (3) (2013) 341–350, https://doi.org/10.1093/scan/nss002.

[44] P. Sokol-Hessner, R.B. Rutledge, The psychological and neural basis of loss aversion, Curr. Dir .Psychol Sci. 28 (1) (2019) 20–27, https://doi.org/10.1177/0963721418806510.
[45] Stan Development Team. (2017). Stan modeling language user ' s guide and reference manual. Version 2.17.0.
[46] K. Starcke, J.D. Agorku, M. Brand, Exposure to unsolvable anagrams impairs performance on the Iowa gambling task, Front. Behav. Neurosci 11 (June) (2017) 1–8, https://doi.org/10.3389/fnbeh.2017.00114.
[47] K. Starcke, M. Brand, Decision making under stress: a selective review, Neurosci. Biobehav. Rev. 36 (4) (2012) 1228–1248, https://doi.org/10.1016/j.neubiorev.2012.02.003.
[48] H. Takahashi, S. Fujie, C. Camerer, R. Arakawa, H. Takano, F. Kodaka, H. Matsui, T. Ideno, S. Okubo, K. Takemura, M. Yamada, Y. Eguchi, T. Murai, Y. Okubo, M. Kato, H. Ito, T. Suhara, Norepinephrine in the brain is associated with aversion to financial loss, Mol. Psychiatry 18 (1) (2013) 3–4, https://doi.org/10.1038/mp.2012.7.
[49] H. Tanaka, K.D. Monahan, D.R. Seals, Age-predicted maximal heart rate revisited, J. Am. Coll. Cardiol. 37 (1) (2001) 153–156, https://doi.org/10.1016/S0735-1097(00)01054-8.
[50] A. Vaish, T. Grossmann, A. Woodward, Not all emotions are created equal: the negativity bias in social-emotional development, Psychol. Bull. 134 (3) (2008) 383–403, https://doi.org/10.1037/0033-2909.134.3.383.
[51] R. van den Bos, M. Harteveld, H. Stoop, Stress and decision-making in humans: performance is related to cortisol reactivity, albeit differently in men and women, Psychoneuroendocrinology 34 (10) (2009) 1449–1458, https://doi.org/10.1016/j.psyneuen.2009.04.016.
[52] J. van Oort, I. Tendolkar, E.J. Hermans, P.C. Mulders, C.F. Beckmann, A.H. Schene, G. Fernández, P.F. van Eijndhoven, How the brain connects in response to acute stress: a review at the human brain systems level, Neurosci. Biobehav. Rev. 83 (November) (2017) 281–297, https://doi.org/10.1016/j.neubiorev.2017.10.015.
[53] K.G. Volz, G. Gigerenzer, Cognitive processes in decisions under risk are not the same as in decisions under uncertainty, Front. Neurosci. 6 (July) (2012) 1–6, https://doi.org/10.3389/fnins.2012.00105.
[54] J. von Neumann, O. Morgenstern, Theory of Games and Economic Behavior, Princeton University Press, 1944.
[55] D. Watson, L. Clark, A. Tellegen, Development and validation of brief measures of positive and negative affect: the PANAS scales, J. Pers. Soc. Psychol. 54 (1988) 1063–1070.
[56] S.E. Wemm, E. Wulfert, Effects of acute stress on decision making, Appl. Psychophysiol. Biofeedback 42 (1) (2017) 1–12, https://doi.org/10.1007/s10484-016-9347-8.
[57] D.W. White, P.B. Raven, Autonomic neural control of heart rate during dynamic exercise: revisited, J. Physiol. 592 (12) (2014) 2491–2500, https://doi.org/10.1113/jphysiol.2014.271858.

9. Highly logical and non-emotional decisions in both risky and social-contexts: understanding decision making in autism spectrum disorder through computational modeling

Highly logical and non-emotional decisions in both risky and social-contexts: understanding decision making in autism spectrum disorder through computational modeling

Francisco Molins[a], Nour Ben Hassen[a], Dolores Garrote[a] and Miguel Ángel Serrano[a]*

[a]*Department of Psychobiology, Universitat de València, Spain*

*Av. Blasco Ibáñez, 13, 46010 Valencia, Spain. Email: maserrar@uv.es

Abstract

Enhanced economic rationality was found when individuals with autism spectrum disorder (ASD) decide in risky-contexts, exhibiting more logical-consistency and non-emotional decisions (lower framing effect, FE) than do typical adults (TAs). However, this way of deciding could be also prevailing in social-contexts, leading to maladaptive decisions, as suggested the higher acceptance of unfair offers found in the ultimatum game (UG). Yet, these evidence are scarce and further research is needed. Recent developments in computational modeling allow analysis of decisional subcomponents during UG and should be considered. We hypothesized that, regarding TAs, people with ASD will show lower FE in risky-contexts, and less emotional decisions in UG. Moreover, the way of deciding in both contexts will be directly associated. 27 individuals with ASD and 25 TAs were submitted to a framing-task and the UG. The Rescorla-Wagner computational model was used to analyze UG decisions. Results seem to support expectations. In the UG, the ASD group exhibited lower aversion to unfairness and higher acceptance of offers. Moreover, this was associated with the lower emotionality found in the framing task, where no significant FE was manifested. These results further suggest an atypical decision-making, highly logical and non-emotional, as a robust feature of ASD.

Keywords: Autism spectrum disorder, decision-making, framing effect, ultimatum game, computational modelling

1. Introduction

The Autism Spectrum Disorder (ASD) is a heterogeneous neurodevelopmental condition characterized by nuclear alterations in reciprocity, communication, and social interaction, as well as a rigid behavioral pattern, linked to deficits in social skills and difficulties in regulating emotions (American Psychiatric Association, 2013; Jin et al., 2020; Reyes et al., 2019). Autobiographical and clinical reports also reveal difficulties in decision-making throughout many situations and daily routines, manifesting mental "freezing" and exhaustion due to their highly logical and slow processing (Fujino et al., 2017; Luke et al., 2012). In fact, it has been recently suggested that atypical decision-making is a robust feature of ASD (Shah et al., 2016). Understanding the decisional process of people with ASD could allow the identification of treatment strategies that favor their independence and quality of life.

Brosnan et al. (2016) highlight that people with ASD manifest an excessively deliberative and logical reasoning, as well as little use of intuition. According to dual-process approaches (Brosnan et al., 2016; Evans, 2008), this could lead to less economically irrational decisions (Rozenkrantz et al., 2021), especially in risky-choices: simplified contexts where all decision's alternatives and outcome's probabilities are known (Volz & Gigerenzer, 2012). In fact, this is what has been seen when studying framing effect (FE), the phenomenon whereby changes in the way alternatives are presented affect relative desirability of these alternatives (De Martino et al., 2006). In this sense, typical adults (TAs) tend to prefer sure options in positive frames and risky options in mathematically identical, but negative frames (Manzoor et al., 2021). According to the classical economic model (Camerer, 2003; von Neumann & Morgenstern, 1944), FE is considered an irrational behavior since it breaks with one of the fundamental axioms of the rational decision-making: the "invariance", i.e., the logical consistency across

decisions regardless of the frame (De Martino et al., 2006; Tversky & Kahneman, 1989). In addition, this phenomenon indexes the influence of emotion on decision-making (Shah et al., 2016) since a greater FE means that the emotional impact of losses (loss aversion; Sokol-Hessner & Rutledge, 2019) is strongly conditioning choices. However, FE is significantly smaller in the ASD population (De Martino et al., 2008; Shah et al., 2016). These results suggest that people with ASD would be less sensitive to emotional signals during the decisional process, being able to isolate the objective value of alternatives and facilitating a logical, rule-based or utility-maximizing decisional strategy (Fujino et al., 2020; Shah et al., 2016). Though more rational in risky-contexts, this way of deciding may be maladaptive if it is also maintained in other situations where emotions are particularly relevant (De Martino et al., 2008). Situations as the social interaction proposed in the Ultimatum Game (UG).

The UG is a widely used tool to study social decision-making (Hinterbuchinger et al., 2018). In this paradigm, the "proposer" must divide a hypothetical amount of money (e.g., 20€) between him/herself and the "responder". The sharing can range from completely balanced (e.g., 10€ each) to completely unequal (e.g., keep 19€ and give 1€ to the responder). Then, the responder must decide whether to accept the split or, on the contrary, reject the offer and no player receive any money. Neuroeconomics research has revealed that human beings usually do not choose in a purely rational and utility-maximizing manner. Again, based on the classical economic model (Camerer, 2003) proposers should always make the smallest possible offers, and responders should accept any offer greater than zero since this is the logical way to maximize benefits. But social decisions are the result of both, rational considerations, and emotional processes (Hinterbuchinger et al., 2018). So, across dozens of studies, typical proposers show generosity and a general preference for fairness and equality, consistently offering 40–

45% of the stake in the UG (Hartley & Fisher, 2018). Likewise, responders use to reject offers of less than a third since they feel aversion against inequity and prefer to punish selfish behavior to force more equitable offers in future interactions (Hinterbuchinger et al., 2018). This way of deciding is considered adaptive since it diminishes the impact of self-interests while promotes cooperation and social cohesion (Hoffman et al., 2008).

Back to the ASD, it would be logical to think that their excessively "cold" and economically rational way of deciding in risky-contexts may also be manifested in the UG, making them fit the assumptions of the classical economic model. Some previous works point in this direction. So, it has been found that people with ASD distribute lower amounts when they make offers (Hinterbuchinger et al., 2018), and in turn, accept more offers, no matter how unfair (Hartley & Fisher, 2018; Hinterbuchinger et al., 2018). Yet, these results are scarce and sometimes incongruent, as also were reported no differences between TAs and people with ASD when accepting offers (Trovato, 2019), or even more altruistic behavior in the latter population when proposing the splits (Ikuse et al., 2018). These inconsistencies could be due to the fact that, as indicated by Gu et al. (Gu et al., 2015), decisions in UG are usually analyzed in a general way, for example, by counting the total of accepted offers. However, decision-making is not a single entity, but rather involves multiple subcomponents (Alacreu-Crespo et al., 2020). Thus, identifying the different cognitive and emotional subprocesses involved in the UG might show subtle alterations that are not captured by the traditional task scoring.

Recently, a computational model for the UG (Gu et al., 2015), in its responder version, has been developed. This model analyzes the underlying learning structure during the task. It assumes that responders have an internal norm on what is the fair amount that should be offered and identifies how sensitive the responder is to the breaking of this expectation, that is, how averse he/she is to inequity. As Gu et al. (Gu et al., 2015)

highlighted, the lower aversion to inequity should lead to a higher acceptance of offers. Complementarily, the model also analyzes whether the internal norm is persistent or is modified throughout the task, providing information on the adaptation to the changing context. Considering the less emotional decision-making exhibited by the ASD population in risky-contexts (Shah et al., 2016), it would be also expected to find less emotionality in the UG, i.e., that they will express a lower aversion to inequity. Moreover, given their rigid behavioral pattern (American Psychiatric Association, 2013) it would also be logical to find a lower adaptation in their internal norm. However, this model has not been tested in ASD to date. Our aim is to fill this gap and shed light on their decision-making process.

We hypothesize that, regarding TAs, the ASD population will exhibit the most economically rational (or non-emotional) way of deciding in both risky and social contexts. That is, they will show a lower FE in a risky-choice task, as well as a higher offers' acceptance and a lower aversion to inequity in the UG. Moreover, they will show a lower internal norm adaptation in the latter task. Finally, although both risky and social contexts have been addressed separately in ASD, and their relationship has been theorized (e.g., Shah, Catmur, et al., 2016), to our knowledge, this association has never been directly tested. We expect that the way of deciding in risky-contexts will predict decision-making in the UG.

2. Material and Methods

2.1. Participants

Based on the effect size found in previous works on the ASD and both, the FE (Shah et al., 2016) and the UG (Hartley & Fisher, 2018; Ikuse et al., 2018), an a priori power analysis using G*Power indicated a requisite between 21 (η^2_p = .44, power = 80%, α = .05) and 36 (η^2_p = .25, power = 80%, α = .05) participants per group to perform a

general lineal model studying differences between people with ASD and TAs in FE and UG. We recruited 27 participants per group, but two participants had to be eliminated from the TAs group due to registration problems. So, our sample was finally composed by a total of 52 participants. The ASD group (N = 27; age: M = 32.19, SD = 10.44; women: N = 13, 48.1%), was recruited from a psychology center specialized in autism spectrum disorder. All members had a clinical diagnosis from an independent clinician according to DSM-5 criteria. TAs (N = 25; age: M = 27.56, SD = 10.66; women: N = 19, 76%), were recruited by the mean of non-probabilistic sampling method. All of them fulfilled the exclusion criteria as follow: not having physical, neurological, or psychiatric diseases; not consuming 10 or more cigarettes a day; not consuming drugs on regular bases; not having consumed drugs 24h before and not having taken stimulant drinks in the 2h before the assessment.

2.2. Procedure

All participants signed informed consent before starting the session and were informed about which activities they had to perform, also insisting on that they were free to withdrawal their consent at any point of the study. Then, a sociodemographic questionnaire was administered asking about age, sex, socioeconomic status, as well as the inclusion criteria mentioned above. Afterwards, the UG and FE tasks were administered. To respect the security measures derived from the COVID-19 situation, the administration was carried out telematically, instructing the participants on the necessary conditions to ensure the standardization of the measures. The study was approved by the Ethics Research Committee of the University of Valencia in accordance with the ethical standards of the 1969 Declaration of Helsinki.

2.3. Instruments

2.3.1. Ultimatum Game (UG)

Following the task from Gu et al. (Gu et al., 2015), all participants played the role of the responder in the UG for a total of 45 trials. In each trial, the subjects were first offered a split of €20. Next, the subjects were presented with the choice options: accept or reject the offer. The offers were predetermined: 6 x €1, 6 x €2, 6 x €3, 6 x €4, 6 x €5, 3 x €6, 3 x €7, 3 x €8, 3 x €9, 3 x €10, presented in a randomized order. The total number of accepted offers was counted for each participant, allowing the average for each group to be extracted. In addition, the Rescorla-Wagner (Delta) computational model (Gu et al., 2015) was applied to each participant to deepen in their underlying learning structure during the task.

Rescorla-Wagner (Delta) Model. As was introduced, this model assumes that participants playing the UG have an internal norm (f_i) on what is the fair amount that should be distributed to them. In addition, this norm can be updated as the context changes, i.e., the norm evolves as a function of observed offers (Xiang et al., 2013). Following Gu et al. (2015), the initial internal norm (f_0) was fitted individually to each participant's data ($f_0 \in [0,20]$) and the Rescorla-Wagner rule (Rescorla & Wagner, 1972) was applied for updating the internal norm. For a detailed math description of the model see Gu et al. (Gu et al., 2015). Specifically, the model allowed to extract 3 parameters. α or "aversion to inequity" ($\alpha \in [0,1]$), represents sensitivity to norm prediction error, in other words, the individual aversion to unequal splits. The higher the α, the greater unwillingness to accept an offer below the internal norm (f_i). ε or the "norm adaptation rate" ($\varepsilon \in [0,1]$) refers to how much the internal norm is modified according to the immediately preceding offer. A lower ε would indicate that the internal norm is more persistent. Finally, γ or the inverse temperature parameter ($\gamma \in [0,1]$) refers to the variability of the choices. The lower is γ, the lower consistence during the choices.

Each parameter of the model was estimated for each participant through

Hierarchical Bayesian Analyses (HBA; see Ahn et al, 2008 for more details), performed with the hBayesDM package (Ahn et al., 2017) for the R software. The hBayesDM uses Stan 2.1.1 (Stan Development Team, 2017) with the Hamiltonian Monte Carlo (HMC) algorithm as MCMC for sampling the posterior distributions. Following Molins et al. (Molins et al., 2021), we drawn 40.000 samples, after burn-in of 23.333 samples, in three different chains (in sum, a total of 120.000 samples and 70.000 burn-in). The Gelman-Rubin test (Gelman & Rubin, 1992) was used to study if the chains converged ($\hat{R}$) to the target distribution. $\hat{R}$ values of all parameters were 1, which means that convergence was achieved. In addition, to confirm this convergence, the MCMC chains were visually inspected.

2.3.2. Framing Effect (FE) task

Participants completed an economical risky-choice framing task adapted from De Martino et al. (De Martino et al., 2006). They were informed that they received an amount of money (€25, €50, €75, and €100) and were asked to choose between a "sure" option and a "risky" option. On the one hand, the "sure" option could be presented either in a negative frame (e.g., "You lose €75") or in a positive frame ("You keep €25"). It must be noted that the actual monetary value is equal in both options and the only difference is how they are worded. By the other side, the "risky" option consisted of gambling to either win or lose the whole amount of money announced before. The probabilities to win were 20%, 40%, 60% and 80%, presenting the same number of trials for each percentage of riskiness. Types of frame, positive or negative, were randomly presented (16 loss and 16 gain frames), but for every positive trial, there was a complementary negative trial (see Figure 1). Following the protocol from the original authors, participants were not given any feedback if they lost or won the gamble, in order to avoid a possible decisions shift because of the context dependence of risk preferences (Tversky & Kahneman, 1992;

Vermeer & Sanfey, 2015; Xue et al., 2011). In addition, 16 "catch" trials were included; where one of the alternatives was notably beneficial in comparison to the other one (e.g., 95% chances to win/lose the whole amount vs. keeping/losing 50% of the initial amount). These were to assess the participant's engagement and to assure that the answers were not random. Following the design developed by De Martino et al. (De Martino et al., 2006), any participant failing in more than 20% of these "catch" trials would be excluded from the study.

The FE was measured by comparing the preference (in percentage) to choose the "gamble" option over the "sure" option within each frame. In other words, the difference between the percentages of trials the participant chose to gamble in a positive frame versus a negative frame.

Imagine you are given €100, but you must choose between A or B: A. Loss €20 B. Gamble, knowing that there is an 80% chance of keeping everything and a 20% chance of keeping nothing.	Imagine you are given €100, but you must choose between A or B: A. Keep €80 B. Gamble, knowing that there is an 80% chance of keeping everything and a 20% chance of keeping nothing.

Figure 1 - Example of a FE trial in its two frames (negative vs. positive).

2.4. Statistical analyses

First, outliers were detected with the 2.5 standard deviations method and normality was checked through the Kolmogorov-Smirnoff test with the Lilliefors correction. The number of offers accepted in the UG, as well as each of the parameters extracted with the computational model, were compared between groups using ANOVAs. FE was analyzed through a repeated-measures ANOVA, comparing the percentage of gambles in positive vs negative frames, and including group as between-participants factor. After that, a two stepped analysis was followed. First, a general linear model was

conducted to study how FE and its interaction with the group predict UG results. Once the significant "framing x group" interaction was assured, Pearson's correlations by group were used to deepen in the relation between variables. The α significance level was set at .05 and Partial eta square (η^2_p) symbolizes the effect size. All analyses were performed with IBM SPSS Statistics 25 and the computational model was extracted with R i386.

3. Results

3.1. Preliminary analyses

First, homogeneity between groups was tested. ASD and TAs groups did not show significant differences in age (ASD: *M* = 32.19, *SD* =10.44; TAs: *M* = 27.56, *SD* = 10.66), *p* = .120; nor in socioeconomic status (ASD: *M* = 6.56, *SD* = 1.47; TAs: *M* = 5.88, *SD* = 1.25), *p* = .082. Nevertheless, the chi-square test revealed that both groups included a different percentage of women (ASD: 48.1%; TAs: 76%) and men (ASD: 51.9%; TAs: 24%), *p* = .039, so the rest of the analyses were performed controlling for sex.

3.2. Ultimatum Game (UG)

As far as our first hypothesis is concerned, the ANOVAs carried out to study differences between groups in the UG revealed that TAs (*M* = 14.04, *SD* = 18.05) accepted on average fewer offers than the ASD group (*M* = 20.57, *SD* = 17.33), *F*(1, 50) = 4.96, *p* = .035, η^2_p = .16. On the other hand, with respect to the parameters extracted with the computational model, the ASD group showed a lower aversion to inequity (α) and a higher norm adaptation rate (ε) than the TAs group; however, both groups did not differ in their consistence during choices or the inverse temperature parameter (γ) (see Table 1). To verify the assumptions of Gu et al. (2015), the relation between these parameters and the total accepted offers was studied. As expected, the greater the aversion to inequity (*r* = -.836, *p* < .001), and the lower the norm adaptation rate (*r* = .598, *p* < .001), the fewer bets were accepted.

Table 1 | Differences between groups in the parameters of the Rescorla-Wagner (Delta) model

	ASD (N = 27)	TAs (N = 25)	*F*	gl between	gl intra	*p*-value	η^2_p
α	*M* = 0.40 ± 0.27	*M* = 0.87 ± 0.12	7.40**	1	50	.01	.16
ε	*M* = 0.71 ± 0.11	*M* = 0.23 ± 0.13	17.50***	1	50	< .001	.81
γ	*M* = 0.37 ± 0.17	*M* = 0.29 ± 0.17	2.30	1	50	.13	.05

ASD, Autism spectrum disorder; TAs, Typical adults; *M*, mean; ±, *SD*, standard deviation; α, aversion to inequity; ε, norm adaptation rate; γ, inverse temperature. ** significant contrast at the .01 level; *** significant contrast at the .001 level.

3.3. Framing Effect (FE)

First, it was checked if any participant failed more than 20% of the "catch" trials. In our case, no participant was excluded for this reason. Then, a repeated measures ANOVA including group as between-participants factor revealed the significant main effect of the frame (positive vs negative), $F(1, 50) = 19.88$, $p < .001$, $\eta^2_p = .30$; and the significant frame x group interaction, $F(1, 50) = 8.75$, $p = .005$, $\eta^2_p = .16$, on the percentage of gambles chosen. Analyzing these results in depth, the TAs group preferred to gamble on significantly more trials in the negative frame (*M* = 53.26%, *SD* = 35.19) than in the positive ones (*M* = 28.53%, *SD* = 26.83), $F(1, 24) = 15.81$, $p = .001$, $\eta^2_p = .41$; however, no differences in gambling were shown between negative (*M* = 35.50%, *SD* = 28.16) and positive frames (*M* = 30.50%, *SD* = 24.29) in the ASD group, $F(1, 26) = 3.04$, $p = .094$, $\eta^2_p = .11$. Thus, only the TAs group showed a significant FE (see Figure 2).

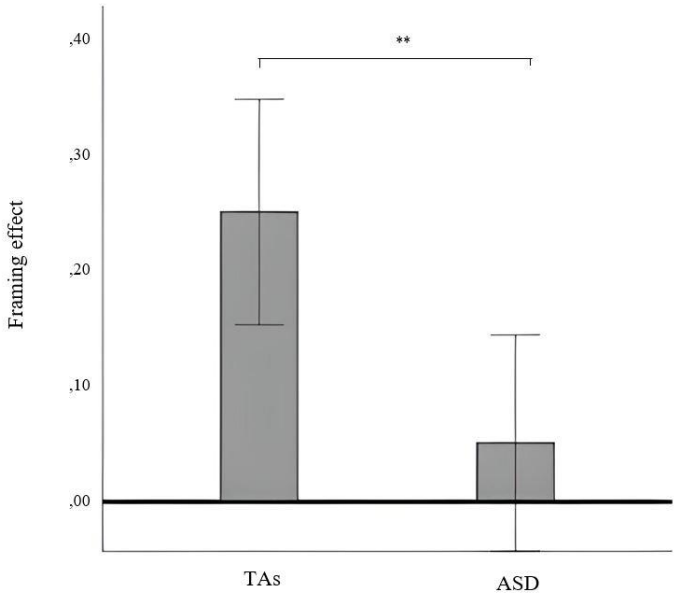


Figure 1 – Difference between gambles accepted in negative vs positive frames (framing effect) by groups. TAs, *M* = 24.73%, *SD* = 29.82; ASD, *M* = 5%, *SD* = 14.32; ** significant contrast at the .01 level.

3.4. Relation between framing effect and Ultimatum Game variables

A general linear model was conducted to study whether FE and its interaction with the group (ASD vs TAs) predict the UG variables. No significant results were found (*p*'s > .05). However, given that the ASD group did not show a significant FE, we repeated this analysis by splitting the FE variable into its two components: percentage of gambles in gain and loss frames. It was found that both the interaction "percentage of gambles in negative frames x group" (*B* = -5.49, *SE* = 1.79, *t* = -3.06, *p* = .004, η^2_p = .19) and "percentage of gambles in positive frames x group" (*B* = -6.35, *SE* = 1.98, *t* = -3.21, *p* = .003, η^2_p = .21) were negatively associated with the level of the α parameter. No other significant associations were found.

When these results were further explored through Pearson's correlations, no significant correlations were found between the framing variables and α parameter in the TAs group (*p*'s > .05); however, in the ASD group, the α parameter was negatively

correlated to the percentage of gambles in both the negative (r = -.456, p = .05) and the positive frames (r = -.485, p = .035). In sum, the higher the percentage of bets placed in both frames, the lower the aversion to unequal splits in UG.

4. Discussion

The present study examined through computational modeling how people with ASD decide in social contexts. As expected, this population made less emotional and more economically rational decisions than the TAs in the UG. So, they manifested a lower aversion to inequity and maximized utility by accepting a greater number of offers, no matter how unfair. Moreover, this way of deciding seems to be explained by the lack of emotionality also shown in risky-contexts. These results will be further developed below.

In line with some previous works (Hartley & Fisher, 2018; Hinterbuchinger et al., 2018), the ASD group accepted significantly more offers than the TAs. Based on the classical economic model (Camerer, 2003; von Neumann & Morgenstern, 1944), since getting 1€ (while the proposer keeps 19€) have a higher utility than getting 0€, this would indicate that people with ASD were following an economically rational strategy and their decisions were not so guided by the feel of unfairness that emerge from selfish offers, as TAs usually do (Camerer, 2003; Frith & Singer, 2008; Hinterbuchinger et al., 2018). In fact, as the α parameter showed, the ASD group also exhibited a lower sensitivity to unfair splits, or lower aversion to inequity, than the TAs. Moreover, this level of aversion was negatively related to the number of accepted offers, supporting the weight that this emotional insensitivity would has on social decisions (Gu et al., 2015). Complementarily, we found that ASD and TAs groups did not differ in the consistency (γ) of their decisions, i.e., neither group made decisions more randomly than the other. However, and contrarily to our hypothesis, the ASD group showed a higher variability in his internal norm about fairness (ε) throughout the task. Yet, this might not necessarily be interpreted as greater

flexibility and adaptation to the context, but could also indicate greater volatility in his internal norm (Gu et al., 2015). In other words, greater inconsistency in the way offers are valued. Along with the lower sensitivity to unfairness, this could further evidence an atypical emotional processing in ASD, as many studies previously reported (e.g. Guastella et al., 2010; Teh et al., 2018; Wicker et al., 2008).

In fact, both a reduced aversion to inequity (α) and a highly variable internal norm about fairness (ε) have been associated with impairments in the ventromedial prefrontal cortex (vmPFC) (Gu et al., 2015). This region plays a key role in emotional processing and valuation (Gu et al., 2015; Rolls et al., 2020). So, patients with vmPFC lesions manifested decreased sensitivity to emotional cues, which leads to difficulties in reinforcement-learning (Bechara et al., 1994; Bechara & Damasio, 2005), decreased guilty (Krajbich et al., 2009), decreased risk and loss aversion (Clark et al., 2008; Genauck et al., 2017; Shiv et al., 2005), and increased preference inconsistency both in risky (Fellows & Farah, 2007) and social contexts (Gu et al., 2015). Multiple studies revealed, precisely, that people with ASD presented an abnormal functional brain development in vmPFC between childhood and adulthood (Murphy et al., 2017), and a smaller structure and function in this region in both children (Kishida et al., 2019; Swartz et al., 2013) and adults (Lau et al., 2020; Rolls et al., 2020; Salehinejad et al., 2021; Watanabe et al., 2012). In addition, these neural findings in ASD were also associated with poor decision-making (Murphy et al., 2017) and social judgements (Watanabe et al., 2012). All this evidence would be in line with the economically rational (or non-emotional) way of deciding exhibited by the ASD group during the UG.

Moreover, our results support a common pattern between risky and social decisions in the ASD. Thus, as previously reported (De Martino et al., 2008; Shah et al., 2016), and as we hypothesized, the ASD group showed less emotionality than the TAs

group in a framing task. In fact, not even significant FE was shown in the first group since no differences were observed between the percentage of bets placed on positive and negative frames. Moreover, this "cold" way of deciding found in the ASD group was associated with their lower emotionality in social contexts. So, the more bets they accepted in both frames, i.e., the less risk and loss aversion (Kahneman, 2003; Tversky & Kahneman, 1989), the less inequity aversion they expressed during the UG. As seen, people with ASD seem to ignore emotional cues and guide their decisions through a entirely economically rational strategy (Camerer, 2003; Rozenkrantz et al., 2021), both in risky and social contexts. Therefore, an atypical emotional processing appears to be a central point in the ASD decision-making, regardless of the context. Nevertheless, as suggested Kinnaird et al. (Kinnaird et al., 2019), rather than a core feature of ASD, emotional processing difficulties could reflect co-occurring alexithymia. This is a personality trait, heightened in ASD compared to the general population, and characterized by difficulties identifying and describing one's own emotions (Kinnaird et al., 2019; Shah et al., 2016). In addition, alexithymia seems to be behind a less emotional risky decision-making in individuals without ASD (Manzoor et al., 2021), although not in the ASD population (Shah et al., 2016). Thus, it is necessary to clarify whether the "cold" way of deciding found in ASD is due to the disorder itself or, on the contrary, is caused by other factors such as alexithymia.

However, the main limitation of this study is the absence of complementary emotional measures such as alexithymia, emotional regulation capacity, as well as other physiological or neural correlates that could shed additional light on their influence on the decisional process. Furthermore, although sex has been controlled for in the analyses, the disproportionate sample does not allow us to explore what variance explains this factor. Future research is needed given that differences have been found in the capacity

to process and regulate emotions between men and women (Rattel et al., 2020). Finally, this study only addressed the role of the responder as the Rescorla-Wagner (delta) computational model can only be applied to this modality (Gu et al., 2015). It would be important to further study whether these emotional deficits also impact on the proposer role, for example, manifesting greater selfishness.

Nevertheless, this is the first study connecting risky and social decision-making in ASD. Moreover, it explored through computational modeling the underlying cognitive process in the latter context. Results are consistent with previous research and point to a lower emotional sensitivity during the decisional process, impeding emotional cues from guiding decisions and, therefore, having to rely on an extremely rational strategy (Rozenkrantz et al., 2021). In line with the need to contextualize posed by the ecological rationality approach (Brighton & Gigerenzer, 2012), while this way of deciding could be useful in risky contexts, it could be responsible for maladaptation in social contexts. All these results reinforce the idea that atypical decision-making is a robust feature of ASD and open up possible therapeutic targets, addressing ASD through techniques that improve emotional awareness and regulation, or even, as some recent studies point out (Salehinejad et al., 2021), by enhancing vmPFC activity through transcranial direct current stimulation.

5. Disclosure statement

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this manuscript.

6. Funding

This work was supported by the University of Valencia under Grant AT/2020.

7. References

Ahn, W. Y., Busemeyer, J. R., Wagenmakers, E. J., & Stout, J. C. (2008). Comparison of decision learning models using the generalization criterion method. *Cognitive Science*, *32*(8), 1376–1402. https://doi.org/10.1080/03640210802352992

Ahn, W. Y., Haines, N., & Zhang, L. (2017). Revealing Neurocomputational Mechanisms of Reinforcement Learning and Decision-Making With the hBayesDM Package. *Computational Psychiatry*, *1*(0), 24. https://doi.org/10.1162/cpsy_a_00002

Alacreu-Crespo, A., Guillaume, S., Sénèque, M., Olié, E., & Courtet, P. (2020). Cognitive modelling to assess decision-making impairments in patients with current depression and with/without suicide history. *European Neuropsychopharmacology*, *36*, 50–59. https://doi.org/10.1016/j.euroneuro.2020.04.006

American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders*. American Psychiatric Association. https://doi.org/10.1176/appi.books.9780890425596

Bechara, A., & Damasio, A. R. (2005). The somatic marker hypothesis: A neural theory of economic decision. *Games and Economic Behavior*, *52*(2), 336–372. https://doi.org/10.1016/j.geb.2004.06.010

Bechara, A., Damasio, A. R., Damasio, H., & Anderson, S. W. (1994). Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition*, *50*(1–3), 7–15. https://doi.org/10.1016/0010-0277(94)90018-3

Brighton, H., & Gigerenzer, G. (2012). Homo heuristicus: Less-is-more effects in adaptive cognition. *Malaysian Journal of Medical Sciences*, *19*(4), 6–17.

Brosnan, M., Lewton, M., & Ashwin, C. (2016). Reasoning on the autism spectrum: A dual process theory account. *Journal of Autism and Developmental Disorders*, *46*(6), 2115–2125.

Camerer, C. F. (2003). Behavioral game theory: Plausible formal models that predict accurately. *Behavioral and Brain Sciences*, *26*(2), 157–158.

Clark, L., Bechara, A., Damasio, H., Aitken, M. R. F., Sahakian, B. J., & Robbins, T. W. (2008). Differential effects of insular and ventromedial prefrontal cortex lesions on risky decision-making. *Brain*, *131*(5), 1311–1322. https://doi.org/10.1093/brain/awn066

De Martino, B., Harrison, N. A., Knafo, S., Bird, G., & Dolan, R. J. (2008). Explaining enhanced logical consistency during decision making in autism. *Journal of Neuroscience*, *28*(42), 10746–10750.

De Martino, B., Kumaran, D., Seymour, B., & Dolan, R. J. (2006). Frames, biases and rational decision-making in the human brain. *Science*, *313*(5787), 684–687. https://doi.org/10.1126/SCIENCE.1128356/SUPPL_FILE/DE_MARTINO.SOM.PDF

Evans, J. S. B. T. (2008). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology*, *59*, 255–278. https://doi.org/10.1146/annurev.psych.59.103006.093629

Fellows, L. K., & Farah, M. J. (2007). The Role of Ventromedial Prefrontal Cortex in Decision Making: Judgment under Uncertainty or Judgment Per Se? *Cerebral Cortex*, *17*(11), 2669–2674. https://doi.org/10.1093/CERCOR/BHL176

Frith, C. D., & Singer, T. (2008). The role of social cognition in decision making. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1511), 3875–3886.

Fujino, J., Tei, S., Hashimoto, R. I., Itahashi, T., Ohta, H., Kanai, C., Okada, R., Kubota, M., Nakamura, M., Kato, N., & Takahashi, H. (2017). Attitudes toward risk and ambiguity in patients with autism spectrum disorder. *Molecular Autism*, *8*(1), 1–10.

https://doi.org/10.1186/S13229-017-0162-8/FIGURES/4

Fujino, J., Tei, S., Itahashi, T., Aoki, Y. Y., Ohta, H., Kubota, M., Hashimoto, R., Nakamura, M., Kato, N., & Takahashi, H. (2020). Impact of past experiences on decision-making in autism spectrum disorder. *European Archives of Psychiatry and Clinical Neuroscience*, *270*(8), 1063–1071.

Gelman, A., & Rubin, D. (1992). Inference from Iterative Simulation Using Multiple Sequences. *Statistical Science*, *7*(4), 457–511.

Genauck, A., Quester, S., Wüstenberg, T., Mörsen, C., Heinz, A., & Romanczuk-Seiferth, N. (2017). Reduced loss aversion in pathological gambling and alcohol dependence is associated with differential alterations in amygdala and prefrontal functioning. *Scientific Reports*, *7*(1), 1–11. https://doi.org/10.1038/s41598-017-16433-y

Gu, X., Wang, X., Hula, X., Wang, S., Xu, S., Lohrenz, T. M., Knight, R. T., Gao, Z., Dayan, P., & Montague, P. R. (2015). Necessary, yet dissociable contributions of the insular and ventromedial prefrontal cortices to norm adaptation: computational and lesion evidence in humans. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *35*(2), 467–473. https://doi.org/10.1523/JNEUROSCI.2906-14.2015

Guastella, A. J., Einfeld, S. L., Gray, K. M., Rinehart, N. J., Tonge, B. J., Lambert, T. J., & Hickie, I. B. (2010). Intranasal Oxytocin Improves Emotion Recognition for Youth with Autism Spectrum Disorders. *Biological Psychiatry*, *67*(7), 692–694. https://doi.org/10.1016/J.BIOPSYCH.2009.09.020

Hartley, C., & Fisher, S. (2018). Do Children with Autism Spectrum Disorder Share Fairly and Reciprocally? *Journal of Autism and Developmental Disorders*, *48*(8), 2714–2726. https://doi.org/10.1007/S10803-018-3528-7

Hinterbuchinger, B., Kaltenboeck, A., Baumgartner, J. S., Mossaheb, N., & Friedrich, F.

(2018). Do patients with different psychiatric disorders show altered social decision-making? A systematic review of ultimatum game experiments in clinical populations. *Cognitive Neuropsychiatry*, *23*(3), 117–141. https://doi.org/10.1080/13546805.2018.1453791

Hoffman, E., McCabe, K., & Smith, V. (2008). Reciprocity in ultimatum and dictator games: An introduction. *Handbook of Experimental Economics Results*, *1*, 411–416.

Ikuse, D., Tani, M., Itahashi, T., Yamada, H., Ohta, H., Morita, T., Arai, G., Saga, N., Tokumasu, T., Ohta, M., Sato, A., & Iwanami, A. (2018). The effect of visual cues on performance in the ultimatum game in individuals with autism spectrum disorder. *Psychiatry Research*, *259*, 176–183. https://doi.org/10.1016/J.PSYCHRES.2017.10.013

Jin, P., Wang, Y., Li, Y., Xiao, Y., Li, C., Qiu, N., Weng, J., Fang, H., & Ke, X. (2020). The fair decision-making of children and adolescents with high-functioning autism spectrum disorder from the perspective of dual-process theories. *BMC Psychiatry*, *20*(1). https://doi.org/10.1186/S12888-020-02562-8

Kahneman, D. (2003). Maps of bounded rationality: Psychology for behavioral economics. *American Economic Review*, *93*(5), 1449–1475. https://doi.org/10.1257/000282803322655392

Kinnaird, E., Stewart, C., & Tchanturia, K. (2019). Investigating alexithymia in autism: A systematic review and meta-analysis. *European Psychiatry*, *55*, 80–89. https://doi.org/10.1016/j.eurpsy.2018.09.004

Kishida, K. T., De Asis-Cruz, J., Treadwell-Deering, D., Liebenow, B., Beauchamp, M. S., & Montague, P. R. (2019). Diminished single-stimulus response in vmPFC to favorite people in children diagnosed with Autism Spectrum Disorder. *Biological Psychology*, *145*, 174–184. https://doi.org/10.1016/J.BIOPSYCHO.2019.04.009

Krajbich, I., Adolphs, R., Tranel, D., Denburg, N. L., & Camerer, C. F. (2009). Economic games quantify diminished sense of guilt in patients with damage to the prefrontal cortex. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *29*(7), 2188–2192. https://doi.org/10.1523/JNEUROSCI.5086-08.2009

Lau, W. K. W., Leung, M. K., & Zhang, R. (2020). Hypofunctional connectivity between the posterior cingulate cortex and ventromedial prefrontal cortex in autism: Evidence from coordinate-based imaging meta-analysis. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, *103*, 109986. https://doi.org/10.1016/J.PNPBP.2020.109986

Luke, L., Clare, I. C. H., Ring, H., Redley, M., & Watson, P. (2012). Decision-making difficulties experienced by adults with autism spectrum conditions. *Autism*, *16*(6), 612–621.

Manzoor, N., Molins, F., & Serrano, M. Á. (2021). Interoception moderates the relation between alexithymia and risky-choices in a framing task: A proposal of two-stage model of decision-making. *International Journal of Psychophysiology*, *162*, 1–7. https://doi.org/10.1016/j.ijpsycho.2021.01.002

Molins, F., Serrano, M. Á., & Alacreu-Crespo, A. (2021). Early stages of the acute physical stress response increase loss aversion and learning on decision making: A Bayesian approach. *Physiology & Behavior*, *237*, 113459. https://doi.org/10.1016/J.PHYSBEH.2021.113459

Murphy, C. M., Christakou, A., Giampietro, V., Brammer, M., Daly, E. M., Ecker, C., Johnston, P., Spain, D., Robertson, D. M., Murphy, D. G., & Rubia, K. (2017). Abnormal functional activation and maturation of ventromedial prefrontal cortex and cerebellum during temporal discounting in autism spectrum disorder. *Human*

Brain Mapping, *38*(11), 5343–5355. https://doi.org/10.1002/HBM.23718

Rattel, J. A., Mauss, I. B., Liedlgruber, M., & Wilhelm, F. H. (2020). Sex differences in emotional concordance. *Biological Psychology*, *151*. https://doi.org/10.1016/J.BIOPSYCHO.2020.107845

Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: Variations in the effectiveness of reinforcement and nonreinforcement. *Current Research and Theory*, 64–99.

Reyes, N. M., Pickard, K., & Reaven, J. (2019). Emotion regulation: A treatment target for autism spectrum disorder. In *Bulletin of the Menninger Clinic* (Vol. 83, Issue Specialissue3, pp. 205–234). Guilford Publications. https://doi.org/10.1521/bumc.2019.83.3.205

Rolls, E. T., Zhou, Y., Cheng, W., Gilson, M., Deco, G., & Feng, J. (2020). Effective connectivity in autism. *Autism Research*, *13*(1), 32–44. https://doi.org/10.1002/AUR.2235

Rozenkrantz, L., D'Mello, A. M., & Gabrieli, J. D. E. (2021). Enhanced rationality in autism spectrum disorder. *Trends in Cognitive Sciences*, *25*(8), 685–696. https://doi.org/10.1016/J.TICS.2021.05.004

Salehinejad, M. A., Paknia, N., Hosseinpour, A. H., Yavari, F., Vicario, C. M., Nitsche, M. A., & Nejati, V. (2021). Contribution of the right temporoparietal junction and ventromedial prefrontal cortex to theory of mind in autism: A randomized, sham-controlled tDCS study. *Autism Research*, *14*(8), 1572–1584. https://doi.org/10.1002/AUR.2538

Shah, P., Catmur, C., & Bird, G. (2016). Emotional decision-making in autism spectrum disorder: the roles of interoception and alexithymia. *Molecular Autism*, *7*, 43. https://doi.org/10.1186/s13229-016-0104-x

Shiv, B., Loewenstein, G., Bechara, A., Damasio, H., & Damasio, A. R. (2005). Investment behavior and the negative side of emotion. *Psychological Science*, *16*(6), 435–439.

Sokol-Hessner, P., & Rutledge, R. B. (2019). The Psychological and Neural Basis of Loss Aversion. *Current Directions in Psychological Science*, *28*(1), 20–27. https://doi.org/10.1177/0963721418806510

Stan Development Team. (2017). *Stan Modeling Language User ' s Guide and Reference Manual*. Version 2.17.0.

Swartz, J. R., Wiggins, J. L., Carrasco, M., Lord, C., & Monk, C. S. (2013). Amygdala Habituation and Prefrontal Functional Connectivity in Youth With Autism Spectrum Disorders. *Journal of the American Academy of Child & Adolescent Psychiatry*, *52*(1), 84–93. https://doi.org/10.1016/J.JAAC.2012.10.012

Teh, E. J., Yap, M. J., & Rickard Liow, S. J. (2018). Emotional Processing in Autism Spectrum Disorders: Effects of Age, Emotional Valence, and Social Engagement on Emotional Language Use. *Journal of Autism and Developmental Disorders*, *48*(12), 4138–4154. https://doi.org/10.1007/S10803-018-3659-X/TABLES/5

Trovato, A. N. (2019). *Social Decision-Making in Individuals With Autism Spectrum Disorder: Examining the Effect of Facial Expression on Ultimatum Game Decisions*. Indiana University of Pennsylvania.

Tversky, A., & Kahneman, D. (1989). Rational choice and the framing of decisions. In *Multiple criteria decision making and risk analysis using microcomputers* (pp. 81–126). Springer.

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, *5*(4), 297–323.

Vermeer, A. B. L., & Sanfey, A. G. (2015). The effect of positive and negative feedback

on risk-taking across different contexts. *PLoS ONE*, *10*(9), 1–13. https://doi.org/10.1371/journal.pone.0139010

Volz, K. G., & Gigerenzer, G. (2012). Cognitive processes in decisions under risk are not the same as in decisions under uncertainty. *Frontiers in Neuroscience*, *6*(JULY), 1–6. https://doi.org/10.3389/fnins.2012.00105

von Neumann, J., & Morgenstern, O. (1944). *Theory of games and economic behavior*. Princeton University Press. https://doi.org/10.1090/s0273-0979-99-00832-0

Watanabe, T., Yahata, N., Abe, O., Kuwabara, H., Inoue, H., Takano, Y., Iwashiro, N., Natsubori, T., Aoki, Y., Takao, H., Sasaki, H., Gonoi, W., Murakami, M., Katsura, M., Kunimatsu, A., Kawakubo, Y., Matsuzaki, H., Tsuchiya, K. J., Kato, N., … Yamasue, H. (2012). Diminished Medial Prefrontal Activity behind Autistic Social Judgments of Incongruent Information. *PLOS ONE*, *7*(6), e39561. https://doi.org/10.1371/JOURNAL.PONE.0039561

Wicker, B., Fonlupt, P., Hubert, B., Tardif, C., Gepner, B., & Deruelle, C. (2008). Abnormal cerebral effective connectivity during explicit emotional processing in adults with autism spectrum disorder. *Social Cognitive and Affective Neuroscience*, *3*(2), 135–143. https://doi.org/10.1093/SCAN/NSN007

Xiang, T., Lohrenz, T., & Read Montague, P. (2013). *Computational Substrates of Norms and Their Violations during Social Exchange*. https://doi.org/10.1523/JNEUROSCI.1642-12.2013

Xue, G., Lu, Z., Levin, I. P., & Bechara, A. (2011). An fMRI study of risk-taking following wins and losses: Implications for the gambler's fallacy. *Human Brain Mapping*, *32*(2), 271–281. https://doi.org/10.1002/hbm.21015

Section 3: General discussion & Conclusions

Adding to the current trends in the field of decision-making research, the primary objective of this thesis was to shed light on the nature of human decisions. Firstly, by deconstructing the negative perception of heuristics and biases, as these could actually be adaptive tools that facilitate sound decision-making. Secondly, by refining and expanding the normative criteria that determine what constitutes good decision-making, since while economic rationality may be appropriate in certain contexts, other criteria such as adaptability or satisfaction may be more relevant in others.

To achieve this general objective, it was necessary to focus on simpler and more operationalizable pieces. Therefore, we decided to approach decision-making through one of the main biases described in scientific literature: loss aversion. Thus, the general objective was divided into three specific objectives: (1) evidencing the emotional origin of loss aversion, (2) analyzing how stress modulates its expression, and (3) exploring the potential adaptive role of this bias. These objectives were addressed through a total of nine studies that contribute to better understand and contextualize why and when the loss aversion bias emerges, as well as when it can be a perfect ally for our decision-making.

In this section, therefore, the same distribution will be maintained, and the results obtained in these studies will be discussed by each of the three specific objectives separately. Finally, in the conclusions section, the most relevant points that can be extracted from this doctoral thesis will be synthesized.

1. Loss aversion is an emotional response that may be rooted in our genes

Previous literature already linked loss aversion to the limbic system (Molins & Serrano, 2019; Sokol-Hessner & Rutledge, 2019). Specifically, two pathways were identified that would process gains and losses separately. On one hand, an appetitive system involving regions such as the nucleus accumbens and the striatum would activate in the presence of potential rewards and promote their acquisition. On the other hand, an aversive system involving regions such as the insula and the amygdala would activate more intensely in the face of proportional threats and promote their avoidance (Molins & Serrano, 2019). Although there is debate on how these systems interact in the decision-making process, recent proposals suggest that both systems would send information to the vmPFC, where it would be processed (Canessa et al., 2017). Depending on which system has more strength —appetitive or aversive— a choice between seeking rewards or avoiding dangers would be made (Croxson et al., 2009). Given that, in the presence of

proportional stimuli, the activity of the aversive system would be more intense, it should be easier to find conservative decisions, preferring not to lose rather than to gain. This difference in intensity between the appetitive and aversive systems is known as neural loss aversion and, although it may be subject to the influence of other factors, it is associated to the behavioral manifestation of loss aversion (Canessa et al., 2017; Charpentier et al., 2016).

With **Study 1** of this thesis, our aim was to analyze whether neural and behavioral loss aversion also had a genetic basis. To achieve this, we conducted a systematic review of published studies that addressed the relationship between various polymorphisms and loss aversion. Given the scarcity of studies on this topic, we decided to broaden the review and include other phenomena closely linked to loss aversion, such as risk aversion and the framing effect (Rabin & Thaler, 2001; Sokol-Hessner et al., 2013; Tversky & Kahneman, 1989). Drawing firm conclusions from this work is challenging, particularly due to the methodological issues inherent in the reviewed studies. Many of them include small and highly heterogeneous samples, and do not conduct a comprehensive assessment of their participants that would allow isolating the weight of genetics in loss aversion. Furthermore, as highlighted by Gao et al. (2017), most studies focus on one or two candidate genes, rather than comprehensively studying the potential involvement and interaction of multiple genes. Finally, these studies often examine a direct relationship between polymorphisms and the level of loss aversion —or risk aversion and framing effect—, but only a few include other moderating or mediating factors in their analyses, such as neural activity or neurotransmitter levels (e.g., Wagels et al., 2017; Zhong et al., 2009). However, despite the heterogeneity and multiple limitations of the studies, most point in the direction that polymorphisms involved in dopamine and serotonin neurotransmission pathways would play a role in the expression of these biases.

Regarding the dopaminergic pathway, alleles associated with lower dopamine availability in the reward pathways, either due to reduced neurotransmitter release or decreased receptor sensitivity, were often followed by lower risk aversion (e.g., Dreber et al., 2011), framing effect (e.g., Gao et al., 2017) and loss aversion (e.g., Voigt et al., 2015). This relationship makes theoretical sense when considering two points. Firstly, the involvement of dopamine in the activity of regions such as the nucleus accumbens and the striatum, which are not only key components of the brain's reward system (Kelley et al., 2005; Wise, 2002) but also integral to the appetitive system found in the neural basis

of loss aversion (Molins & Serrano, 2019). Therefore, if a potential gain triggers dopamine release in these regions, our brain interprets it as a reward and promotes its acquisition, increasing the probability of the behavior that led to dopamine production (Dreber et al., 2009; Knutson & Cooper, 2005; Peterson, 2005). On the other hand, those individuals who start from lower levels of dopamine or who are less sensitive to it will require more intense stimulation to experience the same pleasurable effect that others would experience with less stimulation (Muda et al., 2018). Animal studies, for example, have shown that those with higher levels of dopamine transporters exhibit more impulsivity towards small rewards (Adriani et al., 2009), and in humans, lower dopamine levels have been linked to various risk behaviors such as alcoholism (MacKillop et al., 2007), impulsivity (Congdon et al., 2008), and sexual promiscuity or infidelity (Garcia et al., 2010). This may explain the increased risk-taking behavior and lower loss aversion associated with different alleles that, in one way or another, reduce the effects of dopamine.

With respect to the serotonergic pathway, most studies suggest that alleles associated with higher serotonin transcription or lower serotonin transporter activity are associated with higher levels of risk aversion and susceptibility to the framing effect (Crişan et al., 2009). In line with this, previous studies have shown that elevated serotonin levels, achieved through the administration of its precursor (tryptophan) or inhibitors of its transporters, facilitate the recognition of threatening faces in humans (Attenburrow et al., 2003; Browning et al., 2007) and the acquisition of conditioned fear in rats (Burghardt et al., 2007). Conversely, the depletion of tryptophan impairs the recognition of threatening faces (Harmer et al., 2003) and the distinction between gain and loss contexts when making decisions (Blair et al., 2008). Serotonin is a key neurotransmitter for emotional processing (Crişan et al., 2009) that directly influences regions such as the anterior cingulate cortex, which regulates and connects limbic regions with the prefrontal cortex (PFC) (Etkin et al., 2006; Stevens et al., 2011). Thus, the greater or lesser availability of serotonin, depending on the allele adopted by certain genes involved in its production, could also affect the activity of the neural bases that underlie loss aversion, risk aversion, and the framing effect, ultimately modulating their expression.

Further research is needed to confirm the stability of the genetic basis identified. However, what is undeniable is that our study once again establishes a connection between loss aversion and the limbic system, emphasizing that its manifestation involves

an exaggerated emotional response to negative stimuli. Furthermore, this emotional origin is reinforced by the results obtained in Studies 2 and 3.

In **Study 2**, our objective was to verify the propositions put forth by Kahneman (2011) and Kanouse (1984). These authors argued that loss aversion is another manifestation of a more fundamental emotional phenomenon known as negativity bias. This bias suggests that stimuli perceived as negative, such as something dangerous or threatening, elicit a stronger emotional response —evidenced by increased neural activity in limbic regions and heightened sympathetic activity (Bradley, 2009; Wangelin et al., 2011)—, compared to positive stimuli (Cacioppo & Berntson, 1994; Joseph et al., 2020). This bias gives a boost to negative stimuli, prioritizing their processing and exerting a greater impact on our judgments and decisions (Kauschke et al., 2019). If Kahneman and Kanouse were correct, an individual with a stronger negativity bias should also exhibit greater loss aversion. Our data support the previous hypothesis, albeit with certain nuances. Firstly, our sample did not exhibit explicit negativity bias. Some participants tended to classify ambiguity as negative, while others were more inclined to classify it as positive, resulting in a balanced processing of ambiguity on average. Similarly, participants who showed a propensity towards negativity did not necessarily exhibit greater loss aversion. However, we also captured the possible occurrence of implicit negativity bias by tracking the mouse trajectory during the classification of ambiguity, and here the results were different: we observed a significant manifestation of implicit negativity bias —although ambiguity were classified as positive, there was a prior deviation towards the negative option, indicating that this tends to be the initial impression—, and the level of this bias was positively associated with the loss aversion expression.

These results shed light on two levels. Firstly, they emphasize the importance of studying negativity bias beyond their explicit expression. Previous studies questioned whether this bias is truly an intrinsic characteristic of human beings (Kauschke et al., 2019), and while recent studies provide affirmative conclusions (Joseph et al., 2020), debate still exists. We now know that part of the heterogeneity found in studies could be attributed to this reason: negativity bias is an emotional phenomenon subject to possible conscious regulation (Evans, 2008), which can filter its explicit expression. However, this does not imply that it cannot subtly affect our judgments and decisions or appear in the background, only detectable through more sensitive techniques like the mouse tracker

(Brown et al., 2017). Secondly, our data support the connection between negativity bias and loss aversion, providing new evidence regarding the emotional origin of the latter. This finding aligns with another recent study that reported a similar relationship. Sheng et al. (Sheng et al., 2020), using eye-tracking technology, found that losses captured our attention more than gains. This is known as orienting response (Bradley, 2009; Vuilleumier, 2005) and reflects how a stimulus captures our attention by eliciting a more intense emotional response compared to other stimuli. This orienting response, as revealed by Bradley (2009), is accompanied by increased electrodermal reactivity (EDA), as occurs when loss aversion is manifested (Wu et al., 2016). Once again, loss aversion emerges as an emotional response.

Additionally, previous studies already suggested that emotion regulation strategies can reduce the expression of loss aversion (Sokol-Hessner et al., 2009, 2013). However, it was necessary to delve into the mechanisms through which this expression is modulated: firstly, to verify the connection between the affective system and loss aversion, and secondly, to understand how emotions influence the decision-making process. Our **Study 3** aimed to address these questions.

We evaluated the level of interoception and alexithymia in our participants for this purpose. Both constructs are closely linked to our capacity for emotional regulation (Swart et al., 2009; Venta et al., 2013; Walker et al., 2011) and are capable of influencing our decision-making process (Dunn et al., 2010; Shah, Hall, et al., 2016; Sütterlin et al., 2011). Our data would support this notion. Firstly, participants with higher interoceptive awareness expressed a greater loss aversion, as measured through the framing effect. These physiological changes form the basis of emotional responses, and it seems that the more conscious we are of them, the more intensely emotions are perceived (Herbert et al., 2011; Pollatos et al., 2007) and the greater their potential to impact other cognitive processes, such as decision-making (Barrett et al., 2012; Zaki et al., 2012). On the other hand, participants with higher alexithymia made colder and more rational decisions, less influenced by the framing effect. However, the main contribution of our study lies in shedding light on how interoception and alexithymia interact and jointly influence emotional decision-making. Our results revealed that alexithymia was negatively associated with the framing effect, but only when the level of interoception was high. This led us to propose a two-step model of decision-making: first, a good level of interoception would be necessary to perceive internal physiological changes and therefore adequately

process an emotional response. Without this interoception, alexithymia could be irrelevant since we would not be directly perceiving our emotions. In contrast, if these emotions are adequately processed, our ability to label and express them becomes important, bringing alexithymia into play.

These results are in line with previously published neuroimaging studies. Interoception appears to be closely linked, among other regions, to the activity of the insula and amygdala (Zaki et al., 2012), which in turn are part of the neural basis of loss aversion (Markett et al., 2016; Molins & Serrano, 2019). It makes sense that higher interoceptive capacity, which is associated with increased activity and interconnectivity of the mentioned areas (Critchley et al., 2004), would also result in a stronger emotional response such as loss aversion. On the other hand, alexithymia has been associated with functional deficits in the vmPFC, as well as connectivity problems between this region and limbic regions (Sutherland et al., 2013). As mentioned, one of the proposed mechanisms by which neural loss aversion influences decision-making posits that the appetitive and aversive systems send information to the vmPFC, where it is processed, and decisions are made (Canessa et al., 2017). Even if interoception is functioning properly, with appropriate insular and amygdalar activity, this emotional information may not reach the vmPFC if alexithymia is present due to deficits in this region (Kano et al., 2011; Zhang et al., 2017). As we can see, these evidence could support our model.

Further research is required to validate this model. Future investigations should address neural activity or its physiological correlates to overcome the limitations of our study, which did not provide this type of information. It is also crucial to consider that interoception can be examined through various paradigms that distinguish different dimensions of it, potentially offering additional insights into the process. These studies should also consider the diverse emotional phenomena that can impact decision-making. While the framing effect and loss aversion are closely intertwined, subtle differences in their expression may exist. Despite these limitations, this study aligns with the two previous ones, all pointing in the same direction: loss aversion may be an emotional response originating in our limbic system. Furthermore, its manifestation could be linked to our genes, which regulate it and account for the individual variances found in the scientific literature. However, this regulation would also be influenced by other internal factors, such as levels of interoception and alexithymia, as well as external factors, with stress being one of the most significant factors, as we will explore in the following section.

2. Loss aversion is modulated by stress, but each stressor or stress phase could produce different effects

2.1.Effects of acute stress on loss aversion

In general, the four studies that specifically addressed the relationship between acute stress and loss aversion demonstrated that stress influence the manifestation of this bias. However, different types of stressors, as well as the timing of decision-making evaluation, may involve distinct psychophysiological states. Therefore, the mechanisms by which stress influences loss aversion, as well as the resulting outcome of this influence, may also vary. A common limitation across all our studies is the lack of complementary neural and hormonal measures, which would provide a more comprehensive understanding of these mechanisms. Consequently, it is difficult to determine the levels of catecholamines or cortisol present during the assessment of loss aversion or whether these substances triggered specific brain activity. Nevertheless, our studies were supported by previous literature that validated the use of the stressors employed here, allowing us to infer their effects on our participants. Consequently, in each particular study, we discussed the mechanisms that best explain the observed results. Additionally, a comprehensive discussion encompassing all the studies is now provided.

Firstly, we can focus on Studies 4, 5, and 6, which examined the influence of three acute stressors on loss aversion. Loss aversion was evaluated through the classic mixed gamble task (Tom et al., 2007), a small world. **Study 4** employed vigorous exercise as a physical stressor, **Study 5** used a video depicting a baby circumcision as an emotional stressor, and **Study 6** utilized the virtual version of the TSST (TSST-VR) (Montero-López et al., 2016) as a psychosocial stressor. All these stressors successfully induced physical and psychological stress in the participants, as evidenced by changes in various physiological measures (e.g., increased heart rate and EDA, or reduced heart rate variability) and psychological measures (e.g., increased perceived stress and negative mood), except for vigorous exercise, which only induced physiological stress without an increase in psychological stress.

Regardless of the type of stressor employed, all participants exposed to stress exhibited a reduction in loss aversion compared to controls. This result seems to fit within the alignment hypothesis postulates (Margittai et al., 2018), which suggests that stress enhances the salience of rewards by promoting greater availability of dopamine in reward centers such as the nucleus accumbens and striatum (Mather & Lighthall, 2012; Starcke

& Brand, 2012), thus balancing both gains and losses impact and reducing behavioral loss aversion (Margittai et al., 2018). However, this hypothesis also suggests that the increased activity in reward centers would be particularly evident when cortisol levels are elevated.

Thus, the alignment hypothesis fits well with Study 6, which involved the TSST-VR. In this study, the measurement of decision-making took place 30 minutes after the stressor onset, coinciding with the expected cortisol peak (Hermans et al., 2014; Pabst et al., 2013; Starcke & Brand, 2012). While no hormonal measurements were available to confirm this, the stress group suffered an increase in EDA of 42.85% during the stressor, comparable to the average increase (45.56%) observed in previous literature also using the TSST-VR (Liu & Zhang, 2020; Montero-López et al., 2016; Santl et al., 2019; Shiban et al., 2016). These studies also established a link between sympathetic activity and subsequent cortisol elevation, with cortisol typically peaking between 20 and 40 minutes after the stressor onset. However, further research incorporating direct cortisol measurement is needed to validate these arguments conclusively.

It is important to note that loss aversion is a relative measure, representing the weight assigned to losses compared to gains (Sokol-Hessner et al., 2009). Therefore, a reduction in this phenomenon may imply a stronger attraction to gains, but it could also indicate a diminished impact of the losses themselves. This alternative explanation gains significance due to studies linking cortisol and other stress-related substances (e.g., endorphins and endogenous opioids) to the production of endogenous analgesia (Butler & Finn, 2009; St-Aubin et al., 2019), which reduces physical pain. Some authors highlight the convergence of neural pathways involved in processing physical and emotional pain (Butler & Finn, 2009), while others argue that losses specifically entail emotional pain (Hintze et al., 2015). Consequently, a thorough exploration is necessary to determine whether the reduction in loss aversion arose from a heightened sensitivity to gains, the analgesic effects reducing the painful impact of losses, or both.

In any case, as we can see, both explanations are associated with high levels of cortisol derived from stress. However, Studies 4 and 5 measured decision-making in the early phase of stress, only 5 minutes after the stressor onset. Therefore, although we did not have specific measures to confirm it, it seems more likely that decision-making were influenced by the fast release of catecholamines rather than cortisol (Hermans et al., 2014). Thus, a complementary explanation emerges that may better account for the results of these studies. Concretely, early stages of the acute stress response could favor an optimal

arousal level for the PFC functioning since this region is influenced by an inverted U-shaped curve of catecholamines (Pabst et al., 2013). The PFC constitutes the main hub for the executive control-network and it is responsible for a logical, rule-based and non-biased decision-making (Hermans et al., 2014; Pabst et al., 2013; Starcke & Brand, 2016). Previous studies showed, indeed, that using strategies that enhance PFC over the limbic system reduced loss aversion (Sokol-Hessner et al., 2009, 2013). Therefore, the first mild-to-moderate catecholamines increase could be enhancing the PFC arousal and buffering loss aversion. As seen, this could explain results from Studies 4 and 5, where the decisions of stressed participants were more rule-guided, showed greater consistency, and lower loss aversion.

On the other hand, this explanation could also account for the seemingly contradictory results obtained in **Study 8**. This study addressed the effect of the same physical stressor as in Study 4, vigorous exercise, but this time on ambiguous or large world decision-making, measured by the IGT (Bechara et al., 1997; Chiu et al., 2018). While the induction of the stressor had the same effect on participants —increases in physiological stress without psychological or emotional disturbance—, loss aversion not only did not decrease, but increased after the stressor. It should be noted that, at least in the early stages of IGT, it is not possible to follow a calculating strategy; instead, reinforcement-learning based on the consequences of our decisions is necessary (Starcke & Brand, 2012, 2016). Thus, having a greater sensitivity to losses could enhance learning from punishments (Barros et al., 2017; Vuilleumier, 2005) and help avoid unfavorable options. The increase in loss aversion could also reflect a more cautious attitude towards risk, implying that the most appropriate strategy is being followed since IGT is designed to punish risk (Bechara & Damasio, 2005). As pointed out by Pabst et al. (2013), the choice of this strategy may be promoted by increased catecholaminergic activity and, consequently, PFC activity. In fact, parameters extracted through computational modeling showed that not only loss aversion increased, but sensitivity to feedback in general, including gains, also increased. It is well known the important role that PFC plays in valuation, stablishing preferences, as well as in reward and threats sensitivity (Gu et al., 2015; Pabst et al., 2013; Rolls et al., 2020). Another result supporting this explanation is that the increase in the loss aversion parameter —and the sensitivity to feedback parameter— was associated with more consistent decision-making and greater learning during IGT.

As we can see, early phase of stress led to seemingly contradictory results in our studies —reductions in loss aversion in Studies 4 and 5, and an increase in Study 7—. While these differences could be attributed to the distinct nature of the decisional contexts —risk vs. ambiguity— and the different cognitive processes that may operate within them (Volz & Gigerenzer, 2012), the three studies are consistent in that stressed participants adopted the appropriate strategy according to the specific decisional context. This supports the potential beneficial role of catecholamines on the executive network in the early stages of stress. However, once again, although these explanations find support in previous literature, further research is necessary to confirm the underlying mechanisms involved in the modulation of loss aversion.

2.2.Effects of a persistent natural stressor on loss aversion

Our previous studies addressed how several acute stressors in laboratory settings affect decision-making. However, the ongoing pandemic situation resulting from the COVID-19 outbreak provided the perfect context to study how a natural and persistent stressor —still present at the time of evaluation— influences decision-making and, more specifically, loss aversion bias. Thus, **Study 7** revealed that just one month after the onset of the state of alarm and lockdown in Spain, participants reported an increase in anxiety and depression symptoms, indicating that the experienced situation led to significant psychological distress. Furthermore, this distress was associated with a loss aversion increase, compared to pre-pandemic levels. Our findings are consistent with those obtained in other previous distressing contexts, such as the Fukushima Daiichi nuclear disaster, where increases in loss aversion were also observed (Iwasaki & Sawada, 2015).

Due to the particular characteristics of the study, additional measures were not taken to investigate the specific mechanisms by which distress was associated with an increase in loss aversion. However, previous studies have stated that fear-related stressors that induce emotional discomfort significantly increase amygdala activity (Hermans et al., 2011, 2014), the key node in the aversive system involved in loss aversion (Molins & Serrano, 2019). In our laboratory studies, both the circumcision video and the TSST-VR also caused emotional distress. However, these stressors were acute and had disappeared by the time the decision-making assessment was conducted, unlike in this study, where the stressor is still affecting the participants, and the distress could further alter the decision-making process. In fact, laboratory studies usually result in increased negative mood and perceived stress, but these do not necessarily imply the discomfort associated

with symptoms of anxiety or depression, as observed in this study. Other previous works indicate that individuals suffering from anxiety or depression tend to exhibit deficits in decision-making, which is characterized by a higher loss aversion (Baek et al., 2017; Sip et al., 2018). Therefore, the increase in loss aversion found in our study may reflect the onset of these decisional deficits. Nevertheless, another study conducted during the pandemic revealed that individuals with higher loss aversion were more compliant with government-imposed safety regulations, suggesting that this bias could favor cautious behaviors and risk avoidance (Presti et al., 2022). As we can see, this could be crucial in a dangerous context like the COVID-19 pandemic. Future lines of research should address whether this increased loss aversion should be understood as a protective factor or, on the contrary, as a manifestation of poorer mental health.

Finally, it should be noted that this study followed a similar approach to Study 3 and also analyzed whether the trait of alexithymia modulated the increase in loss aversion. It was observed that the increase in this bias was only significant in individuals with low levels of alexithymia. Furthermore, in the same line, symptoms of anxiety and depression were associated with an increase in loss aversion only when alexithymia was low. From a neuroanatomical perspective, both anxiety and depression —even subclinical— have shown increased amygdala activity, which could explain the higher aversion to losses in patients with these conditions (Klumpp et al., 2012; Laeger et al., 2012; Stein et al., 2007). On the other hand, high alexithymia has been linked to functional and connectivity deficits in the vmPFC (Sutherland et al., 2013). Therefore, even if an increase in symptoms of anxiety and depression and their respective amygdala activity occurred, the cortical deficits associated with alexithymia could hinder the incorporation of emotional responses into the decision-making process (Kano et al., 2011; Zhang et al., 2017), attenuating the increase in loss aversion. Although future research should focus on these mechanisms to shed light and verify them, these results would provide new evidence regarding the potential emotional origin of loss aversion —as discussed in section 1— and suggest potential therapeutic targets for decision-making deficits associated with anxiety and depression disorders.

3. Loss aversion could have a potential adaptive role

The last specific objective of the thesis was to demonstrate that loss aversion could play an adaptive role in certain decision-making contexts, far from always being a bias that leads to errors and, therefore, should be curbed. Except for Study 9, which explicitly

addresses this issue, most of the data shedding light on it come from studies whose main objective was different; however, indirectly, they also provide evidence of the potential adaptive role of loss aversion.

The first study is the systematic review of the genetic basis of loss aversion —**Study 1**—. Although not without limitations, results indicated that certain polymorphic genes involved in the functioning of the dopaminergic and serotonergic pathways could be related to higher or lower loss aversion depending on the allele adopted. While this does not constitute direct evidence of the adaptive role of this bias per se, it does suggest that its origin may be rooted in our genes. Thus, from a Darwinian perspective, loss aversion could be a phenomenon preserved through natural selection, making it, in some way, an adaptive behavior for our survival. Some authors argue that social evolution has been faster than biological evolution, giving rise to new environments where many of our natural characteristics may not be as adaptive or may even be detrimental compared to the environment in which they originated. Many of the emotional responses that give rise to our biases may have had significance for our survival but negatively affect us in the face of current marketing strategies, leading to irrational purchases, for example. In fact, approaches such as the nudge (Frydman & Camerer, 2016; Sunstein, 2014) or liberal paternalism policies (Thaler & Sunstein, 2003) are presented as protective against these possible abuses and seek to always facilitate the most rational option. However, in contrast, the debate arises as to whether this protection should not be exercised by directly regulating those marketing companies —e.g., preventing them from taking advantage of our natural biases and encouraging the objective information— instead of exerting regulation on ourselves, which could condition our free will (Gigerenzer, 2015; Helbing et al., 2019). Whether adaptive or not, it seems that biases such as loss aversion could have an evolutionary origin and be inherently linked to our most basic nature (Haselton et al., 2009; Santos & Rosati, 2015).

Following the classic ideas of Simon (Simon, 1955, 1956), subsequently developed by Gigerenzer (Gigerenzer, 2021), this adaptivity may not be inherent to the bias but dependent on the context in which it operates. In **Study 2**, we demonstrated the association between the negativity bias and loss aversion bias, thereby reaffirming the possible emotional origin of the latter. In risk decision-making, where displaying loss aversion is considered irrational because it hinders utility maximization strategies (Kahneman, 2003; Kahneman et al., 1991), having a high level of negativity bias —which

leads to greater loss aversion— would be considered maladaptive. However, in this study, we also analyzed how the negativity bias would influence an ambiguous or large-world context such as the IGT. Participants who expressed more negativity bias in the face rating task (Brown et al., 2017) also learned more quickly which decision options were most adaptive in the IGT. Since the IGT is designed to punish risk-taking (Bechara & Damasio, 2005), someone with a higher negativity bias may be particularly sensitive to these punishments, favoring reinforcement-based learning based on the consequences of previous decisions (Barros et al., 2017; Vaish et al., 2008; Vuilleumier, 2005). As we can see, the same bias —the negativity bias in this case— could be considered maladaptive or adaptive depending on whether its effect is evaluated in one context or another.

In this line, thanks to the development of modern computational models that allow for the analysis of decision processes in their different subcomponents (Ahn et al., 2017; Serrano et al., 2022), in **Study 8**, we directly addressed the role that loss aversion played in the IGT. As mentioned in the previous section, the results of this study revealed that acute stress caused an increase in loss aversion, and furthermore, this increase was related to faster learning during the task and more consistent decision-making. Just as suggested with the negativity bias, having a higher loss aversion could be making participants more sensitive to the punishments. This would be adaptive because it would encourage them to abandon unfavorable choices quickly and perform better in the task (Barros et al., 2017; Vaish et al., 2008; Vuilleumier, 2005). These results would be compatible with the classic studies of Bechara & Damasio (2005), where it was already shown that patients with lesions in emotional regions, who expressed less risk aversion, also performed worse in the IGT by persisting in unfavorable options due to their inability to learn through reinforcement. Additionally, they are in line with other recent studies showing how various pathological conditions, such as patients with suicide attempts, also exhibit significant decision-making deficits characterized specifically by low levels of loss aversion (Alacreu-Crespo et al., 2020; Hadlaczky et al., 2018; Sagiv et al., 2019).

Finally, but still in clinical populations, our **Study 9** highlights the possible adaptive role of loss aversion in a population with autism spectrum disorder (ASD). Previous studies had already revealed that individuals with ASD exhibit extremely logical and rational decision making (Brosnan et al., 2016), little affected by biases such as the framing effect —based on loss aversion— (Shah, Catmur, et al., 2016; Shah, Hall, et al., 2016). Moreover, they link this way of deciding to two possible causes: on one hand,

individuals with ASD often have a high comorbidity with alexithymia (Kinnaird et al., 2019). Thus, similar to what occurred in our Study 3, the difficulty in identifying, expressing, and regulating emotions due to alexithymia could prevent these emotions from being incorporated into the decision-making process, resulting in colder decisions (Shah, Hall, et al., 2016). On the other hand, ASD itself has been associated with deficits in the development, functionality, and connectivity of the vmPFC (Kishida et al., 2019; Murphy et al., 2017; Salehinejad et al., 2021). As we know, this region appears to be crucial for integrating emotional information from subcortical areas into the decision-making process (Gu et al., 2015; Rolls et al., 2020). Therefore, in line with expectations, our sample of patients with ASD also showed a lower framing effect in their individual decisions.

Although this way of deciding may seem appropriate from the perspective of economic rationality (Camerer, 2003; Rozenkrantz et al., 2021; von Neumann & Morgenstern, 1944), the reality is that these same patients often exhibit significant decision-making deficits in their daily lives, struggling to adapt to the environment, especially in social interactions (Fujino et al., 2017; Luke et al., 2012). Previous studies had indicated that the utilitarianism displayed by individuals with ASD in individual decisions also extends to social decisions. Thus, in line with other previous studies that used social decision-making paradigms such as the Ultimatum Game (Hartley & Fisher, 2018; Hinterbuchinger et al., 2018), our results showed that patients with ASD made utilitarian decisions, accepting unfair economic offers that maximize utility —receiving one euro is more useful than rejecting the offer and receiving nothing, for example—. Furthermore, they showed little inequity aversion and difficulties incorporating environmental information —i.e., learning whether it is favorable and adjusting— in subsequent decisions.

However, the importance of our study lies in highlighting that the decision-making deficits in social contexts —i.e., in the Ultimatum Game— were linked to the lower presence of biases in individual risk contexts. Thus, the less framing effect exhibited by patients with ASD, the lower inequity aversion they showed during the Ultimatum Game, and the more unfair money distributions they accepted. As we can see, this data suggests that the same lack of emotional involvement that leads to rational and appropriate decisions in individual contexts may be the cause of maladaptive decisions made in another complex context, such as social situations.

Once again, this reinforces Gigerenzer's perspective of ecological rationality (Gigerenzer, 2021), making it necessary to analyze each bias in the specific environment to judge whether it will be adaptive, when, and where. Additionally, the data from our studies also emphasize the broadening of evaluation criteria. If everything is judged according to the standards of economic rationality, then most biases will be seen as negative and should be restrained. However, by considering criteria such as biological rationality, adaptability, the ability to learn through reinforcement, or the ability to socialize, among others, many biases like loss aversion —and its derivatives, such as the framing effect— can be important allies in our decision-making.

4. Limitations and future directions

Our studies are not exempt from limitations. Specific limitations for each study can be found in Section 2, discussing the individual articles. However, this section summarizes the global limitations that are common to most studies and should be addressed as a priority in future research.

The main limitation is the lack of neural and hormonal measures that would allow for a more detailed understanding of the underlying mechanisms behind the findings. One of the objectives, for example, aimed to link the loss aversion bias to our affective system, demonstrating that this phenomenon is an emotional response. Although most data point in that direction, it would be necessary to validate them by contrasting them with the neural activity of the theoretically implicated limbic regions. It would also shed light on whether the negativity bias and the loss aversion bias truly produce activity in common brain areas, or whether the two-step decision-making model, dependent on interoception and alexithymia levels, follows a pattern of brain activity that supports it. Additionally, recording the activity of the executive and salience networks would be necessary to test the validity of the stress results. This would inevitably involve measuring levels of catecholamines and cortisol to also verify the physiological environment that is producing stress and how it relates to the neural activity. Therefore, future studies should incorporate these biological measures to strengthen many of the results obtained in this thesis and empirically demonstrate arguments that are currently speculative.

Furthermore, most of the samples used in our studies consisted of Spanish young, healthy university students recruited through non-probabilistic convenience sampling. This potentially limits the ecological validity of our work as we cannot guarantee that our

results are generalizable to a more diverse population. Future studies should expand the sample by including different population groups in terms of age and educational level. Both factors have been shown in previous studies to modulate the decision-making process (Bruine de Bruin et al., 2012; Huang et al., 2015; Mrkva et al., 2020), so it is necessary to address how they might influence our results. On the other hand, all analyses were replicated controlling for sex and did not yield significant results. However, our sample was disproportionate and included significantly more women than men. Therefore, these analyses could be underpowered, and caution is advisable. In fact, previous studies showed sex differences in the psychophysiological response to stress, as well as in the effects of stress on decision making (Hidalgo et al., 2019; van den Bos et al., 2009). For example, Daughters et al. (2013) found that, while men took more risks under stress, women showed the opposite response. Therefore, future studies should incorporate a more balanced distribution of genders to more specifically address whether this factor influences our results.

Another factor to consider is the decision-making context. This thesis primarily focuses on risky decision-making in small worlds, such as mixed gambles (Tom et al., 2007). However, as reiterated, cognitive processes may not be the same in these contexts as in more complex or large worlds (Volz & Gigerenzer, 2012). The only more complex environment we have employed is the IGT, and precisely in that task, results contrary to those observed in mixed gambles were obtained when examining how a stressor influences loss aversion. These results have been interpreted based on the possible neural activity promoted by stress, but they could also be due to the different nature of the decision-making environment. Future research should investigate whether our results can be extended to different contexts, from less to more ambiguous, or if in each environment, factors such as stress have a particular influence. In fact, as introduced, new lines of research in decision-making are moving towards the exploration of complex decision-making environments that recreate the richness of the decision-making process in real life while maintaining laboratory control. This is done to obtain more ecological assessments and determine whether previous results, usually obtained in small worlds, can also be extrapolated to more complex environments. Moreover, it would provide more accurate information about the nature of human decision-making.

In line with this, the final phase of the doctoral thesis addressed the development of a new virtual decision-making environment in collaboration with the Polytechnic

University of Valencia: Kalliste Decision Task (KDT). This task is currently in the registration and validation phase. Similar to previously developed environments like AEMIN (De-Juan-Ripoll et al., 2021) or SSMT (De-Juan-Ripoll et al., 2020), KDT aims to comprehensively evaluate decision-making. On the one hand, as participants progress through the corridors of KDT —see Figure 2—, they are presented with a spectrum of situations ranging from less ambiguous to more ambiguous, which allows extracting data on the decision capacity of the participants depending on the complexity of the environment (i.e., more or less information to decide, more or less risk, etc.). On the other hand, KDT addresses both explicit and implicit decisions. While most classic tasks involve consciously decisions, KDT presents situations where implicit decisions can also be analyzed, such as choosing to move along a path with more or less danger, activating or not activating a shield, among others. As highlighted in previous literature, these implicit decisions can be more revealing, for example, of participants' propensity for risk-taking or impulsivity level (De-Juan-Ripoll et al., 2021). Additionally, KDT allows for the analysis of decision-making capacity beyond the classic economic rationality criterion, delving into the decision-making process itself and not just the outcome. Impulsivity, reflection time, satisfaction, exploration, resilience after failure, cognitive flexibility, and other characteristics can be evaluated using KDT. Since operating KDT is straightforward —only requiring the use of arrow keys— previous behavioral data can be complemented with the recording of neural activity and peripheral physiology during the assessment. We are currently beginning to use KDT in the laboratory alongside the evaluation of decision-making with other classic tasks, with the intention of testing its validity. We hope to obtain the first results soon and disseminate them in internationally renowned journals, making KDT available to the scientific community for future decision-making studies.

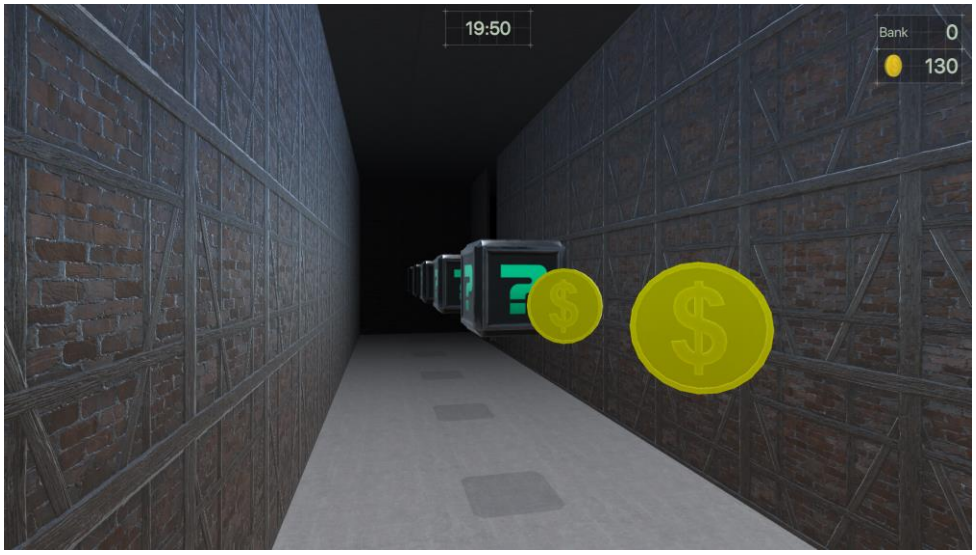


Figure 2. An example of Kalliste Decision Task (KDT). A corridor of KDT where two of the multiple tokens are observed, presenting two different types of decisions. Firstly, if someone approaches the coins, they provide guaranteed gains. On the other hand, the ambiguous boxes can yield gains or losses if one decides to open them.

Lastly, focusing on the part of the thesis that addresses the influence of stress, we observed that, except for Study 7, which includes a natural stressor —the distressing context caused by the COVID-19 pandemic— the remaining studies utilize acute laboratory stressors that disappear by the time decision-making is assessed. Different acute stressors may already present different effects, which is why this thesis addresses stressors of various natures: physical, emotional, and psychosocial stress. However, as our own results reveal, it is also important to consider the psychological impact of the stressor, that is, whether it affects the participants' mental health. It is evident that a stressor that transiently increases negative affect cannot produce the same effect as one that even exacerbates symptoms of anxiety and depression. It is also known that the effects of acute stress and chronic stress are very different at a psychophysiological level. Therefore, future studies should delve deeper into the heterogeneity of stress, including not only different acute stressors but also persistent or even chronic stressors.

5. Conclusions

Despite limitations, this doctoral thesis fulfills its purpose of providing a more positive perspective on cognitive biases, particularly the loss aversion bias. As introduced, biases have been *demonized* since their inception, being seen as limiting phenomena in our judgments and decisions. The term 'bias' itself implies a distortion, a deviation from

the norm, which is classical rationality derived from economic models. Thanks to new lines of research in decision-making, in which this thesis contributes its grain of sand, we now know that such economic rationality is just one of many possible norms and may not be the most suitable depending on the decisional context. The degree of adaptability, satisfaction, reinforcement-learning, impulsivity, cognitive flexibility, and even the propensity to seek help when we lack sufficient knowledge, all constitute possible criteria to consider when evaluating individuals' decision-making capacity. It is under these criteria, precisely, that biases like loss aversion can prove to be particularly necessary. While they may lead us to *illogical* decisions from the economic rationality focus, they can also have adaptive value and provide support in ambiguous contexts where logic is overwhelmed. For example, as we have seen in this thesis, loss aversion could increase our sensitivity to threatening or unfavorable stimuli, facilitating their avoidance and favoring more adaptive decisions. Therefore, instead of suppressing biases by default, it is advisable to acquire more knowledge about them: why they originate, what their nature is, in which contexts they appear most prominently, what factors condition their expression, and in which of these contexts they serve as support or, conversely, it is better to suppress them and be guided by pure logic. This thesis delved into these questions, and as a conclusion, the main findings are summarized below:

- Loss aversion could be an emotional response to the pain caused by losses, which is generally more intense than the pleasure derived from proportional gains.

- Maybe the specific response to losses is learned, but it could be based on an innate tendency to prioritize processing stimuli perceived as negative over those perceived as positive. In other words, loss aversion could be an extension of the negativity bias.

- The potential genetic basis of loss aversion could support this innate tendency, as well as the emotional nature of this phenomenon. Genes involved in the functioning of the dopaminergic and serotoninergic pathways, both crucial in regulating emotional processes, are associated with a greater or lesser tendency to express loss aversion.

- Similarly, individuals with greater capacity to regulate their emotions, influenced by their interoceptive abilities and levels of alexithymia, could better modulate the expression of biases during decision-making. As we can see, biases like loss aversion would not be ubiquitous and stable, but rather modulated by internal and external factors, with stress being one of the most studied.

- The influence of stress on biases is heterogeneous, depending on the characteristics of the stressor and the temporal phase of stress. In general, acute stress can reduce loss aversion. However, the mechanisms behind this reduction may vary. In very early stages of stress, the slight increase in catecholamines could enhance the prefrontal cortex (PFC) and, in turn, logical thinking, thereby reducing loss aversion. In later stages, cortisol could increase attraction to gains and blunt the pain of losses, yielding the same result as the early phase. These mechanisms need to be verified in future research, as well as whether other intermediate phases produce different effects.

- Persistent or chronic stress, such as that experienced during the COVID-19 pandemic, could have a different impact. This stress is associated with an increase in symptoms of depression and anxiety, which tend to lead to an increase in loss aversion. Future research should determine if this increase represents the onset of maladaptive decision-making typically observed in these disorders.

- Today, we know that although illogical, many decisions influenced by loss aversion are adaptive. It facilitates reinforcement-learning and consistency in our decisions and promotes necessary emotions for proper social interaction —such as the inequity aversion found in the Ultimatum Game—.

- These findings lead us to reconsider how we evaluate what constitutes a good decision. The criteria should not be limited to classical economic rationality, and decision-making models should align with human nature, relying on recent contributions from neuroscience.

Section 4: References

Adriani, W., Boyer, F., Gioiosa, L., Macrì, S., Dreyer, J. L., & Laviola, G. (2009). Increased impulsive behavior and risk proneness following lentivirus-mediated dopamine transporter over-expression in rats' nucleus accumbens. *Neuroscience*, *159*(1), 47–58. https://doi.org/10.1016/j.neuroscience.2008.11.042

Ahn, W. Y., Haines, N., & Zhang, L. (2017). Revealing Neurocomputational Mechanisms of Reinforcement Learning and Decision-Making With the hBayesDM Package. *Computational Psychiatry*, *1*(0), 24. https://doi.org/10.1162/cpsy_a_00002

Alacreu-Crespo, A., Guillaume, S., Sénèque, M., Olié, E., & Courtet, P. (2020). Cognitive modelling to assess decision-making impairments in patients with current depression and with/without suicide history. *European Neuropsychopharmacology*, *36*, 50–59. https://doi.org/10.1016/j.euroneuro.2020.04.006

Alcañiz Raya, M., Chicchi Giglioli, I. A., Marín-Morales, J., Higuera-Trujillo, J. L., Olmos, E., Minissi, M. E., Teruel Garcia, G., Sirera, M., & Abad, L. (2020). Application of supervised machine learning for behavioral biomarkers of autism spectrum disorder based on electrodermal activity and virtual reality. *Frontiers in Human Neuroscience*, 90.

Anstrom, K. K., & Woodward, D. J. (2005). Restraint increases dopaminergic burst firing in awake rats. *Neuropsychopharmacology*, *30*(10), 1832–1840.

Ashraf, N., Camerer, C. F., & Loewenstein, G. (2005). Adam Smith, behavioral economist. *Journal of Economic Perspectives*, *19*(3), 131–145. https://doi.org/10.1257/089533005774357897

Attenburrow, M. J., Williams, C., Odontiadis, J., Reed, A., Powell, J., Cowen, P. J., & Harmer, C. J. (2003). Acute administration of nutritionally sourced tryptophan increases fear recognition. *Psychopharmacology*, *169*(1), 104–107. https://doi.org/10.1007/s00213-003-1479-x

Baek, K., Kwon, J., Chae, J. H., Chung, Y. A., Kralik, J. D., Min, J. A., Huh, H., Choi, K. M., Jang, K. I., Lee, N. Bin, Kim, S., Peterson, B. S., & Jeong, J. (2017). Heightened aversion to risk and loss in depressed patients with a suicide attempt history. *Scientific Reports*, *7*(1), 1–13. https://doi.org/10.1038/s41598-017-10541-5

Barrett, L., Quigley, K. S., Bliss-Moreau, E., & Aronson, K. R. (2012). Interoceptive Sensitivity and Self-Reports of Emotional. *J Pers Soc Psychol.*, *23*(1), 1–7. https://doi.org/10.1038/jid.2014.371

Barros, P., Parisi, G. I., Weber, C., & Wermter, S. (2017). Emotion-modulated attention improves expression recognition: A deep learning model. *Neurocomputing*, *253*, 104–114. https://doi.org/10.1016/j.neucom.2017.01.096

Bechara, A., & Damasio, A. R. (2005). The somatic marker hypothesis: A neural theory of economic decision. *Games and Economic Behavior*, *52*(2), 336–372. https://doi.org/10.1016/j.geb.2004.06.010

Bechara, A., Damasio, H., Tranel, D., & Damasio, A. R. (1997). Deciding Advantageously Before Knowing the Advantageous Strategy. *Science*, *275*(February), 1293–1295.

Berejikian, J. D., & Early, B. R. (2013). Loss aversion and foreign policy resolve. *Political Psychology*, *34*(5), 649–671. https://doi.org/10.1111/pops.12012

Bernoulli, D. (1738). Specimen theoriae novae de mensura sortis. *Commentarii Academiae Scientiarum Imperialis Petropolitanae*, *5*, 175–192.

Bernoulli, D. (1954). Exposition of a New Theory on the Measurement of Risk. *Econometrica*, *22*(1), 23–36. https://doi.org/10.2307/1909829

Blair, K. S., Finger, E., Marsh, A. A., Morton, J., Mondillo, K., Buzas, B., Goldman, D., Drevets, W. C., & Blair, R. J. R. (2008). The role of 5-HTTLPR in choosing the lesser of two evils, the better of two goods: Examining the impact of 5-HTTLPR genotype and tryptophan depletion in object choice. *Psychopharmacology*, *196*(1), 29–38. https://doi.org/10.1007/s00213-007-0920-y

Bossaerts, P., & Murawski, C. (2015). From behavioural economics to neuroeconomics to decision neuroscience: The ascent of biology in research on human decision making. *Current Opinion in Behavioral Sciences*, *5*, 37–42. https://doi.org/10.1016/j.cobeha.2015.07.001

Boyce, C. J., Wood, A. M., & Ferguson, E. (2016). Individual Differences in Loss Aversion: Conscientiousness Predicts How Life Satisfaction Responds to Losses Versus Gains in Income. *Personality and Social Psychology Bulletin*, *42*, 471–484.

Bradley, M. M. (2009). Natural selective attention: Orienting and emotion. *Psychophysiology*, *46*(1), 1–11. https://doi.org/10.1111/j.1469-8986.2008.00702.x.Natural

Brosnan, M., Lewton, M., & Ashwin, C. (2016). Reasoning on the autism spectrum: A dual process theory account. *Journal of Autism and Developmental Disorders*, *46*(6), 2115–2125.

Brown, C. C., Raio, C. M., & Neta, M. (2017). Cortisol responses enhance negative valence perception for ambiguous facial expressions /631/477 /631/378/1457 /631/378/1831 article. *Scientific Reports*, *7*(1), 1–8. https://doi.org/10.1038/s41598-017-14846-3

Browning, M., Reid, C., Cowen, P. J., Goodwin, G. M., & Harmer, C. J. (2007). A single dose of citalopram increases fear recognition in healthy subjects. *Journal of Psychopharmacology*, *21*(7), 684–690. https://doi.org/10.1177/0269881106074062

Brugnach, M., Dewulf, A., Henriksen, H. J., & van der Keur, P. (2011). More is not always better: Coping with ambiguity in natural resources management. *Journal of Environmental Management*, *92*(1), 78–84. https://doi.org/10.1016/j.jenvman.2010.08.029

Bruine de Bruin, W., Parker, A. M., & Fischhoff, B. (2012). Explaining adult age differences in decision-making competence. *Journal of Behavioral Decision Making*, *25*(4), 352–360. https://doi.org/10.1002/BDM.712

Burghardt, N. S., Bush, D., McEwen, B., & Ledoux, J. E. (2007). Acute SSRIs Increase Conditioned Fear Expression: Blockade with a 5-HT2C Receptor Antagonist N.S. *Biological Psychiatry*, *62*(10), 1111–1118.

Butler, R. K., & Finn, D. P. (2009). Stress-induced analgesia. *Progress in Neurobiology*, *88*(3), 184–202. https://doi.org/10.1016/j.pneurobio.2009.04.003

Cacioppo, J. T., & Berntson, G. G. (1994). Relationship Between Attitudes and Evaluative Space: A Critical Review, With Emphasis on the Separability of Positive and Negative Substrates. *Psychological Bulletin*, *115*(3), 401–423. https://doi.org/10.1037/0033-2909.115.3.401

Camerer, C., Babcock, L., Loewenstein, G., & Thaler, R. (1997). Labor supply of New York city cabdrivers: One day at a time. *Quarterly Journal of Economics*, *112*(2), 406–441. https://doi.org/10.1162/003355397555244

Camerer, C. F. (2003). Behavioral game theory: Plausible formal models that predict accurately. *Behavioral and Brain Sciences*, *26*(2), 157–158.

Canessa, N., Crespi, C., Baud-Bovy, G., Dodich, A., Falini, A., Antonellis, G., & Cappa, S. F. (2017). Neural markers of loss aversion in resting-state brain activity. *NeuroImage*, *146*(September 2016), 257–265. https://doi.org/10.1016/j.neuroimage.2016.11.050

Charpentier, C. J., De Martino, B., Sim, A. L., Sharot, T., & Roiser, J. P. (2016). Emotion-induced loss aversion and striatal-amygdala coupling in low-anxious individuals. *Social Cognitive and Affective Neuroscience*, *11*(4), 569–579. https://doi.org/10.1093/scan/nsv139

Chater, N., Felin, T., Funder, D. C., Gigerenzer, G., Koenderink, J. J., Krueger, J. I., Noble, D., Nordli, S. A., Oaksford, M., Schwartz, B., Stanovich, K. E., & Todd, P. M. (2018). Mind, rationality, and cognition: An interdisciplinary debate. *Psychonomic Bulletin and Review*, *25*(2), 793–826. https://doi.org/10.3758/s13423-017-1333-5

Chiu, Y. C., Huang, J. T., Duann, J. R., & Lin, C. H. (2018). Editorial: Twenty years after the Iowa Gambling Task: Rationality, emotion, and decision-making. *Frontiers in Psychology*, *8*(JAN), 1–5. https://doi.org/10.3389/fpsyg.2017.02353

Congdon, E., Lesch, K. P., & Canli, T. (2008). Analysis of DRD4 and DAT polymorphisms and behavioral inhibition in healthy adults: Implications for impulsivity. *American Journal of Medical Genetics, Part B: Neuropsychiatric Genetics*, *147*(1), 27–32. https://doi.org/10.1002/ajmg.b.30557

Constantinople, C. M., Piet, A. T., & Brody, C. D. (2019). An Analysis of Decision under Risk in Rats. *Current Biology*, *29*(12), 2066-2074.e5. https://doi.org/10.1016/j.cub.2019.05.013

Crişan, L. G., Pană, S., Vulturar, R., Heilman, R. M., Szekely, R., Drugă, B., Dragoş, N., & Miu, A. C. (2009). Genetic contributions of the serotonin transporter to social learning of fear and economic decision making. *Social Cognitive and Affective Neuroscience*, *4*(4), 399–408. https://doi.org/10.1093/scan/nsp019

Critchley, H. D., Wiens, S., Rotshtein, P., Öhman, A., & Dolan, R. J. (2004). Neural systems supporting interoceptive awareness. *Nature Neuroscience*, *7*(2), 189–195. https://doi.org/10.1038/nn1176

Croxson, P. L., Walton, M. E., O'Reilly, J. X., Behrens, T. E. J., & Rushworth, M. F. S. (2009). Effort-

based cost–benefit valuation and the human brain. *Journal of Neuroscience*, *29*(14), 4531–4541.

da Silva, A. N., Vasco, A. B., & Watson, J. C. (2017). Alexithymia and Emotional Processing: A Mediation Model. *Journal of Clinical Psychology*, *73*(9), 1196–1205. https://doi.org/10.1002/jclp.22422

Daughters, S. B., Gorka, S. M., Matusiewicz, A., & Anderson, K. (2013). Gender specific effect of psychological stress and cortisol reactivity on adolescent risk taking. *Journal of Abnormal Child Psychology*, *41*(5), 749–758. https://doi.org/10.1007/S10802-013-9713-4/FIGURES/3

De-Juan-Ripoll, C., Llanes-Jurado, J., Giglioli, I. A. C., Marín-Morales, J., & Alcañiz, M. (2021). An immersive virtual reality game for predicting risk taking through the use of implicit measures. *Applied Sciences (Switzerland)*, *11*(2), 1–21. https://doi.org/10.3390/app11020825

De-Juan-Ripoll, C., Soler-Domínguez, J. L., Chicchi Giglioli, I. A., Contero, M., & Alcañiz, M. (2020). The Spheres & Shield Maze Task: A Virtual Reality Serious Game for the Assessment of Risk Taking in Decision Making. *Cyberpsychology, Behavior, and Social Networking*, *23*(11), 773–781. https://doi.org/10.1089/cyber.2019.0761

Dolan, R. J., & Sharot, T. (2011). *Neuroscience of preference and choice: cognitive and neural mechanisms*. Academic Press.

Dreber, A., Apicella, C. L., Eisenberg, D. T. A., Garcia, J. R., Zamore, R. S., Lum, J. K., & Campbell, B. (2009). The 7R polymorphism in the dopamine receptor D4 gene (DRD4) is associated with financial risk taking in men. *Evolution and Human Behavior*, *30*(2), 85–92. https://doi.org/10.1016/j.evolhumbehav.2008.11.001

Dreber, A., Rand, D. G., Wernerfelt, N., Garcia, J. R., Vilar, M. G., Lum, J. K., & Zeckhauser, R. (2011). Dopamine and risk choices in different domains: Findings among serious tournament bridge players. *Journal of Risk and Uncertainty*, *43*(1), 19–38. https://doi.org/10.1007/s11166-011-9119-z

Duke, É., Schnuerch, R., Heeren, G., Reuter, M., Montag, C., & Markett, S. (2018). Cortical alpha asymmetry at central and posterior – but not anterior – sites is associated with individual differences in behavioural loss aversion. *Personality and Individual Differences*, *121*, 206–212. https://doi.org/10.1016/j.paid.2017.04.056

Dunn, B. D., Galton, H. C., Morgan, R., Evans, D., Oliver, C., Meyer, M., Cusack, R., Lawrence, A. D., & Dalgleish, T. (2010). Listening to your heart: How interoception shapes emotion experience and intuitive decision making. *Psychological Science*, *21*(12), 1835–1844. https://doi.org/10.1177/0956797610389191

Ert, E., & Erev, I. (2013). On the descriptive value of loss aversion in decisioErt, E., & Erev, I. (2013). On the descriptive value of loss aversion in decisions under risk: Six clarifications. Judgment and Decision Making, 8(3), 214–235. https://doi.org/10.2139/ssrn.1012022ns unde. *Judgment and Decision Making*, *8*(3), 214–235. http://journal.sjdm.org/12/12712/jdm12712.html

Etkin, A., Egner, T., Peraza, D. M., Kandel, E. R., & Hirsch, J. (2006). Resolving Emotional Conflict: A

Role for the Rostral Anterior Cingulate Cortex in Modulating Activity in the Amygdala. *Neuron*, *51*(6), 871–882. https://doi.org/10.1016/j.neuron.2006.07.029

Evans, J. S. B. T. (2008). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology*, *59*, 255–278. https://doi.org/10.1146/annurev.psych.59.103006.093629

Evans, J. S. B. T. (2014). Rationality and the illusion of choice. *Frontiers in Psychology*, *5*(FEB), 1–4. https://doi.org/10.3389/fpsyg.2014.00104

Felin, T., Koenderink, J., & Krueger, J. I. (2017). Rationality, perception, and the all-seeing eye. *Psychonomic Bulletin and Review*, *24*(4), 1040–1059. https://doi.org/10.3758/s13423-016-1198-z

Frydman, C., & Camerer, C. F. (2016). The Psychology and Neuroscience of Financial Decision Making. *Trends in Cognitive Sciences*, *20*(9), 661–675. https://doi.org/10.1016/j.tics.2016.07.003

Fujino, J., Tei, S., Hashimoto, R. I., Itahashi, T., Ohta, H., Kanai, C., Okada, R., Kubota, M., Nakamura, M., Kato, N., & Takahashi, H. (2017). Attitudes toward risk and ambiguity in patients with autism spectrum disorder. *Molecular Autism*, *8*(1), 1–10. https://doi.org/10.1186/S13229-017-0162-8/FIGURES/4

Gal, D., & Rucker, D. D. (2018). The Loss of Loss Aversion: Will It Loom Larger Than Its Gain? *Journal of Consumer Psychology*, *28*(3), 497–516. https://doi.org/10.1002/jcpy.1047

Gao, X., Liu, J., Gong, P., Wang, J., Fang, W., Yan, H., Zhu, L., & Zhou, X. (2017). Identifying new susceptibility genes on dopaminergic and serotonergic pathways for the framing effect in decision-making. *Social Cognitive and Affective Neuroscience*, *12*(9), 1534–1544. https://doi.org/10.1093/scan/nsx062

Garcia, J. R., Mackillop, J., Aller, E. L., Merriwether, A. M., Wilson, D. S., & Lum, J. K. (2010). Associations between dopamine d4 receptor gene variation with both infidelity and sexual promiscuity. *PLoS ONE*, *5*(11). https://doi.org/10.1371/journal.pone.0014162

Geisler, M., & Allwood, C. M. (2015). Competence and quality in real-life decision making. *PLoS ONE*, *10*(11), 1–22. https://doi.org/10.1371/journal.pone.0142178

Gigerenzer, G. (2015). On the Supposed Evidence for Libertarian Paternalism. *Review of Philosophy and Psychology*, *6*(3), 361–383. https://doi.org/10.1007/s13164-015-0248-1

Gigerenzer, G. (2021). Axiomatic rationality and ecological rationality. *Synthese*, *198*(4), 3547–3564. https://doi.org/10.1007/s11229-019-02296-5

Gigerenzer, G., & Gaissmaier, W. (2011). Heuristic decision making. *Annual Review of Psychology*, *62*, 451–482. https://doi.org/10.1146/annurev-psych-120709-145346

Gigerenzer, G., Gaissmaier, W., Kurz-Milcke, E., Schwartz, L. M., & Woloshin, S. (2007). Helping doctors and patients make sense of health statistics. *Psychological Science in the Public Interest*, *8*(2), 53–96.

Gonzalez, C., Fakhari, P., & Busemeyer, J. (2017). Dynamic Decision Making: Learning Processes and New Research Directions. *Human Factors*, *59*(5), 713–721. https://doi.org/10.1177/0018720817710347

Gore, J., Banks, A., Millward, L., & Kyriakidou, O. (2006). Naturalistic decision making and organizations: Reviewing pragmatic science. *Organization Studies*, *27*(7), 925–942. https://doi.org/10.1177/0170840606065701

Gu, X., Wang, X., Hula, X., Wang, S., Xu, S., Lohrenz, T. M., Knight, R. T., Gao, Z., Dayan, P., & Montague, P. R. (2015). Necessary, yet dissociable contributions of the insular and ventromedial prefrontal cortices to norm adaptation: Computational and lesion evidence in humans. *Journal of Neuroscience*, *35*(2), 467–473. https://doi.org/10.1523/JNEUROSCI.2906-14.2015

Hadlaczky, G., Hökby, S., Mkrtchian, A., Wasserman, D., Balazs, J., Machín, N., Sarchiapone, M., Sisask, M., & Carli, V. (2018). Decision-making in suicidal behavior: The protective role of loss aversion. *Frontiers in Psychiatry*, *9*(APR), 1–9. https://doi.org/10.3389/fpsyt.2018.00116

Harmer, C. J., Rogers, R. D., Tunbridge, E., Cowen, P. J., & Goodwin, G. M. (2003). Tryptophan depletion decreases the recognition of fear in female volunteers. *Psychopharmacology*, *167*(4), 411–417. https://doi.org/10.1007/s00213-003-1401-6

Hartley, C., & Fisher, S. (2018). Do Children with Autism Spectrum Disorder Share Fairly and Reciprocally? *Journal of Autism and Developmental Disorders*, *48*(8), 2714–2726. https://doi.org/10.1007/s10803-018-3528-7

Haselton, M. G., Bryant, G. A., Wilke, A., Frederick, D. A., Galperin, A., Frankenhuis, W. E., & Moore, T. (2009). Adaptive rationality: An evolutionary perspective on cognitive bias. *Social Cognition*, *27*(5), 733–763. https://doi.org/10.1521/soco.2009.27.5.733

Helbing, D., Frey, B. S., Gigerenzer, G., Hafen, E., Hagner, M., Hofstetter, Y., Hoven, J. van den, Zicari, R. V, & Zwitter, A. (2019). Will democracy survive big data and artificial intelligence? In *Towards digital enlightenment* (pp. 73–98). Springer.

Herbert, B. M., Herbert, C., & Pollatos, O. (2011). On the relationship between interoceptive awareness and alexithymia: Is interoceptive awareness related to emotional awareness? *Journal of Personality*, *79*(5), 1149–1175. https://doi.org/10.1111/j.1467-6494.2011.00717.x

Hermans, E. J., Henckens, M. J. A. G., Joëls, M., & Fernández, G. (2014). Dynamic adaptation of large-scale brain networks in response to acute stressors. *Trends in Neurosciences*, *37*(6), 304–314. https://doi.org/10.1016/j.tins.2014.03.006

Hermans, E. J., Van Marle, H. J. F., Ossewaarde, L., Henckens, M. J. A. G., Qin, S., Van Kesteren, M. T. R., Schoots, V. C., Cousijn, H., Rijpkema, M., Oostenveld, R., & Fernández, G. (2011). Stress-related noradrenergic activity prompts large-scale neural network reconfiguration. *Science*, *334*(6059), 1151–1153. https://doi.org/10.1126/science.1209603

Hernandez, J. (2012). Heuristicas y racionalidad acotada. Hacia una concepción pluralista del agente racional. *Tesis*, *March*. https://doi.org/10.13140/RG.2.2.29980.59527

Hertwig, R., Pleskac, T. J., & Pachur, T. (2020). The Robust Beauty of Heuristics in Choice under Uncertainty. *Taming Uncertainty*, *July*. https://doi.org/10.7551/mitpress/11114.003.0006

Hidalgo, V., Pulopulos, M. M., & Salvador, A. (2019). Acute psychosocial stress effects on memory performance: Relevance of age and sex. *Neurobiology of Learning and Memory*, *157*(November 2018), 48–60. https://doi.org/10.1016/j.nlm.2018.11.013

Hinterbuchinger, B., Kaltenboeck, A., Baumgartner, J. S., Mossaheb, N., & Friedrich, F. (2018). Do patients with different psychiatric disorders show altered social decision-making? A systematic review of ultimatum game experiments in clinical populations. *Cognitive Neuropsychiatry*, *23*(3), 117–141. https://doi.org/10.1080/13546805.2018.1453791

Hintze, A., Olson, R. S., Adami, C., & Hertwig, R. (2015). Risk sensitivity as an evolutionary adaptation. *Scientific Reports*, *5*, 1–7. https://doi.org/10.1038/srep08242

Hochman, G., & Yechiam, E. (2011). Loss Aversion in the Eye and in the Heart: The Autonomic Nervous System's Responses to Losses. *Journal of Behavioral Decision Making*, *24*, 140–156.

Hsu, C.-T., Jacobs, A. M., & Conrad, M. (2015). Can Harry Potter still put a spell on us in a second language? An fMRI study on reading emotion-laden literature in late bilinguals. *Cortex*, *63*, 282–295.

Huang, Y. H., Wood, S., Berger, D. E., & Hanoch, Y. (2015). Age differences in experiential and deliberative processes in unambiguous and ambiguous decision making. *Psychology and Aging*, *30*(3), 675–687. https://doi.org/10.1037/pag0000038

Iwasaki, K., & Sawada, Y. (2015). Evacuation and Psychological Distress: New Evidence of Reference-Dependent Utility and Loss Aversion. 行動経済学, *8*, 77–80. https://doi.org/10.11167/JBEF.8.77

Jarrow, R., & Zhaou, F. (2006). Downside loss aversion and portfolio management. *Management Science*, *52*(4), 558–566. https://doi.org/10.1287/mnsc.1050.0486

Joseph, D., Chan, M., Heintzelman, S., Tay, L., Diener, E., & Scotney, V. (2020). The manipulation of affect: A meta-analysis of affect induction procedures. *Psychological Bulletin*, *146*(4), 355–375.

Kahneman, D. (2003). Maps of bounded rationality: Psychology for behavioral economics. *American Economic Review*, *93*(5), 1449–1475. https://doi.org/10.1257/000282803322655392

Kahneman, D. (2011). *Thinking, fast and slow*. Macmillan.

Kahneman, D., Knetsch, J. L., & Thaler, R. H. (1991). Anomalies: The endowment effect, loss aversion, and status quo bias. *Journal of Economic Perspectives*, *5*(1), 193–206. https://doi.org/10.1017/CBO9780511803475.009

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*,

47(2), 263–291. https://doi.org/10.1017/CBO9780511803475.003

Kahneman, D., & Tversky, A. (1984). Choices, Values, and Frames. *American Psychologist*, *39*(4), 341–350.

Kalivas, P. W., & Duffy, P. (1995). Selective activation of dopamine transmission in the shell of the nucleus accumbens by stress. *Brain Research*, *675*(1–2), 325–328.

Kano, M., Ito, M., & Fukudo, S. (2011). Neural substrates of decision making as measured with the iowa gambling task in men with alexithymia. *Psychosomatic Medicine*, *73*(7), 588–597. https://doi.org/10.1097/PSY.0b013e318223c7f8

Kanouse, D. E. (1984). Explaining negativity biases in evaluation and choice behavior: Theory and research. *ACR North American Advances*.

Kauschke, C., Bahn, D., Vesker, M., & Schwarzer, G. (2019). Review: The role of emotional valence for the processing of facial and verbal stimuli - positivity or negativity bias? *Frontiers in Psychology*, *10*(JULY), 1–15. https://doi.org/10.3389/fpsyg.2019.01654

Kelley, A. E., Schiltz, C. A., & Landry, C. F. (2005). Neural systems recruited by drug- and food-related cues: Studies of gene activation in corticolimbic regions. *Physiology and Behavior*, *86*(1–2), 11–14. https://doi.org/10.1016/j.physbeh.2005.06.018

Kenning, P., & Plassmann, H. (2005). NeuroEconomics: An overview from an economic perspective. *Brain Research Bulletin*, *67*(5), 343–354.

Kinnaird, E., Stewart, C., & Tchanturia, K. (2019). Investigating alexithymia in autism: A systematic review and meta-analysis. *European Psychiatry*, *55*, 80–89. https://doi.org/10.1016/J.EURPSY.2018.09.004

Kishida, K. T., De Asis-Cruz, J., Treadwell-Deering, D., Liebenow, B., Beauchamp, M. S., & Montague, P. R. (2019). Diminished single-stimulus response in vmPFC to favorite people in children diagnosed with Autism Spectrum Disorder. *Biological Psychology*, *145*, 174–184. https://doi.org/10.1016/J.BIOPSYCHO.2019.04.009

Klumpp, H., Angstadt, M., & Phan, K. L. (2012). Insula reactivity and connectivity to anterior cingulate cortex when processing threat in generalized social anxiety disorder. *Biological Psychology*, *89*(1), 273–276. https://doi.org/10.1016/j.biopsycho.2011.10.010

Knutson, B., & Cooper, J. C. (2005). Functional magnetic resonance imaging of reward prediction. *Current Opinion in Neurology*, *18*(4), 411–417. https://doi.org/10.1097/01.wco.0000173463.24758.f6

Koehler, D. J., & Harvey, N. (2004). Blackwell Handbook of Judgment & Decision Making. In *Handbooks of Experimental Psychology*. Blackwell Publishing. https://doi.org/10.1002/9780470752937.ch22

Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research - Recommendations for experiment planning, data analysis, and data

reporting. *Frontiers in Psychology*, *8*(FEB), 1–18. https://doi.org/10.3389/fpsyg.2017.00213

Laeger, I., Dobel, C., Dannlowski, U., Kugel, H., Grotegerd, D., Kissler, J., Keuper, K., Eden, A., Zwitserlood, P., & Zwanzger, P. (2012). Amygdala responsiveness to emotional words is modulated by subclinical anxiety and depression. *Behavioural Brain Research*, *233*(2), 508–516. https://doi.org/10.1016/j.bbr.2012.05.036

Lasrado, S. (2019). *Physiology, Ear*.

Liu, Q., & Zhang, W. (2020). Sex differences in stress reactivity to the trier social stress test in virtual reality. *Psychology Research and Behavior Management*, *13*, 859–869. https://doi.org/10.2147/PRBM.S268039

Luan, S., Reb, J., & Gigerenzer, G. (2019). Ecological rationality: Fast-and-frugal heuristics for managerial decision making under uncertainty. *Academy of Management Journal*, *62*(6), 1735–1759. https://doi.org/10.5465/amj.2018.0172

Luke, L., Clare, I. C. H., Ring, H., Redley, M., & Watson, P. (2012). Decision-making difficulties experienced by adults with autism spectrum conditions. *Autism*, *16*(6), 612–621.

MacKillop, J., Menges, D. P., McGeary, J. E., & Lisman, S. A. (2007). Effects of craving and DRD4 VNTR genotype on the relative value of alcohol: An initial human laboratory study. *Behavioral and Brain Functions*, *3*, 1–12. https://doi.org/10.1186/1744-9081-3-11

Marewski, J. N., Gaissmaier, W., & Gigerenzer, G. (2010). We favor formal models of heuristics rather than lists of loose dichotomies: A reply to Evans and over. *Cognitive Processing*, *11*(2), 177–179. https://doi.org/10.1007/s10339-009-0340-5

Marewski, J. N., & Gigerenzer, G. (2012). Heuristic decision making in medicine. *Dialogues in Clinical Neuroscience*, *14*(1), 77–89. https://doi.org/10.31887/dcns.2012.14.1/jmarewski

Margittai, Z., Nave, G., Van Wingerden, M., Schnitzler, A., Schwabe, L., & Kalenscher, T. (2018). Combined Effects of Glucocorticoid and Noradrenergic Activity on Loss Aversion. *Neuropsychopharmacology : Official Publication of the American College of Neuropsychopharmacology*, *43*(2), 334–341. https://doi.org/10.1038/npp.2017.75

Markett, S., Heeren, G., Montag, C., Weber, B., & Reuter, M. (2016). Loss aversion is associated with bilateral insula volume. A voxel based morphometry study. *Neuroscience Letters*, *619*, 172–176. https://doi.org/10.1016/j.neulet.2016.03.029

Mather, M., & Lighthall, N. R. (2012). Risk and reward are processed differently in decisions made under stress. *Current Directions in Psychological Science*, *21*(1), 36–41. https://doi.org/10.1177/0963721411429452

Mega, L. F., Gigerenzer, G., & Volz, K. G. (2015). Do intuitive and deliberate judgments rely on two distinct neural systems? A case study in face processing. *Frontiers in Human Neuroscience*, *9*(AUGUST), 1–15. https://doi.org/10.3389/fnhum.2015.00456

Metz, S., Waiblinger-Grigull, T., Schulreich, S., Chae, W. R., Otte, C., Heekeren, H. R., & Wingenfeld, K. (2020). Effects of hydrocortisone and yohimbine on decision-making under risk. *Psychoneuroendocrinology*, *114*(August 2019), 104589. https://doi.org/10.1016/j.psyneuen.2020.104589

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81.

Mintoft, B., Callaghan, K., Buetow, S., Kydd, R., & Sollers, J. J. (2012). Money, Sex, and Self Control: Predicting the Disposition Effect? *SSRN Electronic Journal*, 1–14. https://doi.org/10.2139/ssrn.2136922

Molins, F., Pérez-Calleja, T., Abad-Tortosa, D., Alacreu-Crespo, A., & Serrano-Rosa, M. Á. (2021). Positive emotion induction improves cardiovascular coping with a cognitive task. *PeerJ*, *9*(March). https://doi.org/10.7717/peerj.10904

Molins, F., & Serrano, M. A. (2019). Bases neurales de la aversión a las pérdidas en contextos económicos: revisión sistemática según las directrices PRISMA. *Revista de Neurología*, *68*(02), 47. https://doi.org/10.33588/rn.6802.2018276

Montero-López, E., Santos-Ruiz, A., García-Ríos, M. C., Rodríguez-Blázquez, R., Pérez-García, M., & Peralta-Ramírez, M. I. (2016). A virtual reality approach to the Trier Social Stress Test: Contrasting two distinct protocols. *Behavior Research Methods*, *48*(1), 223–232. https://doi.org/10.3758/s13428-015-0565-4

Morgan, M. S. (2006). Economic man as model man: Ideal types, idealization and caricatures. *Journal of the History of Economic Thought*, *28*(1), 1–27. https://doi.org/10.1080/10427710500509763

Mrkva, K., Johnson, E. J., Gächter, S., & Herrmann, A. (2020). Moderating Loss Aversion: Loss Aversion Has Moderators, But Reports of its Death are Greatly Exaggerated. *Journal of Consumer Psychology*, *30*(3), 407–428. https://doi.org/10.1002/JCPY.1156

Muda, R., Kicia, M., Michalak-Wojnowska, M., Ginszt, M., Filip, A., Gawda, P., & Majcher, P. (2018). The dopamine receptor d4 gene (Drd4) and financial risk-taking: Stimulating and instrumental risk-taking propensity and motivation to engage in investment activity. *Frontiers in Behavioral Neuroscience*, *12*(March), 1–10. https://doi.org/10.3389/fnbeh.2018.00034

Mullainathan, S., & Thaler, R. H. (2015). Behavioral Economics. *International Encyclopedia of the Social & Behavioral Sciences: Second Edition*, *3*, 437–442. https://doi.org/10.1016/B978-0-08-097086-8.71007-5

Murphy, C. M., Christakou, A., Giampietro, V., Brammer, M., Daly, E. M., Ecker, C., Johnston, P., Spain, D., Robertson, D. M., Murphy, D. G., & Rubia, K. (2017). Abnormal functional activation and maturation of ventromedial prefrontal cortex and cerebellum during temporal discounting in autism spectrum disorder. *Human Brain Mapping*, *38*(11), 5343–5355. https://doi.org/10.1002/HBM.23718

Nagaya, K. (2021). Why and Under What Conditions Does Loss Aversion Emerge? *Japanese Psychological Research*. https://doi.org/10.1111/jpr.12385

Pabst, S., Brand, M., & Wolf, O. T. (2013). Stress and decision making: A few minutes make all the difference. *Behavioural Brain Research*, *250*, 39–45. https://doi.org/10.1016/j.bbr.2013.04.046

Park, G., & Thayer, J. F. (2014). From the heart to the mind: Cardiac vagal tone modulates top-down and bottom-up visual perception and attention to emotional stimuli. *Frontiers in Psychology*, *5*(MAY), 1–8. https://doi.org/10.3389/fpsyg.2014.00278

Peterson, R. L. (2005). The neuroscience of investing: fMRI of the reward system. *Brain Research Bulletin*, *67*(5), 391–397. https://doi.org/10.1016/j.brainresbull.2005.06.015

Pollatos, O., Herbert, B. M., Matthias, E., & Schandry, R. (2007). Heart rate response after emotional picture presentation is modulated by interoceptive awareness. *International Journal of Psychophysiology*, *63*(1), 117–124. https://doi.org/10.1016/j.ijpsycho.2006.09.003

Pope, D. G., & Schweitzer, M. E. (2011). Is tiger woods loss averse? Persistent bias in the face of experience, competition, and high stakes. *American Economic Review*, *101*(1), 129–157. https://doi.org/10.1257/aer.101.1.129

Presti, S. Lo, Mattavelli, G., Canessa, N., & Gianelli, C. (2022). Risk perception and behaviour during the COVID-19 pandemic: Predicting variables of compliance with lockdown measures. *PLOS ONE*, *17*(1), e0262319. https://doi.org/10.1371/JOURNAL.PONE.0262319

Raab, M., & Gigerenzer, G. (2015). The power of simplicity: A fast-and-frugal heuristics approach to performance science. *Frontiers in Psychology*, *6*(OCT), 1–6. https://doi.org/10.3389/fpsyg.2015.01672

Rabin, M., & Thaler, R. H. (2001). Anomalies, Risk Aversion. *Journal of Economic Perspectives*, *15*(1), 219–232.

Rangel, A., Camerer, C., & Montague, P. R. (2008). A framework for studying the neurobiology of value-based decision making. *Nature Reviews Neuroscience*, *9*(7), 545–556.

Rolls, E. T., Zhou, Y., Cheng, W., Gilson, M., Deco, G., & Feng, J. (2020). Effective connectivity in autism. *Autism Research*, *13*(1), 32–44. https://doi.org/10.1002/AUR.2235

Rozenkrantz, L., D'Mello, A. M., & Gabrieli, J. D. E. (2021). Enhanced rationality in autism spectrum disorder. *Trends in Cognitive Sciences*, *25*(8), 685–696. https://doi.org/10.1016/J.TICS.2021.05.004

Saaty, T. L., & Ozdemir, M. S. (2003). Why the magic number seven plus or minus two. *Mathematical and Computer Modelling*, *38*(3–4), 233–244.

Sagiv, E., Hadlaczky, G., Sheetrit, N., Gur, E., Horesh, N., & Gvion, Y. (2019). The Fear of Losing—Nonsuicidal Self-Injury as a Protective Mechanism in Eating Disorders. *Frontiers in Psychiatry*, *10*(November), 1–11. https://doi.org/10.3389/fpsyt.2019.00825

Salehinejad, M. A., Paknia, N., Hosseinpour, A. H., Yavari, F., Vicario, C. M., Nitsche, M. A., & Nejati, V. (2021). Contribution of the right temporoparietal junction and ventromedial prefrontal cortex to theory of mind in autism: A randomized, sham-controlled tDCS study. *Autism Research*, *14*(8), 1572–1584. https://doi.org/10.1002/AUR.2538

Santl, J., Shiban, Y., Plab, A., Wüst, S., Kudielka, B. M., & Mühlberger, A. (2019). Gender Differences in Stress Responses during a Virtual Reality Trier Social Stress Test. *International Journal of Virtual Reality*, *19*(2), 2–15. https://doi.org/10.20870/ijvr.2019.19.2.2912

Santos, L. R., & Rosati, A. G. (2015). The evolutionary roots of human decision making. *Annual Review of Psychology*, *66*, 321–347. https://doi.org/10.1146/annurev-psych-010814-015310

Schmidt, K. L., Ambadar, Z., Cohn, J. F., & Reed, L. I. (2006). Movement differences between deliberate and spontaneous facial expressions: Zygomaticus major action in smiling. *Journal of Nonverbal Behavior*, *30*(1), 37–52. https://doi.org/10.1007/s10919-005-0003-x

Scott, D. J., Heitzeg, M. M., Koeppe, R. A., Stohler, C. S., & Zubieta, J.-K. (2006). Variations in the human pain stress experience mediated by ventral and dorsal basal ganglia dopamine activity. *Journal of Neuroscience*, *26*(42), 10789–10795.

Serrano, M. Á., Molins, F., & Alacreu-Crespo, A. (2022). Human Decision-Making Evaluation: From Classical Methods to Neurocomputational Models. In *Algorithms and Computational Techniques Applied to Industry* (pp. 163–181). Springer.

Shah, P., Catmur, C., & Bird, G. (2016). Emotional decision-making in autism spectrum disorder: the roles of interoception and alexithymia. *Molecular Autism*, *7*, 43. https://doi.org/10.1186/s13229-016-0104-x

Shah, P., Hall, R., Catmur, C., & Bird, G. (2016). Alexithymia, not autism, is associated with impaired interoception. *Cortex*, *81*, 215–220. https://doi.org/10.1016/j.cortex.2016.03.021

Sheng, F., Ramakrishnan, A., Seok, D., Zhao, W. J., Thelaus, S., Cen, P., & Platt, M. L. (2020). Decomposing loss aversion from gaze allocation and pupil dilation. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(21). https://doi.org/10.1073/pnas.1919670117

Shiban, Y., Diemer, J., Brandl, S., Zack, R., Mühlberger, A., & Wüst, S. (2016). Trier Social Stress Test in vivo and in virtual reality: Dissociation of response domains. *International Journal of Psychophysiology*, *110*, 47–55. https://doi.org/10.1016/j.ijpsycho.2016.10.008

Simon, H. A. (1955). A behavioral model of rational choice. *Quarterly Journal of Economics*, *69*(1), 99–118. https://doi.org/10.2307/1884852

Simon, H. A. (1956). Rational choice and the structure of the environment. *Psychological Review*, *63*(2).

Simon, H. A. (1990). Invariants of human behavior. *Annual Review of Psychology*, *41*(1), 1–20.

Sip, K. E., Gonzalez, R., Taylor, S. F., & Stern, E. R. (2018). Increased loss aversion in unmedicated patients with obsessive-compulsive disorder. *Frontiers in Psychiatry*, *8*(JAN), 1–10. https://doi.org/10.3389/fpsyt.2017.00309

Smith, A. (1776). *The Wealth of Nations*.

Sokol-Hessner, P., Camerer, C. F., & Phelps, E. A. (2013). Emotion regulation reduces loss aversion and decreases amygdala responses to losses. *Social Cognitive and Affective Neuroscience*, *8*(3), 341–350. https://doi.org/10.1093/scan/nss002

Sokol-Hessner, P., Hsu, M., Curley, N. G., Delgado, M. R., Camerer, C. F., & Phelps, E. A. (2009). Thinking like a trader selectively reduces individuals' loss aversion. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(13), 5035–5040. https://doi.org/10.1073/pnas.0806761106

Sokol-Hessner, P., & Rutledge, R. B. (2019). The Psychological and Neural Basis of Loss Aversion. *Current Directions in Psychological Science*, *28*(1), 20–27. https://doi.org/10.1177/0963721418806510

St-Aubin, M. O., Chalaye, P., Counil, F. P., & Lafrenaye, S. (2019). Beneficial effects of regular physical activity on exercise-induced analgesia in adolescent males. *Pediatric Exercise Science*, *31*(4), 425–431. https://doi.org/10.1123/pes.2018-0089

Stancak, A., Xie, Y., Fallon, N., Bulsing, P., Giesbrecht, T., Thomas, A., & Pantelous, A. A. (2015). Unpleasant odors increase aversion to monetary losses. *Biological Psychology*, *107*, 1–9. https://doi.org/10.1016/j.biopsycho.2015.02.006

Starcke, K., & Brand, M. (2012). Decision making under stress: A selective review. *Neuroscience and Biobehavioral Reviews*, *36*(4), 1228–1248. https://doi.org/10.1016/j.neubiorev.2012.02.003

Starcke, K., & Brand, M. (2016). Effects of stress on decisions under uncertainty: A meta-analysis. *Psychological Bulletin*, *142*(9), 909–933. https://doi.org/10.1037/bul0000060

Stein, M. B., Simmons, A. N., Feinstein, J. S., & Paulus, M. P. (2007). Increased Amygdala and Insula Activation During Emotion Processing in Anxiety-Prone Subjects. *American Journal of Psychiatry*, *164*, 318–327.

Stevens, F. L., Hurley, R. A., & Taber, K. H. (2011). Anterior cingulate cortex: Unique role in cognition and emotion. *Journal of Neuropsychiatry and Clinical Neurosciences*, *23*(2), 121–125. https://doi.org/10.1176/jnp.23.2.jnp121

Sunstein, C. R. (2014). *Why nudge?: The politics of libertarian paternalism*. Yale University Press.

Sutherland, M. T., Carroll, A. J., Salmeron, B. J., Ross, T. J., & Stein, E. A. (2013). Insula's functional connectivity with ventromedial prefrontal cortex mediates the impact of trait alexithymia on state tobacco craving. *Psychopharmacology*, *228*(1), 143–155. https://doi.org/10.1007/s00213-013-3018-8

Sütterlin, S., Herbert, C., Schmitt, M., Kübler, A., & Vögele, C. (2011). Frames, decisions, and cardiac-autonomic control. *Social Neuroscience*, *6*(2), 169–177. https://doi.org/10.1080/17470919.2010.495883

Swart, M., Kortekaas, R., & Aleman, A. (2009). Dealing with feelings: Characterization of trait Alexithymia on emotion regulation strategies and cognitive-emotional processing. *PLoS ONE*, *4*(6). https://doi.org/10.1371/journal.pone.0005751

Swartz, J. R., Wiggins, J. L., Carrasco, M., Lord, C., & Monk, C. S. (2013). Amygdala Habituation and Prefrontal Functional Connectivity in Youth With Autism Spectrum Disorders. *Journal of the American Academy of Child & Adolescent Psychiatry*, *52*(1), 84–93. https://doi.org/10.1016/J.JAAC.2012.10.012

Takahashi, H., Fujie, S., Camerer, C., Arakawa, R., Takano, H., Kodaka, F., Matsui, H., Ideno, T., Okubo, S., Takemura, K., Yamada, M., Eguchi, Y., Murai, T., Okubo, Y., Kato, M., Ito, H., & Suhara, T. (2013). Norepinephrine in the brain is associated with aversion to financial loss. *Molecular Psychiatry*, *18*(1), 3–4. https://doi.org/10.1038/mp.2012.7

Thaler, R. H. (2017). The rise of behavioural economics. *Nature Human Behaviour*, *1*(11), 767. https://doi.org/10.1038/s41562-017-0252-9

Thaler, R. H. (2018). Behavioral economics: Past, present, and future. *Revista de Economia Institucional*, *20*(38), 9–43. https://doi.org/10.18601/01245996.v20n38.02

Thaler, R. H., & Sunstein, C. R. (2003). Libertarian paternalism. *American Economic Review*, *93*(2), 175–179. https://doi.org/10.1257/000282803321947001

Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart-brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, *33*(2), 81–88. https://doi.org/10.1016/j.neubiorev.2008.08.004

Thrailkill, E. A., DeSarno, M., & Higgins, S. T. (2022). Loss aversion and risk for cigarette smoking and other substance use. *Drug and Alcohol Dependence*, *232*, 109307.

Tom, S. M., Fox, C. R., Trepel, C., & Poldrack, R. A. (2007). The neural basis of loss aversion in decision-making under risk. *Science*, *315*(5811), 515–518. https://doi.org/10.1126/science.1134239

Trovato, A. N. (2019). *Social Decision-Making in Individuals With Autism Spectrum Disorder: Examining the Effect of Facial Expression on Ultimatum Game Decisions*. Indiana University of Pennsylvania.

Tversky, A., & Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *Science*, *185*(4157), 1124–1131.

Tversky, A., & Kahneman, D. (1989). Rational choice and the framing of decisions. In *Multiple criteria decision making and risk analysis using microcomputers* (pp. 81–126). Springer.

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of

uncertainty. *Journal of Risk and Uncertainty*, *5*(4), 297–323.

Vaish, A., Grossmann, T., & Woodward, A. (2008). Not All Emotions Are Created Equal: The Negativity Bias in Social-Emotional Development. *Psychological Bulletin*, *134*(3), 383–403. https://doi.org/10.1037/0033-2909.134.3.383

van den Bos, R., Harteveld, M., & Stoop, H. (2009). Stress and decision-making in humans: Performance is related to cortisol reactivity, albeit differently in men and women. *Psychoneuroendocrinology*, *34*(10), 1449–1458. https://doi.org/10.1016/j.psyneuen.2009.04.016

Venta, A., Hart, J., & Sharp, C. (2013). The relation between experiential avoidance, alexithymia and emotion regulation in inpatient adolescents. *Clinical Child Psychology and Psychiatry*, *18*(3), 398–410. https://doi.org/10.1177/1359104512455815

Viswanathan, V., Lee, S., Gilman, J. M., Kim, B. W., Lee, N., Chamberlain, L., Livengood, S. L., Raman, K., Lee, M. J., Kuster, J., Stern, D. B., Calder, B., Mulhern, F. J., Blood, A. J., & Breiter, H. C. (2015). Age-related striatal BOLD changes without changes in behavioral loss aversion. *Frontiers in Human Neuroscience*, *9*(APR), 1–12. https://doi.org/10.3389/fnhum.2015.00176

Voigt, G., Montag, C., Markett, S., & Reuter, M. (2015). On the genetics of loss aversion: An interaction effect of BDNF Val66Met and DRD2/ANKK1 Taq1a. *Behavioral Neuroscience*, *129*(6), 801–811. https://doi.org/10.1037/bne0000102

Volz, K. G., & Gigerenzer, G. (2012). Cognitive processes in decisions under risk are not the same as in decisions under uncertainty. *Frontiers in Neuroscience*, *6*(JULY), 1–6. https://doi.org/10.3389/fnins.2012.00105

von Neumann, J., & Morgenstern, O. (1944). *Theory of games and economic behavior*. Princeton University Press. https://doi.org/10.1090/s0273-0979-99-00832-0

Vuilleumier, P. (2005). How brains beware: Neural mechanisms of emotional attention. *Trends in Cognitive Sciences*, *9*(12), 585–594. https://doi.org/10.1016/j.tics.2005.10.011

Wagels, L., Votinov, M., Radke, S., Clemens, B., Montag, C., Jung, S., & Habel, U. (2017). Blunted insula activation reflects increased risk and reward seeking as an interaction of testosterone administration and the MAOA polymorphism. *Human Brain Mapping*, *38*(9), 4574–4593. https://doi.org/10.1002/hbm.23685

Walker, S., O'Connor, D. B., & Schaefer, A. (2011). Brain potentials to emotional pictures are modulated by alexithymia during emotion regulation. *Cognitive, Affective and Behavioral Neuroscience*, *11*(4), 463–475. https://doi.org/10.3758/s13415-011-0042-1

Wang, M., Rieger, M. O., & Hens, T. (2017). The Impact of Culture on Loss Aversion. *Journal of Behavioral Decision Making*, *30*(2), 270–281. https://doi.org/10.1002/bdm.1941

Wang, Y., Luan, S., & Gigerenzer, G. (2022). Modeling fast-and-frugal heuristics. *PsyCh Journal*, *May*, 1–12. https://doi.org/10.1002/pchj.576

Wangelin, B. C., Löw, A., McTeague, L. M., Bradley, M. M., & Lang, P. J. (2011). Aversive picture processing: Effects of a concurrent task on sustained defensive system engagement. *Psychophysiology*, *48*(1), 112–116. https://doi.org/10.1111/j.1469-8986.2010.01041.x

Ward, G., Collins, H., Norton, M. I., & Whillans, A. V. (2020). *Work values shape the relationship between stress and (un) happiness*. Harvard Business School.

Watson, D., Clark, L., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*, 1063–1070.

Wise, R. A. (2002). Brain reward circuitry: Insights from unsensed incentives. *Neuron*, *36*(2), 229–240. https://doi.org/10.1016/S0896-6273(02)00965-0

Wood, P. B., Schweinhardt, P., Jaeger, E., Dagher, A., Hakyemez, H., Rabiner, E. A., Bushnell, M. C., & Chizh, B. A. (2007). Fibromyalgia patients show an abnormal dopamine response to pain. *European Journal of Neuroscience*, *25*(12), 3576–3582.

Wu, Y., Van Dijk, E., Aitken, M., & Clark, L. (2016). Missed losses loom larger than missed gains: Electrodermal reactivity to decision choices and outcomes in a gambling task. *Cognitive, Affective and Behavioral Neuroscience*, *16*(2), 353–361. https://doi.org/10.3758/s13415-015-0395-y

Zaki, J., Davis, J. I., & Ochsner, K. N. (2012). Overlapping activity in anterior insula during interoception and emotional experience. *Neuroimage*, *62*(1), 493–499. https://doi.org/10.1016/j.neuroimage.2012.05.012.Overlapping

Zamariola, G., Vlemincx, E., Luminet, O., & Corneille, O. (2018). Relationship between interoceptive accuracy, interoceptive sensibility, and alexithymia. *Personality and Individual Differences*, *125*(January 2018), 14–20. https://doi.org/10.1016/j.paid.2017.12.024

Zeelenberg, R., Wagenmakers, E. J., & Rotteveel, M. (2006). The impact of emotion on perception: Bias or enhanced processing? *Psychological Science*, *17*(4), 287–291. https://doi.org/10.1111/j.1467-9280.2006.01700.x

Zhang, L., Wang, X., Zhu, Y., Li, H., Zhu, C., Yu, F., & Wang, K. (2017). Selective impairment of decision making under ambiguity in alexithymia. *BMC Psychiatry*, *17*(1), 1–8. https://doi.org/10.1186/s12888-017-1537-2

Zhao, Y. (2012). R and Data Mining: Examples and Case Studies. *R and Data Mining: Examples and Case Studies*, *December 2012*, 1–234. https://doi.org/10.1016/C2011-0-06686-3

Zhong, S., Israel, S., Xue, H., Sham, P. C., Ebstein, R. P., & Chew, S. H. (2009). A neurochemical approach to valuation sensitivity over gains and losses. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1676), 4181–4188. https://doi.org/10.1098/rspb.2009.1312

Section 5: Appendix

Resumen en español / Summary in Spanish

Introducción

El criterio normativo que impera a la hora de evaluar si tomamos buenas decisiones es la racionalidad económica, derivada de las teorías económicas clásicas y del modelo por el que éstas se rigen: el *homo economicus*. Este criterio ha recibido múltiples críticas en sus más de doscientos años de vida, siendo Kahneman y Tversky, con su Teoría Prospectiva, quienes parecían haberle asestado el golpe más duro al demostrar que las decisiones humanas se ven afectadas por sesgos cognitivos que nos alejan de ser racionales. No obstante, lejos de cuestionarse si el criterio normativo era inadecuado para representar la naturaleza humana, interpretaron que los sesgos son errores que deben frenarse para que nos ajustemos a ese criterio y, ahora sí, logremos ser racionales. Así, la racionalidad económica continuó más viva que nunca. Hoy son muchas más las críticas sobre lo abstracto —incluso irreal— que es el criterio de racionalidad económica. De ellas se originan importantes líneas de investigación que, en las últimas décadas, están enriqueciendo el campo de estudio de la toma de decisiones. Por un lado, más allá de meramente identificar y etiquetar los sesgos, los enfoques actuales pretenden descifrar su naturaleza: sus posibles bases psicobiológicas y el porqué de su manifestación. También se centran en descubrir qué factores modulan su expresión y analizan qué papel juega un determinado sesgo en distintos entornos, pues lejos de ser siempre negativos, podrían aportar una ventaja adaptativa en ciertos contextos. Este enfoque constituye el marco teórico de esta tesis doctoral. Desde la misma se pretende arrojar luz al campo de estudio de la toma de decisiones siguiendo la estela de los estudios a la vanguardia. Sin embargo, aun con las líneas bien definidas, este campo continúa siendo muy amplio y es necesario acotarlo. Así, de entre la cantidad de sesgos cognitivos que afectarían al proceso decisional, hemos decidido focalizar la tesis en el más destacable de todos. Pilar central de la Teoría Prospectiva y base de otros muchos sesgos que dependen de este fenómeno, estamos hablando de la *aversión a las pérdidas*.

El sesgo de aversión a las pérdidas es el fenómeno según el cual las pérdidas pesan más que las ganancias. Específicamente, la literatura científica señala que las pérdidas tendrían de 2 a 2.5 veces más impacto psicológico que las ganancias proporcionales. Así, cuando enfrentamos una decisión que entraña una potencial ganancia versus una potencial pérdida, la magnitud de la primera debería ser el doble de grande que la segunda para que, ganancia y pérdida, sean procesadas de forma proporcional. De igual forma, el dolor que produciría perder una cantidad sería aproximadamente el doble que el placer que

produciría ganar esa misma cantidad. En consecuencia, debido al sesgo de aversión a las pérdidas, nos moveremos con mayor facilidad hacia la evitación de las pérdidas que hacia la búsqueda de ganancias, condicionando nuestras decisiones.

La forma habitual de medir la aversión a las pérdidas es a través de tareas decisionales simples o de riesgo, siendo las más frecuentes las que plantean apuestas mixtas donde hay un 50% de probabilidad de ganar y un 50% de perder. Las cuantías económicas que pueden ganarse/perderse van cambiando en cada ensayo y generan distintos escenarios más o menos favorables donde cada participante debe decidir si jugar la apuesta o rechazarla. Basándose en las respuestas que los participantes vayan dando a las distintas apuestas se estimaría la conducta de aversión a las pérdidas mediante el cálculo del parámetro λ. Además, hoy en día también es posible evaluar la aversión a las pérdidas en otras tareas decisionales más complejas o ambiguas gracias al reciente desarrollo de modelos computacionales que permiten desgranar el complejo proceso decisional en sus distintos subprocesos cognitivos, siendo uno de los principales la propia aversión a las pérdidas.

La neurociencia ha descubierto una base neural estable para la aversión a las pérdidas, relacionándola con el sistema límbico y las emociones. Los estudios de neuroimagen revelan que nuestro cerebro tiene un sistema aversivo que responde de manera desproporcionada a las pérdidas en comparación con cómo responde un sistema apetitivo ante las ganancias. En la misma línea, la genética también podría influir en la expresión de la aversión a las pérdidas a través de ciertos genes relacionados con la neurotransmisión dopaminérgica y serotoninérgica, que a su vez reforzarían el posible origen emocional de este sesgo. No obstante, estos estudios son escasos y todavía no hay conclusiones firmes. También se ha planteado de forma teórica la conexión entre la aversión a las pérdidas y otro fenómeno emocional más básico: el sesgo de negatividad, que se refiere a una mayor sensibilidad a los estímulos emocionales negativos en comparación con los positivos; pero hasta la fecha no se ha demostrado empíricamente esta conexión. Por último, se ha sugerido que la interocepción y la alexitimia, variables que juegan un importante papel en la regulación emocional, podrían también modular la influencia de las emociones en nuestras decisiones y, por ende, la expresión de sesgos como la aversión a las pérdidas. Sin embargo, nunca se ha estudiado la interacción entre estas variables, ni explorado en profundidad los mecanismos por los que operan sobre el proceso decisional. Por todo ello, se necesita más investigación para comprender mejor

el origen emocional de la aversión a las pérdidas, su conexión con el sesgo de negatividad, y los mecanismos subyacentes que la modulan.

Por otro lado, además de la interocepción y la alexitimia, hay muchos factores que pueden influir en la expresión de la aversión a las pérdidas. Uno de los más estudiados es el estrés. Sin embargo, existen dos hipótesis opuestas sobre cómo el estrés afecta sobre este sesgo. La hipótesis de "salience-of-losses" propone que el estrés agudo favorece la activación de la red de saliencia en el cerebro, lo que aumentaría la aversión a las pérdidas. Por otro lado, la hipótesis de "reward alignment" sugiere que el estrés potencia las vías dopaminérgicas y la actividad de los centros de recompensa cerebrales, lo que podría equilibrar la susceptibilidad a las ganancias y las pérdidas, reduciendo la aversión a estas últimas. Aun contrarias, estas hipótesis podrían no ser excluyentes y estar reflejando diferentes fases de estrés, dependiendo de las vías fisiológicas activadas. Además, es necesario tener en cuenta que, según su naturaleza, los distintos estresores pueden variar en la expresión y magnitud de sus respuestas fisiológicas y psicológicas. Por lo tanto, es importante estudiar cómo diferentes tipos y etapas de estrés influyen sobre la aversión a las pérdidas para obtener respuestas más específicas sobre su modulación.

Por último, hasta ahora hemos hablado de la aversión a las pérdidas sin considerar si este fenómeno es adaptativo o no. Sin embargo, algunos estudios investigan si la aversión a las pérdidas puede ser beneficiosa para la toma de decisiones en lugar de ser un sesgo que conduce a decisiones erróneas. Algunos teorizan que este sesgo ha sido seleccionado evolutivamente debido a su función conservadora, que ayuda a evitar peligros en lugar de buscar recompensas. Y otros han demostrado empíricamente que la aversión a las pérdidas puede ser necesaria para que se produzca aprendizaje por reforzamiento en contextos complejos y, además, que podría constituir un factor protector frente a comportamientos desadaptativos, como las adicciones, las autoagresiones o el mismismo suicidio. A pesar de estas evidencias, se requiere más investigación para confirmar el papel adaptativo de este sesgo y comprender mejor cómo se comporta en diferentes contextos.

Así pues, en base a todo lo anterior, esta tesis doctoral persigue el objetivo general de conocer más acerca de la naturaleza del sesgo de aversión a las pérdidas y su potencial papel adaptativo. Por qué, cómo y cuándo se expresa este sesgo, así como en qué contextos nos puede ser favorable, son las preguntas a partir de las cuales se derivan los objetivos más específicos de la tesis.

Objetivos y metodología

Evidenciando el origen emocional de la aversión a las pérdidas

El primer objetivo de la tesis se centra en recopilar más evidencia que aclare el posible origen emocional de la aversión a la pérdida. Antes de comenzar el programa de doctorado, nuestro equipo realizó una revisión sistemática sobre la base neural de este sesgo, la cual ya indicaba la participación del sistema límbico en el procesamiento desequilibrado de las ganancias y las pérdidas. Ahora, la tesis comienza con una nueva revisión sistemática siguiendo el método PRISMA —Estudio 1—, esta vez sobre las bases genéticas que podrían respaldar este sesgo. Ésta recopila estudios publicados que abordan cómo diversos polimorfismos se relacionan con una mayor o menor expresión de aversión a las pérdidas y analiza si los genes implicados también están relacionados con nuestro sistema afectivo y la expresión de las emociones. Dada la escasez de estudios genéticos específicamente enfocados en la aversión a las pérdidas, esta revisión también incluye otros fenómenos estrechamente vinculados a ella: la aversión al riesgo y el efecto marco.

Por otro lado, aunque en línea con el mismo objetivo, se llevó a cabo el Estudio 2, que aborda de manera empírica si el sesgo de negatividad, medido mediante la tarea *Face Rating* y utilizando el software *Mouse Tracker* para captar también su posible manifestación implícita, podría predecir los niveles de aversión a las pérdidas —medida con la tarea *Lottery Choice*—. Si este es el caso, las personas con mayor sensibilidad hacia los estímulos negativos también deberían mostrar una mayor aversión a la pérdida. El Estudio 2 examina estas ideas y ofrece más información sobre el origen emocional de la aversión a las pérdidas.

Finalmente, si la aversión a las pérdidas tiene un origen emocional, su expresión podría verse influenciada por la capacidad del individuo para regular sus emociones. Varios estudios ya han explorado esta idea y han encontrado que una mayor regulación emocional, medida a través de cuestionarios o fisiología periférica como la variabilidad de la frecuencia cardíaca, se asocia con niveles más bajos de aversión a la pérdida durante tareas de toma de decisiones económicas. Sin embargo, para comprender mejor los orígenes de la aversión a la pérdida, es necesario explorar los mecanismos específicos que subyacen a esta relación. En el Estudio 3, investigamos cómo la interocepción —medida mediante la tarea *Heart beat tracking*— y la alexitimia —medida mediante el cuestionario de alexitimia de Toronto—, interactúan entre sí y se relacionan con la toma

de decisiones emocionales: es decir, si las decisiones se ven afectadas en mayor o menor medida por sesgos como la aversión a la pérdida. El Estudio 3 aborda la aversión a las pérdidas a través de una tarea de efecto marco, que plantea apuestas económicas en contextos positivos y negativos.

Analizando cómo el estrés modula la expresión de la aversión a las pérdidas

La manifestación de la aversión a la pérdida no es tan ubicua ni estable como se creía originalmente. Uno de los factores más estudiados que afecta en su expresión es el estrés, pero hasta ahora los resultados obtenidos han sido heterogéneos. Para arrojar luz sobre la relación entre el estrés y la aversión a las pérdidas, esta tesis doctoral incluye cinco estudios que examinan la influencia de diferentes estresores sobre este sesgo.

Los dos primeros estudios examinan los efectos de un estresor agudo en su fase temprana, específicamente 5 minutos después de su inicio. El estudio 4 utiliza ejercicio vigoroso —en un cicloergómetro— como estresor físico que desencadena estrés fisiológico, pero que no afecta el estado de ánimo ni la percepción subjetiva del estrés. Por otro lado, el estudio 5 utiliza un video de una circuncisión como estresor emocional que induce tanto estrés fisiológico como psicológico. Ambos estudios tienen como objetivo investigar si las dos dimensiones del estrés, fisiológica y psicológica, tienen diferentes efectos en la aversión a las pérdidas, medida mediante una tarea de apuestas mixtas. En contraste, el estudio 6 se centra en la fase tardía del estrés agudo, específicamente 30 minutos después del inicio del estresor. Este estudio utiliza el prominente *Trier Social Stress test*, que se considera el estándar los estresores de laboratorio, y tiene como objetivo investigar si la fase posterior del estrés tiene un impacto diferente en la aversión a las pérdidas en comparación con la fase temprana.

Los tres estudios emplean estresores agudos de laboratorio que han concluido en el momento en que se evalúa la toma de decisiones. Sin embargo, la influencia de estos estresores puede diferir de la de los estresores naturales que ocurren fuera del laboratorio y que aún están presentes durante el proceso decisional. El estudio 7 fue diseñado para abordar este problema durante el contexto de la pandemia de COVID-19. Examinamos si la situación de la pandemia y las medidas de confinamiento eran estresores capaces de causar malestar psicológico. Después de confirmarlo mediante el cuestionario breve *General Health*, investigamos cómo este malestar afectaba a la aversión a las pérdidas,

medida antes y durante el confinamiento mediante la misma tarea que el estudio 2, la *Lottery Choice*.

Por último, los estudios mencionados anteriormente, bien sea a través de las apuestas mixtas o de las *Lottery Choice*, evaluaban la aversión a las pérdidas en contextos decisionales simples, donde los posibles resultados y sus probabilidades están bien definidos. Sin embargo, los procesos cognitivos pueden diferir durante las decisiones en contextos más complejos. Por lo tanto, el impacto del estrés en estos contextos también puede diferir. Con la ayuda de modelos computacionales recientes que nos permiten estimar el nivel de aversión a la pérdida en estos contextos complejos llevamos a cabo el estudio 8. En él se utiliza nuevamente ejercicio vigoroso como estresor fisiológico agudo en su fase inicial, pero emplea el *Iowa Gambling Task* (IGT) —una tarea decisional compleja que pone de manifiesto la necesidad de otras funciones cognitivas, como el aprendizaje por reforzamiento—, para ver cómo el estrés influye sobre la aversión a las pérdidas en este contexto.

Explorando el potencial rol adaptativo de la aversión a las pérdidas

La aversión a las pérdidas ha sido considerada durante mucho tiempo un sesgo con implicaciones negativas para nuestra capacidad de tomar decisiones lógicas. Sin embargo, investigaciones recientes sugieren la aversión a las pérdidas puede tener un valor adaptativo y servir a una racionalidad biológica, especialmente cuando nos enfrentamos a decisiones complejas en las que la intuición puede ser más valiosa que la razón. Esta tesis doctoral tiene como objetivo explorar esta cuestión desde diferentes perspectivas.

Por un lado, el Estudio 1 en sí mismo, al revisar las bases genéticas de la aversión a la pérdida, también proporcionaría evidencia de que este fenómeno está arraigado en nuestros genes y, por lo tanto, dado que se habría conservado a través de selección natural, puede tener algún valor adaptativo para nuestra especie. Si bien este estudio no proporcionaría un vínculo directo entre la aversión a las pérdidas y las decisiones adaptativas, busca enfatizar que los sesgos pueden ser parte de nuestra naturaleza más básica. Por otro lado, Estudio 2, además de relacionar la aversión a las pérdidas con el sesgo de negatividad, también intenta mostrar que este último puede ser muy útil en entornos decisionales complejos. Así, dado que las personas con un mayor sesgo de negatividad tendrían una mayor sensibilidad a los estímulos negativos, también deberían

ser más sensibles a los castigos —e.g., pérdidas económicas— que sufren durante una tarea decisional compleja como IGT. Esto contribuiría a un mejor aprendizaje por refuerzo a lo largo de la tarea. Si el sesgo de negatividad subyace a la aversión a las pérdidas, considerada un error decisional en entornos simples como las apuestas económicas, y a su vez mejora las decisiones en entornos complejos como el *Iowa Gambling Task*, esto constituiría una evidencia a favor del enfoque de racionalidad ecológica. Es decir, el mismo sesgo puede ser bueno o malo, adaptativo o desadaptativo, dependiendo del entorno en el que se analice. Por otro lado, volviendo al Estudio 3, que abordaba si el estrés agudo afecta la toma de decisiones en un entorno complejo como el propuesto en IGT, este estudio nos permite no solo probar si el nivel de aversión a las pérdidas se ve alterado por el estrés, sino también estudiar cómo se relaciona esta alteración con el resto del proceso decisional. Es decir, nos permite comprobar si un aumento o disminución de la aversión a las pérdidas a causa del estrés, beneficia o dificulta la toma de decisiones en IGT.

Finalmente, analizar cómo la ausencia de aversión a las pérdidas afecta a una población que tiende a no manifestar este fenómeno, como las personas con trastorno del espectro autista, puede proporcionar ideas sobre el posible papel adaptativo de este sesgo. Las personas con autismo tienden a tomar decisiones más lógicas en contextos individuales, menos influenciadas por sesgos como la aversión a las pérdidas. Así, según los modelos económicos, las personas con autismo tomarían decisiones racionales y, por lo tanto, adecuadas. Sin embargo, estas mismas personas a menudo tienen dificultades para adaptarse al entorno, especialmente al tomar decisiones con un componente social, como las que plantea el *Ultimatum Game*, caracterizándose por un utilitarismo excesivo. Sin embargo, hasta donde sabemos, nunca se ha probado empíricamente si la menor ocurrencia de sesgos en las decisiones individuales está asociada con el mayor utilitarismo en los contextos sociales. El Estudio 9 trata de arrojar luz sobre esta cuestión, testando si la menor aversión a las pérdidas de una población con autismo, medida mediante una tarea de efecto marco, es capaz de predecir las decisiones más utilitarias en un contexto social como el *Ultimatum Game*.

Conclusiones

Esta tesis doctoral cumple su propósito de proporcionar una perspectiva más positiva sobre los sesgos cognitivos, particularmente el sesgo de aversión a las pérdidas. Como se ha introducido, los sesgos han sido *demonizados* desde su origen, siendo vistos

como fenómenos limitantes en nuestros juicios y decisiones. El propio término *sesgo* implica una distorsión, una desviación respecto la norma que representa la racionalidad clásica derivada de los modelos económicos. Gracias a nuevas líneas de investigación en la toma de decisiones, en las cuales esta tesis aporta su *granito de arena*, ahora sabemos que esa racionalidad es solo una de las muchas normas posibles y puede no ser la más adecuada dependiendo del contexto decisional. El grado de adaptabilidad, satisfacción, aprendizaje por refuerzo, impulsividad, flexibilidad cognitiva e incluso la propensión a buscar ayuda cuando carecemos de suficiente conocimiento, todos constituyen posibles criterios a considerar al evaluar la capacidad de toma de decisiones de los individuos. Es bajo estos criterios, precisamente, cuando sesgos como la aversión a las pérdidas pueden resultar particularmente necesarios. Aunque pueden llevarnos a decisiones ilógicas desde el enfoque de la racionalidad económica, también pueden tener un valor adaptativo y proporcionar apoyo en contextos ambiguos donde la lógica se ve superada. Por ejemplo, como puede verse en esta tesis, la aversión a las pérdidas podría aumentar nuestra sensibilidad hacia estímulos amenazantes o desfavorables, facilitando su evitación y favoreciendo decisiones más adaptativas. Por lo tanto, en lugar de intentar suprimir los sesgos de forma predeterminada, es aconsejable adquirir más conocimiento sobre ellos: por qué se originan, cuál es su naturaleza, en qué contextos aparecen con mayor prominencia, qué factores condicionan su expresión y en qué contextos sirven como apoyo o, por el contrario, es mejor tratar de suprimirlos y guiarse por la pura lógica. Esta tesis profundizó en estas preguntas y, como conclusión, se resumen a continuación los principales hallazgos:

- La aversión a la pérdida podría ser una respuesta emocional al dolor causado por las pérdidas, que generalmente es más intenso que el placer derivado de las ganancias proporcionales.

- Este origen emocional se apoya en la actividad neural desproporcionada que subyace a la aversión a las pérdidas: las regiones asociadas con el sistema límbico tienden a responder de manera más intensa a las pérdidas que a las ganancias.

- Tal vez la respuesta específica a las pérdidas se aprenda, pero podría basarse en una tendencia innata a priorizar el procesamiento de estímulos percibidos como negativos sobre aquellos percibidos como positivos. En otras palabras, la aversión a las pérdidas podría ser una extensión de un fenómeno emocional más básico: el sesgo de negatividad.

- La potencial base genética de la aversión a las pérdidas podría respaldar esta tendencia innata, así como la naturaleza emocional de este fenómeno. Los genes involucrados en el funcionamiento de las vías dopaminérgicas y serotoninérgicas, ambos cruciales en la regulación de los procesos emocionales, están asociados con una mayor o menor tendencia a expresar aversión a las pérdidas en función de los alelos que adoptan diversos polimorfismos.

- Del mismo modo, las personas con una mayor capacidad para regular sus emociones, influenciadas por sus habilidades interoceptivas y niveles de alexitimia, podrían modular mejor la expresión de sesgos durante la toma de decisiones. Como podemos ver, los sesgos como la aversión a las pérdidas no serían ubicuos ni estables, sino más bien modulados por factores internos y externos, siendo el estrés uno de los más estudiados.

- La influencia del estrés en los sesgos es heterogénea, dependiendo de las características del estresor y de la fase temporal en la que se evalúa la toma de decisiones con respecto al inicio del mismo.

- En general, esta tesis demuestra que el estrés agudo puede reducir la aversión a la pérdida. Sin embargo, los mecanismos detrás de esta reducción pueden variar. En etapas muy tempranas del estrés, el ligero aumento de las catecolaminas podría potenciar la actividad neural de la corteza prefrontal y, a su vez, el pensamiento lógico, reduciendo así la aversión a las pérdidas. En etapas posteriores, el cortisol podría potenciar la actividad de los centros de recompensa, aumentar la atracción por las ganancias y atenuar el dolor de las pérdidas, produciendo el mismo resultado que en la fase temprana, pero por otra vía. Estos mecanismos deben ser verificados en investigaciones futuras, al igual que si otras fases intermedias producen efectos diferentes.

- Por otro lado, el estrés más persistente o crónico, como el experimentado durante la pandemia de COVID-19, podría tener un impacto diferente. Este estrés se asocia con un aumento en los síntomas de depresión y ansiedad, que tienden a llevar a un aumento en la aversión a las pérdidas. Las investigaciones futuras deberían determinar si este aumento representa el inicio de una toma de decisiones desadaptativa típicamente observada en estos trastornos.

- De hecho, los nuevos estudios deberían analizar el contexto decisional para obtener conclusiones más precisas sobre el papel que desempeña la aversión a la pérdida, y cualquier otro sesgo, en nuestras decisiones.

- Hoy en día sabemos que, aunque ilógicas, muchas decisiones influenciadas por la aversión a las pérdidas son adaptativas. Este sesgo facilita el aprendizaje por refuerzo y la coherencia en nuestras decisiones, promueve las emociones necesarias para una interacción social adecuada, como la aversión a la injusticia, e incluso puede ser protectora contra comportamientos dañinos como las autolesiones y el suicidio.

- Estos hallazgos nos llevan a reconsiderar cómo evaluamos lo que constituye una buena decisión. Los criterios no deben limitarse a la racionalidad clásica, y los modelos de toma de decisiones deben alinearse con la naturaleza humana, tal vez alejándose de los modelos económicos y confiando en las contribuciones recientes de la neurociencia.

- Las nuevas líneas de estudio deben considerar aspectos como la satisfacción, la adaptación, la salud o el estatus que nuestras decisiones nos brindan, así como otros factores inherentes al proceso decisional. Los subprocesos cognitivos como el aprendizaje por refuerzo, la sensibilidad al *feedback*, la memoria de trabajo, el control de impulsos y la flexibilidad cognitiva pueden evaluarse para establecer estándares y detectar desviaciones basadas en ellos.

- La evaluación de la toma de decisiones también debe considerar el uso de contextos decisionales ecológicamente válidos, representativos de nuestras decisiones tomadas en la vida real. Las nuevas tecnologías son grandes aliadas en este sentido y, a través del desarrollo de entornos virtuales, se espera contribuir al crecimiento de un campo de estudio tan complejo como es la toma de decisiones.