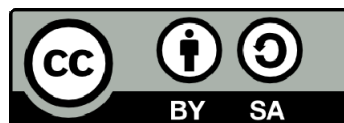




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The role of curiosity and absorption in regulating music reward: evidence from laboratory and natural settings

Gemma Cardona Caballero



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BARCELONA

**The role of curiosity and absorption
in regulating music reward:
evidence from laboratory and natural settings**

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Abstract

Music listening is widely regarded as one of the most pleasurable experiences in life. Accordingly, extensive research has shown the engagement of reward circuits during music-induced affective responses. However, existing studies on musical reward have often overlooked key processes, such as absorption and curiosity, which may significantly shape the musical experience and the reward derived from it.

Importantly, the activation of the reward system and subsequent dopamine release during music listening have been suggested to enhance memory processes. While studies have shown a positive impact of musical pleasure on memory for music itself, it remains unexplored whether it could affect memory for related information as well. In a similar vein, no research to date has investigated whether other musical reward-related processes, such as musical curiosity, may promote memory formation.

In the present thesis, we investigated how different music-related processes influence musical reward and subsequent memory performance through a series of behavioural studies in both laboratory and naturalistic settings.

The first study focused on pleasure and its effects on memory. We demonstrated that the previously reported positive effect of pleasant music on memory for music itself extends to verbal material presented simultaneously. Additionally, we showed that this effect is particularly strong in participants with higher musical hedonia.

In the second study, we adopted a psychometric approach to investigate the role of absorption – understood as individuals’ proneness to get carried away by music – in shaping musical reward. As a result, we developed the extended Barcelona Music Reward Questionnaire (eBMRQ), which includes a new four-item facet measuring absorption.

The third study assessed how curiosity states influence exploratory behavior and memory for music. Conducted in both laboratory and naturalistic settings, this study revealed that heightened music-induced curiosity states significantly enhance exploratory behaviors and improve memory performance. These effects are modulated by individual differences in electronic music liking and musical hedonia.

Finally, the fourth study examined the temporal dynamics and potential interplay of pleasure and curiosity in a naturalistic setting. Additionally, we assessed their effects on memory for music and information. Results revealed a complex interaction between the two constructs: while curiosity precedes pleasure when the music is unfamiliar, this pattern is reversed after providing abundant

information about the musical piece. Again, participants' musical hedonia correlates with both curiosity and pleasure ratings and significantly predicts memory performance.

Taken together, the present doctoral dissertation provides new evidence on the influence of absorption and curiosity processes on musical reward. It also offers novel insights into the temporal interplay between pleasure and curiosity. Finally, it corroborates the positive effects of these constructs on memory for music and information and highlights the importance of individual differences in musical hedonia in modulating these effects. We believe these findings pave the way for future research to consider the multifaceted nature of musical reward, thereby contributing to a broader understanding of reward mechanisms and their influence on memory enhancement.

Resum

Escotar música és considerat com una de les activitats més agradables de la vida. De fet, hi ha una àmplia evidència científica sobre la implicació dels circuits de recompensa durant les respostes afectives induïdes per la música. No obstant, els estudis existents sobre la recompensa musical sovint han passat per alt processos clau, com l'absorció i la curiositat, que poden influir significativament en l'experiència musical i la recompensa que n'extraïem.

S'ha suggerit que l'activació del sistema de recompensa i el posterior alliberament de dopamina durant l'escolta musical contribueixen a una millora de la memòria. Fins ara, els estudis han mostrat un impacte positiu del plaer musical en la memòria per a la música en si, però es desconeix si aquest plaer musical podria afectar també la memòria per a informació relacionada. De la mateixa manera, encara no s'ha investigat si altres processos relacionats amb la recompensa musical, com ara la curiositat per la música, poden promoure la formació de records.

En aquesta tesi hem investigat com els diferents processos relacionats amb la música influeixen en la recompensa musical i la memòria a través d'una sèrie d'estudis conductuals duts a terme tant al laboratori com en contextos ecològics.

El primer estudi se centra en el plaer i els seus efectes sobre la memòria. Demostrem que l'efecte positiu de la música plaent sobre la memòria per a la pròpia música s'estén a estímuls verbals presentats simultàniament. A més, veiem que aquest efecte és particularment fort en els participants amb major hedònia musical.

En el segon estudi, adoptem un enfocament psicomètric per investigar el paper de l'absorció – entesa com la propensió dels individus a deixar-se endur per la música – en la recompensa musical. Com a resultat, hem desenvolupat una versió extesa del Barcelona Music Reward Questionnaire (eBMRQ), que inclou una nova faceta que mesura l'absorció.

El tercer estudi avalua com els estats de curiositat influeixen en el comportament exploratori i la memòria per a la música. Aquest estudi revela que els estats de curiositat induïts per la música promouen els comportaments exploratoris i milloren el rendiment de la memòria. Aquests efectes són modulats per diferències individuals en la preferència per la música electrònica i l'hedònia musical.

Finalment, el quart estudi examina la dinàmica temporal i la possible interacció entre el plaer i la curiositat en un entorn ecològic. A més, avaluem els seus efectes sobre la memòria per a la música i la informació. Els resultats revelen una complexa interacció entre els dos constructes: mentre que la curiositat precedeix el plaer quan la música no és familiar, aquest patró s'inverteix després de proporcionar informació abundant sobre la peça musical. De nou, l'hedònia musical dels

participants correlaciona tant amb la curiositat com amb el plaer i prediu significativament la memòria.

En conjunt, la present tesi doctoral aporta noves evidències sobre la influència dels processos d'absorció i curiositat en la recompensa musical. També ofereix nous coneixements sobre la interacció temporal entre plaer i curiositat. Finalment, corrobora els efectes positius d'aquests constructes sobre la memòria per a la música i la informació i destaca la importància de les diferències individuals en l'hedònia musical en la modulació d'aquests efectes. Aquestes troballes conviden els investigadors a tenir en compte la naturalesa polifacètica de la recompensa musical, contribuint així a una comprensió més àmplia dels mecanismes de recompensa i la seva influència en la millora de la memòria.

List of abbreviations

AIMS	Absorption In Music Scale
AM	Absorption in music
BMRQ	Barcelona Music Reward Questionnaire
eBMRQ	Extended Barcelona Music Reward Questionnaire
EE	Emotion evocation
FBM	Flashbulb memory
fMRI	Functional Magnetic Resonance Imaging
IPE	Information prediction error
MR	Music reward
MS	Musical seeking
NAcc	Nucleus accumbens
PE	Prediction error
PET	Positron Emission Tomography
PSE	Point of subjective equality
RPE	Reward prediction error
SM	Sensory-motor
SN	Substantia nigra
SR	Social reward
SV	Subjective value
TMS	Transcranial Magnetic Stimulation
VTa	Ventral tegmental area
WTP	Willingness to pay

Introduction

1 Introduction

Music constitutes an essential part of our lives. It not only accompanies us in our daily routines but it is also present in the most significant moments, creating unforgettable memories. While the study of music perception and the reasons for its presence across thousands of years and cultures is important, music also serves as a valuable tool for investigating various domain-general cognitive processes. One of these processes is reward. Originally, the term *reward* merely described an event that produced pleasant or positive affective experiences. Later on, it was also used to describe an event that, when linked to a specific behaviour, increased the likelihood of that behaviour occurring again, what it is also known as reinforcement (White, 2011). Integrating these ideas, Berridge (2009) proposed reward to encompass three main components: a) wanting, that refers to a type of incentive motivation that promotes approach toward and consumption of rewards; b) liking, which is related to the hedonic experience of pleasure that results from obtaining the desired item, and c) learning, referring to associations, representations, and predictions about future rewards based on past experiences. According to their nature, rewarding stimuli are classified as primary and secondary. While primary rewards (e.g., food, sex, or water) are critical for individuals and species survival, secondary or abstract rewards (e.g., money, power, or music) do not satisfy any biological need by themselves, thus lacking a clear evolutionary advantage. Thus, it is worth studying them separately. Among the secondary rewards, music is one of the most studied (Blood & Zatorre, 2001; Ferreri et al., 2019; Gold, Mas-Herrero, et al., 2019; Mas-Herrero et al., 2013; Mas-Herrero, Dagher, et al., 2018; Salimpoor et al., 2011, 2013). However, so far it has not been sufficiently acknowledged that reward may be modulated by other processes, such as absorption or curiosity. Therefore, the aim of the present thesis is to investigate, by using music, how processes like absorption and curiosity influence the experience of reward. Additionally, we examine their impact on cognitive functions, specifically how pleasure and curiosity affect the encoding of new information.

In this introduction, we will begin by summarizing the current research on musical reward, focusing specifically on pleasure and its effects on learning and memory. Next, we will discuss the concept of absorption and its relationship with music. Finally, we will review the concept of curiosity, its effects on learning and memory, and the limited studies that have explored curiosity in the context of music.

1.1 Musical pleasure

1.1.1 Definition and neural mechanisms

Musical pleasure (or liking) refers to the general pleasantness experienced when listening or playing music. Intensely pleasurable responses to music are known as chills (also referred to as *frisson*, *shivers*, or *goose bumps*), which are accompanied by a series of psychophysiological responses including increased heart rate, skin conductance, and respiration (see De Fleurian & Pearce, 2021, for a review).

Musical pleasure is thought to arise from the surprise elicited when expectations of upcoming events are not entirely met (D. B. Huron, 2006; Meyer, 1956). This relationship is not linear but follows an inverted-U shape (Berlyne, 1971; Wundt, 1904), so that pleasure is maximal at intermediate values of surprise, where complexity is neither too high nor too low. Additionally, it is modulated by uncertainty (i.e., how well the context of a given piece of music allows predictions to be made; Cheung et al., 2019; Gold, Pearce, et al., 2019): in a context where uncertainty is low, listeners prefer (i.e., report higher pleasure ratings) intermediate-to-higher complexity and, thus, some degree of surprise. On the other hand, when uncertainty is high, listeners prefer less surprise “because even the most likely outcome is still somewhat uncertain, and this confirmation can still generate a positive prediction error” (Zatorre, 2024, p. 258).

The same inverted-U shape is found when assessing the relationship between musical pleasure and familiarity. When music is presented repeatedly (i.e., increased familiarity), it tends to become better liked (Peretz et al., 1998; Schellenberg et al., 2008) because repetition leads to better memory representations, which, in turn, allow for better predictive models, thus enhancing pleasure. However, excessive exposure can lead to an overly precise model, resulting in boredom and decreased pleasure (Zatorre, 2024, p. 256).

Regarding the neural mechanisms supporting musical pleasure, strong evidence has been found on the implication of the reward system. The first evidence was provided by Blood & Zatorre (2001), who used the Positron Emission Tomography (PET) imaging technique to measure cerebral blood flow changes during intensely pleasurable responses to music (i.e., chills). They observed that the intensity of these chills was associated with an increased blood flow in reward-related brain regions including the ventral striatum, midbrain, amygdala, orbitofrontal cortex, and ventromedial prefrontal cortex. After this groundbreaking study, Salimpoor and colleagues (2011), using a [^{11}C]raclopride PET technique, observed that these peak emotional responses during music listening were associated with the simultaneous release of dopamine in the bilateral

dorsal and ventral striatum. In 2013, the same team, by using functional magnetic resonance imaging (fMRI), found that activity in the nucleus accumbens (NAcc), a specific region of the ventral striatum, was associated with how much money participants were subsequently willing to pay for the songs that they found pleasurable. More recently, Mas-Herrero et al. (2018), combined excitatory and inhibitory transcranial magnetic stimulation (TMS) over the participants' left dorsolateral prefrontal cortex, known to modulate striatal function, together with measures of pleasure and motivation during music listening. Results showed that perceived pleasure and the monetary value assigned to music significantly increased (or decreased) when exciting (or inhibiting) fronto-striatal pathways. Finally, in 2019, Ferreri et al. performed a pharmacological study in which they altered dopamine signaling by using levodopa (a dopamine precursor) or risperidone (a dopamine antagonist). Results revealed that both pharmaceutical agents influenced perceived pleasure as well as the monetary value assigned to music. Thus, the latter two studies established not only a correlation but a causal implication of dopamine in both the affective responses (i.e., liking) and motivational aspects (i.e., wanting) of music-induced reward.

1.1.2 The multifaceted nature of music reward

While it might be inconceivable for those of us who deeply cherish music, there exist individuals who do not enjoy music at all. Anhedonia is a well-known psychological condition involving a diminished capacity to experience pleasure or motivation in response to stimuli like food or sex and it has been attributed to a dysfunction of the reward system (Harvey et al., 2007). Consequently, and given that music is a rewarding stimulus, individuals with anhedonia often exhibit low emotional responses and reduced activation in the reward system when exposed to music (Keller et al., 2013). Interestingly, there exist specific types of anhedonia where individuals are able to derive pleasure from all rewarding stimuli except for one, such as music. This particular case is called musical anhedonia. While musical anhedonics exhibit completely normal behavioural and psychophysiological responses to non-musical rewarding events, such as winning money in a monetary incentive delay task (Mas-Herrero et al., 2014) or engaging with other art-related activities (e.g., looking at visual art or listening to emotional sounds, Mas-Herrero, Karhulahti, et al., 2018), they report no pleasure when listening to music and, more importantly, they do not show significant changes in reliable psychophysiological indicators of pleasure such as skin conductance or heart rate (Mas-Herrero et al., 2014, 2018). This effect was found to be due to a reduced functional connectivity between the right auditory cortex and the striatum (Martínez-Molina et al., 2016), which was related to a less well-organized anatomical connectivity between these regions (Martínez-Molina et al., 2019).

Introduction

Importantly, the ability to derive pleasure from music is not a binary trait but rather varies along a spectrum. In order to quantify individuals' music reward sensitivity (i.e., musical hedonia), Mas-Herrero and colleagues (2013) developed the Barcelona Music Reward Questionnaire (BMRQ). The scale includes 20 items representing five different facets that can contribute to musical hedonia: i) *musical seeking*, that refers to the way individuals engage in music-related activities (like attending concerts or playing an instrument) or seek additional information about music they listen to (performers, composers) (e.g., "I'm always looking for new music"), ii) *emotion evocation*, which is related to the emotional impact of music on individuals (e.g., "I sometimes feel chills when I hear a melody that I like"), iii) *mood regulation*, assessing the ability of listeners to leverage music for emotional modulation (such as stress relief or emotional release) (e.g., "Music helps me chill out"), iv) *social reward*, which examines the social bonding effect of music on individuals (e.g., "I like to sing or play an instrument with other people"), and v) *sensory-motor*, that addresses the capacity of music to naturally induce body movements synchronized to its rhythm in certain individuals (like nodding or dancing) (e.g., "Music often makes me dance"). The overall test shows a 0.92 reliability, indicating that BMRQ scores are extremely consistent across different occasions of testing. In the validation process, all factors and the overall scale positively correlated with Feeling and Aesthetics facets and the overall measure of Openness to experience (Spanish version of the NEO-PI-R; Costa & McCrae, 1992), as well as Fun Seeking, BAS Drive, and Reward Responsiveness from the BIS/BAS questionnaire (Carver & White, 1994). On the other hand, they were negatively correlated with the Physical Anhedonia Scale (Chapman et al., 1976). In addition, all facets except Musical Seeking positively correlated with the BIS scale. These findings pointed the BMRQ as a useful psychometric tool for assessing and controlling for individual differences in musical hedonia. Its reliability was further demonstrated in subsequent experiments showing, for example, a positive correlation between BMRQ scores and activity in the right NAcc during music listening (Gold, Mas-Herrero, et al., 2019), significant effects of BMRQ scores on memory performance for music material (Ferreri, Mas-Herrero, et al., 2021; Ferreri & Rodriguez-Fornells, 2017), and a positive correlation between some BMRQ facets and music use during the COVID-19 pandemic (Ferreri, Singer, et al., 2021). Interestingly, a recent study found that genetic factors substantially explain the variance in music reward sensitivity (as measured by the BMRQ) above and beyond generic influences shared with music perception and general reward sensitivity. Furthermore, results revealed that partially distinct sources of genetic variation contribute to different facets of music reward sensitivity (Bignardi et al., 2024).

Thus, the BMRQ not only proved to be a robust instrument for assessing affective responses but also showed implications on a cognitive level, underscoring its importance in comprehending the

multifaceted nature of music reward in its complexity. Further refinement of this tool could involve exploring additional potential facets of reward.

1.1.3 The effect of musical pleasure on learning and memory

Across many cognitive domains, items that are better liked and that activate dopaminergic reward circuitry, are also usually better remembered (Adcock et al., 2006; Gruber et al., 2014; Shohamy & Adcock, 2010; Wittmann et al., 2005; Wolosin et al., 2012). This effect has been attributed to the interaction between the substantia nigra/ventral tegmental area complex (SN/VTA) and the hippocampus (Goto & Grace, 2005; Lisman et al., 2011; Lisman & Grace, 2005). Specifically, reward-motivated activation of midbrain dopamine neurons might result in dopamine release in the hippocampus. According to the neo-Hebbian framework for episodic memory (Lisman et al., 2011), this dopamine release would strengthen synaptic long-term potentiation, thus promoting long-term memory formation (Schultz, 2002) and consolidation (Chowdhury et al., 2012). Importantly, these improvements can be observed not only for the rewarding stimulus itself, but also for associated non-rewarding information (Gruber et al., 2014). According to the Behavioral Tagging hypothesis (also known as the penumbra hypothesis, Duncan et al., 2012; Lisman et al., 2011), a short-lasting memory induced by a weak event can be consolidated into a long-term memory if paired relatively close in time with an independent strong event (e.g., a novel or rewarding stimulus inducing dopamine release). Notably, strong events have been observed to rescue weak memories both proactively (up until 2-3 hours afterwards) and retroactively (up to 1 hour before; see Dunsmoor et al., 2022, for a recent review on the penumbra effect).

According to this evidence, all the stimuli triggering dopaminergic transmission in the hippocampus, including money (Adcock et al., 2006), internal curiosity states (Gruber et al., 2014), or self-regulated learning processes (Ripollés et al., 2016), can result in long-term memory improvements. And music is no exception.

In 2017, Ferreri & Rodríguez-Fornells provided the first experimental evidence regarding the impact of musical pleasure on learning and memory. In their study, participants rated the pleasure experienced from various musical excerpts, along with other control measures including arousal, valence, and familiarity. Twenty-four hours later, participants underwent a recognition-recollection memory task, where they had to identify previously presented items among new ones (i.e., old/new recognition). Those items categorized as old were then subjected to an additional question to determine the nature of the memory (i.e., remember/know/guess paradigm; Yonelinas, 2002). The findings revealed that the higher the pleasure elicited by a particular excerpt, the better recognized and remembered it was the next day (Ferreri & Rodríguez-Fornells,

2017). Notably, the strength of this effect varied according to individuals' sensitivity to musical reward; participants with higher musical hedonia demonstrated better musical memory performance. Subsequently, Ferreri et al. (2021) investigated the neurochemical brain mechanisms underlying this phenomenon through a double-blind, within-subject pharmacological study. Prior to listening to the music, participants were administered levodopa (i.e., a dopamine precursor), risperidone (i.e., a dopamine antagonist), or placebo. Once again, the results highlighted a positive association between pleasure and recollection the following day. Crucially, this effect was modulated by both dopaminergic signalling and individual differences in musical hedonia. Specifically, while greater pleasure was consistently associated with improved memory outcomes in participants with high sensitivity to musical reward, this effect was lost when dopaminergic signalling was disrupted in individuals with average or low musical hedonia (Ferreri, Mas-Herrero, et al., 2021).

Importantly, music has been shown to influence not only memory for music itself, but also memory for verbal material (Ferreri et al., 2013, 2015; Jäncke et al., 2014; Ludke et al., 2014). Several experimental paradigms have been used to test this effect, from learning sung vs. spoken lists of words (Ludke et al., 2014; Peterson & Thaut, 2007; Racette & Peretz, 2007; Rainey & Larsen, 2002; Thaut et al., 2014) to learning word lists with background music vs. silence or white noise (De Groot, 2006; Ferreri et al., 2013, 2015; Jäncke et al., 2014; Jäncke & Sandmann, 2010). However, contradictory results have been found. Some studies report no effect or even a detrimental effect of music on verbal learning (Jäncke et al., 2014; Jäncke & Sandmann, 2010; Peterson & Thaut, 2007; Racette & Peretz, 2007), suggesting that music may attract attention away from the relevant information to remember (Ferreri & Verga, 2016). Conversely, other studies indicate positive effects of music on verbal memory (De Groot, 2006; Ferreri et al., 2013, 2015; Ludke et al., 2014; Rainey & Larsen, 2002; Thaut et al., 2014). Three mechanisms have been proposed to explain music's facilitation effect on verbal memory (Ferreri & Verga, 2016). First, because of its melodic and rhythmic properties, music may provide a temporal scaffolding that supports learning by facilitating the processing, interpretation, and integration of information. Second, according to the arousal and mood hypothesis (Thompson et al., 2001), music may positively influence cognitive abilities through changes in listeners' arousal or mood. Lastly, music may act as an enhancer of emotional responses that influence the reward system, leading to dopamine release and improved memory formation (Lisman et al., 2011).

Given the contradictory results on verbal memory and considering the evidence that memory for music is at least partly driven by reward-related responses (Ferreri, Mas-Herrero, et al., 2021; Ferreri & Rodriguez-Fornells, 2017), it would be worth to investigate the role of the reward

system in music's potential to facilitate non-musical memory (e.g., verbal information) – either directly, by pharmacologically altering dopamine levels, or indirectly, by exploring the relationship between subjective pleasurable responses or musical hedonia and verbal memory improvements.

1.2 Absorption

1.2.1 Definition and neural mechanisms

The concept of absorption originated in the late 1950s, a period marked by research into the personality traits associated with hypnosis and suggestibility (Lifshitz et al., 2019). While examining hypnotic susceptibility questionnaires, Tellegen and Atkinson (1974) identified several items that referenced a deep involvement with the object of experience. As a result, they developed the Tellegen Absorption Scale (TAS, Tellegen & Atkinson, 1974) to measure a personality trait they termed *absorption*. Tellegen and Atkinson (1974) described absorption as a disposition for experiencing “episodes of total attention involving a full commitment of available perceptual, motoric, imaginative, and ideational resources to a unified representation of the attentional object” (Tellegen & Atkinson, 1974, p.274). Additionally, they explained that absorption was believed to “result in a heightened sense of reality of the attentional object, imperviousness to distracting events, and an altered sense of reality in general, including an empathically altered sense of the self” (Tellegen & Atkinson, 1974, p. 268).

Later, Tellegen distinguished between two different ways of engaging with the attentional object. The *instrumental set* employs “active, realistic, voluntary, and relatively effortful planning, and decision making and goal directed behaviour” (Tellegen, 1981, p. 222). On the other hand, the *experiential set* is characterized by “an effortless, non-volitional quality of deep involvement with the objects of consciousness” (Jamieson, 2005, p. 120). The trait of absorption was defined as the disposition to surrender the instrumental set and adopt the experiential one.

The TAS consists of 34 items that are answered using a true/false response format. In a further study (Tellegen, 1992), a factorial analyses revealed that the items may be representing six different facets: i) *responsiveness to engaging stimuli*, characterizing intensive and emotional responses to the beauty of nature and art, ii) *synaesthesia*, assessing cross-modal associations, iii) *enhanced cognition*, accounting for extra-sensory perception and imaginal thinking, iv) *oblivious/dissociative involvement*, referring to states of absorption during daydreaming, watching a film or listening to music, v) *vivid reminiscence*, related to the fact of remembering past events

vividly, and vi) *enhanced awareness*, assessing mystical peak experiences. However, the high correlations found between the factors spoke for a general absorption dimension and discouraged the use of subscales (Tellegen, 1992).

There has been much debate over the validity and structure of the absorption construct. Consequently, researchers have suggested different factor solutions as well as potential improvements to the original dichotomous response format (Glicksohn & Barrett, 2003; Jamieson, 2005). For example, Jamieson (2005) published the MODTAS, a 5-point Likert scale version with improved psychometric properties which presented five primary facets (*synaesthesia*, *altered states of consciousness*, *aesthetic involvement*, *imaginative involvement*, and *extra sensory perception*) and a single higher order factor.

In spite of the numerous critiques, and even if Tellegen and Atkinson (1974) affirmed that their scale should be considered as a starting point for further refinement and extension, the original 34-item scale has become the gold standard for measuring absorption. Thus, several studies have used the scale and have reported interesting correlations. For example, absorption has been linked to hypnotic susceptibility (Tellegen & Atkinson, 1974), mental imagery ability (McConkey & Nogrady, 1986; Sweeney et al., 1986), fantasy-proneness (Lynn & Rhue, 1986, 1987, 1988), synaesthesia (Chun & Hupé, 2016; Rader & Tellegen, 1987), flow (Marty-Dugas & Smilek, 2019), feelings of self-transcendence (Cardeña & Terhune, 2014), and experiences of dissociation and hallucinations (Glicksohn & Barrett, 2003; Perona-Garcelán et al., 2013, 2016). Interestingly, as it happens for musical hedonia (Mas-Herrero et al., 2013), the absorption trait has been related to the personality trait of *openness to experience* (Glisky et al., 1991) which hangs together with a propensity for artistic sensitivity, imaginative daydreams, awareness of emotional responses, intellectual curiosity, and willingness to try new activities (McCrae & Costa, 1983).

The use of questionnaires tends to emphasize absorption as a trait. However, like many other constructs, absorption differentiates between trait and state manifestations. Whereas the personality trait denotes individual differences in the propensity and ability to become absorbed, the state refers to actually being in a different state of mind.

The state of absorption is a key element of exceptional experiences. Several authors have attempted to formalize the study of these kind of experiences. One of the first was Maslow, who coined the term *peak experiences* to describe “moments of highest happiness and fulfilment” (Maslow, 1968, p. 73) characterized by a disorientation of time and space, a loss of fear, anxiety, and inhibition, a total absorption by the phenomenon, a loss of self-consciousness, and a sense of being part of something larger; all this together with strong feelings (Maslow, 1968, p. 80-94).

Later on, Csikszentmihalyi (1990) developed the concept of *flow*, which he defined as “the state in which people are so involved in an activity that nothing else seems to matter; the experience itself is so enjoyable that people will do it even at a great cost, for the sheer sake of doing it” (Csikszentmihalyi, 1990, p. 4). Thus, flow states involve absorption, enjoyment, and intrinsic motivation. Other conceptualizations of exceptional experiences include *transcendent ecstasy* (Laski, 1961), *joyous experience* (Panzarella, 1980), and *strong experience* (Gabrielsson & Lindström-Wik, 2003). Importantly, all these concepts include the state of absorption as a fundamental characteristic.

Research investigating the neural mechanisms underlying absorption states is scarce and reports mixed results. The only finding that seems to be consistent across studies is a decreased activation of the default mode network (Huskey et al., 2018; Ju & Wallraven, 2019; Ulrich et al., 2014, 2016; Van Elk et al., 2019), which is involved in self-referential processing and autobiographical memory (Davey et al., 2016; Gusnard et al., 2001). On the other hand, in search of the neural correlates of flow state (involving absorption, enjoyment, and intrinsic motivation), several brain systems and networks have been pointed out as potential neural underpinnings of this experience including the reward system, attentional networks, and the default mode network (see Alameda et al., 2022; Van Der Linden et al., 2021, for a review). Given its inherent difficulty, research that explicitly tests the involvement of the reward system in the experience of flow is scarce. De Manzano et al. (2013) showed that individual differences in the proneness to experience flow are related to higher availability of dopamine D2 receptors in the striatum. However, one may argue that flow proneness is not the same as the actual experience of flow. For that reason, Ulrich et al. (2014, 2016) used a within-subject fMRI design in which participants had to do calculations in three different conditions: a boredom condition, in which the task was relatively easy, an overload condition, in which the task was too difficult for the participants' skill levels and a condition that was assumed to induce flow due to the matching of task difficulty and participant's skill level. The flow condition was related to significantly increased activity in the basal ganglia, including the NAcc, thus suggesting a connection between flow (and, therefore, absorption) and the reward system.

1.2.2 Absorption and music

Studies across a range of disciplines suggest that certain activities are inherently particularly absorbing. These activities include, among others, dancing (Bachner-Melman et al., 2005), reading (Nell, 1988), art appreciation (Combs et al., 1988), playing music (Høffding, 2019), and listening to music (Rhodes et al., 1988). Indeed, during his extensive research on exceptional experiences,

Maslow realized that music is one of the easiest ways of getting peak experiences (Maslow, 1971, p. 169). Accordingly, throughout history, diverse forms of music, such as Sufi, tarantella, or minimalism have served as catalysts for inducing altered states of consciousness (Becker, 2004; Forstmann et al., 2020; Hills & Argyle, 1998; Kirkegaard, 2012). Furthermore, musical activities including performance, composition, and listening, have been found to be elicitors of flow states (Forbes, 2021; Høffding, 2019; see Chirico et al., 2015, for a review).

Music is thought to be a particularly effective inducer of absorption since it affords multiple potential entry points to involvement, including: i) *acoustic attributes* (e.g., timbre, resonance, pitch, rhythm, etc.), ii) *source specification* (i.e. memories and personal or cultural associations which trigger imaginative involvement), iii) *physical entrainment*, iv) *emotion* (either induced or represented by music), and v) *fusion of modalities* (aural, visual, and kinaesthetic) (Herbert, 2012).

Some studies have examined absorption during music listening, primarily through questionnaires and written reports. For instance, Nagy and Szabó (2002, 2003) developed a 29-item scale of musical involvement (MIS) and combined it with open-ended essays concerning the meaning of music to establish differences within music-listening experiences. In the same year, Gabrielsson and Lindström Wik (2003) explored absorption in real-world music experiences. Based on nearly 900 descriptions of listening experiences, they developed a 7-category descriptive system for strong experiences of music (SEM), and absorption was included in one of the categories.

More recently, Sandstrom and Russo (2013) developed the *Absorption in Music Scale (AIMS)*, a 34-item questionnaire aimed at measuring individuals' ability and willingness to allow music to draw them into an emotional experience. In order to create the initial pool of items, the authors adapted some TAS questions to make them refer to music. Next, six musically trained individuals who had performed a thorough literature review, incorporated some additional questions. The first phase of the study served to select the final 34 items to be included in the questionnaire. Subsequently, the new psychometric tool was tested. It presented a good internal consistency and strong test-retest reliability. Convergent validity was further supported by its correlation with similar scales, such as the TAS and the MIS.

Further supporting the involvement of absorption in music-related peak experiences, recent studies demonstrate that the personality trait of absorption predicts the intensity of feelings of awe and self-transcendence when presented with engaging music (Van Elk et al., 2016) or rhythms (Rhodes et al., 1988).

Given that absorption is usually present when actively engaging in music-related activities and having seen that the reward system might be implicated in the experience of flow (a state in which

absorption plays a central role), it is reasonable hypothesizing that absorption may be one of the processes modulating musical reward.

1.3 Curiosity

1.3.1 Definition and neural mechanisms

Curiosity began to be studied in the 60s, but it fell into oblivion. It was not until the 90s that research in this field was resumed. The absence of a universally accepted definition has hindered the progress of a formal study of curiosity. Nonetheless, this diversity of definitions reflects the early stage and vitality of this emerging field (Kidd & Hayden, 2015). In the following section we will consider some of the most cited views of curiosity.

William James, a leading philosopher and psychologist considered the father of American Psychology, defined curiosity as the “impulse toward better cognition” (James, 1890). He distinguished two types of curiosity, sensational and theoretic. While sensational curiosity referred to a mechanism of intrinsically driven behavior that serves in approaching new objects, theoretic curiosity was associated to the “rational relations between things”. He considered theoretic curiosity as a higher, more intellectual form of curiosity in which “the practical instinctive root has probably nothing to do”, but instead “the philosophic brain responds to an inconsistency or a gap in its knowledge”.

In 1954, Daniel Berlyne, a pioneer in experimental research on curiosity, proposed a two-axis model to categorize curiosity. One axis extended between perceptual and epistemic curiosity, while the other ranged from specific to diversive curiosity. Perceptual curiosity referred to the drive that motivates organisms to explore and to seek out new information that enhances their perception of the environment. In contrast, epistemic curiosity was described as a drive to access information that, further than dispelling uncertainties about the surroundings, allows organisms to acquire knowledge. Regarding the second dimension, specific curiosity represented the desire for a particular piece of information that is lacking, whereas diversive curiosity referred to the seeking of novel, complex, or surprising information to reduce feelings of boredom (Berlyne, 1954, 1960, 1966). In the four-way categorization derived from these two dimensions, specific perceptual curiosity could be exemplified by a child trying to solve a puzzle, diversive perceptual curiosity by a bored teenager scrolling through TikTok, specific epistemic curiosity by a PhD student searching for relevant papers on Google Scholar, and diversive epistemic curiosity by a woman watching a TED talk on a random subject. Notably, Berlyne (1960) considered that

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curiosity was an aversive state that could only be mitigated through information-seeking. However, this theory failed to explain why people frequently and intentionally seek out opportunities that spark their curiosity (Gruber et al., 2019).

Thirty years later, George Loewenstein (1994) initiated a renewed period of curiosity research and proposed the *information gap theory*, suggesting that epistemic curiosity emerges from a discrepancy between the observer's existing knowledge and what they would like to know. Accordingly, Loewenstein described curiosity as a "cognitively induced deprivation that results from the perception of a gap in one's knowledge" (Loewenstein, 1994, p. 76). By framing curiosity in this manner, it can be viewed as a deprivation phenomenon that seeks to fill a need (i.e., minimizing uncertainty about the state of the world) similar to other biological drives such as hunger or sex. Therefore, the information gap theory links the study of epistemically-based actions with the understanding of motivated behaviors.

Other definitions of curiosity include "the burning desire to know and understand" (Gottlieb et al., 2013), "a drive state for information" (Kidd & Hayden, 2015), "a manifestation of the drive for sense-making" (Chater & Loewenstein, 2016), "the feeling of wanting to know" (Sharot & Sunstein, 2020), or "a value signal that guides attention to predicted sources of value" (Wojtowicz & Loewenstein, 2020). It is worth noting that most definitions of curiosity consider it as an intrinsically motivated behavior "independent of a foreseeable profit" (Gottlieb et al., 2013) that leads us to seek for certain experiences for the inherent value of learning from them, not because they are rewarding in a more tangible way (Ten et al., 2022), as opposed to extrinsically motivated behaviors, which lead to separable outcomes (see the Self-Determination Theory by Deci & Ryan, 1985).

As mentioned before, there is not a globally accepted definition of curiosity. Nonetheless, in this thesis, we will use the term *curiosity* to describe an intrinsic motivation/drive to explore/seek for information that allows us to acquire some knowledge.

Note that the term *curiosity* can refer to both state and trait. Based on the aforementioned definitions and dissociations of curiosity, several personality questionnaires were developed to measure different facets of trait curiosity. For example, drawing from Berlyne's distinction between perceptual vs. epistemic and specific vs. diversive, Litman and Spielberg (2003) developed the Epistemic Curiosity Scale, which included two subdimensions: diversive curiosity (consisting of 5 items including, for example, "I enjoy learning about subjects which are unfamiliar"), and specific curiosity (5 items, e.g. "When I see an incomplete puzzle, I like to try and imagine the final solution"). In the same line, Collins, Litman, and Spielberg (2004), created the

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Perceptual Curiosity Scale, including diversive (consisting of 5 items including, for instance, “I like travelling to places I have never been to”), and specific curiosity (5 items, e.g. “When I hear strange sound I try to find out what caused it”) facets. Contrary to the research investigating different factors that induce curiosity, Kashdan and colleagues focused on the nature and processes underlying trait curiosity. To that aim, they created the Curiosity and Exploration Inventory (Kashdan et al., 2004), a 7-item scale including two facets: exploration, or the tendency to seek out new experiences and new information; and absorption, or the tendency to be fully engaged in these experiences.

Importantly, unless stated otherwise, whenever the term *curiosity* is mentioned in the present thesis, it will refer to the state and not the trait.

A couple of decades ago, the study of curiosity transitioned from abstract philosophical definitions to practical, task-oriented research providing insights into the neural mechanisms underlying curiosity. Kang and colleagues (2009) were pioneers in this respect. To manipulate curiosity, participants were presented with a set of trivia questions while undergoing fMRI. They were asked to read the trivia questions, silently guess the answer, and then rate their curiosity and their confidence in knowing the answer. Subsequently, the trivia question was shown again followed by the correct answer. Results showed increased activity for high- compared to low-curiosity questions in the caudate nucleus and the inferior frontal gyrus, which are typically activated by anticipation of many types of reward, thus suggesting that curiosity elicits an anticipation of a reward state (Kang et al., 2009). Surprisingly, the NAcc, which is one of the most reliably activated structures of reward anticipation, was not activated. In order to test the reward anticipation hypothesis, Kang and colleagues performed a new experiment in which participants were required to spend scarce resources (either limited tokens or time) if they wished to find out the answer to the trivia questions. Specifically, in the token condition, subjects had to spend one of their tokens to find out the answer to a question. Since there were only twenty-five tokens for fifty questions, spending a token on an answer meant skipping another answer. The hypothesis was that, the more curious the participants, the higher the anticipated reward from learning information, so the more likely to spend a token (Kang et al., 2009). In the time condition, subjects had to wait for a random amount of time between 5 and 25 seconds until the answer appeared. Subjects could quit waiting and skip to the next question at any time, but then they would not get to see the correct answer. In this case, the hypothesis was that subjects would wait longer for the answers that they were more curious about. This experimental design allowed the researchers to measure, by means of psychometric functions, participants’ willingness to pay for information they were curious about. Furthermore, the use of the different conditions tested the robustness of

the effect of curiosity to changes in the type of resource that was spent. Results showed that, indeed, the higher the curiosity ratings, the greater the amount of resources the participants were willing to pay for the answer.

Building on Kang et al.'s experiment, Gruber and colleagues (2014) modified the design so that curiosity and confidence ratings were obtained during a prescreening phase outside the scanner. Furthermore, during the task, after presenting the trivia question and before revealing the answer (i.e., anticipation period), a neutral, unknown face was shown for memory-related purposes. They observed that, during presentation of trivia questions, that is, when curiosity was elicited, activity in the bilateral NAcc and the left SN/VTA increased linearly with participants' curiosity ratings. This suggests that key regions of the dopaminergic circuit involved during extrinsic reward anticipation also correlate with the level of curiosity. In contrast, however, once curiosity had been satisfied (i.e., when the answer was shown), these two regions no longer showed an increase of activation for high- compared to low-curiosity states. In line with Kang et al.'s hypothesis, these findings underscored the role of anticipatory activity during curiosity states ahead of upcoming information.

Recent studies have also shown activity in several brain areas outside the dopaminergic system when comparing high- versus low-curiosity states (Gruber et al., 2014; Ligneul et al., 2018; Van Lieshout et al., 2018) or when participants act on their curiosity to choose which stimuli they would like to see (Chiew & Adcock, 2019; Lau et al., 2020; Oosterwijk et al., 2020). These regions include the anterior cingulate cortex (ACC, Lau et al. 2020; Ligneul et al., 2018; Oosterwijk et al., 2020;), which has been suggested to support information-based prediction errors (Alexander & Brown, 2019; Gruber et al., 2019), the lateral prefrontal cortex (Chiew and Adcock, 2019; Gruber et al., 2014; Kang et al., 2009; Lau et al., 2020; Ligneul et al., 2018), which may provide informational input to the dopaminergic midbrain to initiate actions such as exploration (Ballard et al., 2011) and plays a fundamental role in supporting cognitive control processes (Miller & Cohen, 2001), and the anterior insula (Lau et al. 2020; Ligneul et al., 2018; Oosterwijk et al., 2020), which has been implicated in salience detection and uncertainty processing (Menon & Uddin, 2010; Singer et al., 2009).

One key difference between state curiosity and states associated with reward motivation is that reward delivery is generally thought to motivate future behaviour that leads to the same reward. By contrast, information that completely resolves uncertainty no longer motivates exploratory behaviour. Therefore, curiosity motivates us to constantly seek new, unknown information (Berlyne, 1950; Litman et al., 2005). Interestingly, the effects of reward and curiosity are not additive, and reward has been shown to undermine curiosity and its effect on memory (Murayama

et al., 2010; Murayama & Kuhbandner, 2011). Thus, curiosity can be seen as a motivational state that is at least partially distinct from states that motivate the acquisition of primary reinforcers.

The aforementioned studies investigated curiosity in itself by asking participants how curious they were about the stimuli. However, and since we have defined curiosity as the intrinsic motivation to seek for information, research investigating information-seeking behaviour is also relevant to this field.

Information seeking is often described as the active pursuit of knowledge (Sharot & Sunstein, 2020) and it can be either instrumental or non-instrumental. Instrumental information seeking refers to all those activities in which agents seek information for immediate strategic reasons (Kidd & Hayden, 2015). An example of that would be paying to know the outcome of a gamble before choosing it to make a more profitable choice. These forms of information seeking are externally triggered. On the other hand, non-instrumental information seeking is internally triggered and seems to be independent of a foreseeable profit.

Traditionally, information seeking has been studied by using k-arm bandit tasks in which participants are faced with a series of choices between stochastic rewards. The optimal strategy requires a balance between exploration (sampling to improve knowledge and, therefore, future choices) and exploitation (choosing known best options). Although sampling often yields lower immediate gains, it can provide information that improves decision-making in the future, resulting in greater overall performance (Kidd & Hayden, 2015). In this case, information seeking (or exploration) would be instrumental since participants try to optimize the obtained reward. But, what about when the information has no clear benefit? How to study non-instrumental information seeking?

Bromberg-Martin and Hikosaka (2009) addressed that by designing a temporal resolution of uncertainty task. In this task, monkeys needed to choose between two options, an informative option that provided a reliable cue about whether the water reward they would get at the end of the trial was big or small, and an uninformative option that showed a random cue. Therefore, the only difference between the two options was whether they received advanced information about the reward or not. Results showed that monkeys reliably chose the informative option. Importantly, this choice was not strategic because the information could not be used to influence the outcome. Therefore, this suggested that monkeys intrinsically valued non-instrumental information and opened the door to the idea of information being a rewarding stimulus.

Further experiments tried to quantify the value monkeys assigned to information. For instance, Blanchard et al. (2015), building upon Bromberg-Martin and Hikosaka's task, created a paradigm

where monkeys had to choose between informative and uninformative options indicating (reliably or not, respectively) whether they would actually get the indicated reward or not. Notably, the key manipulation here was that each option was associated to a different magnitude of reward (i.e., amount of water). By using this approach, researchers were able to reconstruct psychometric functions and determine the indifference point or point of subjective equality (PSE), representing the subjective value monkeys assigned to advanced information. In other words, they measured how much water monkeys were willing to sacrifice in order to get advanced information about whether they would actually receive the reward or not. Results showed that the value of reward-related information was about 25% of the value of the reward itself, with higher stakes leading to increased information value (Blanchard et al., 2015).

The idea that information is a reward in itself was further supported by neuroimaging data. In Bromberg-Martin & Hikosaka (2009), the task included a forced choice condition in which the program only showed one of the two options (that is, informative or uninformative) so monkeys were not able to choose. Critically, the authors performed single-neuron recordings in and around the SN/VTA. Results showed that midbrain dopamine neurons are excited when the monkeys learn that they will see an informative cue ('more information than predicted') just as when monkeys learn that they will get a large water reward ('more water than predicted'). This suggests that information seeking is motivated by the same reward prediction errors (RPEs) circuitry that motivates primary reward seeking. Importantly, these findings were replicated and extended in humans. For example, Charpentier and colleagues (2018) used fMRI to compare information and reward prediction errors for gains and losses. In line with previous findings in monkeys, they demonstrated BOLD signals for information prediction errors (IPEs) in SN/VTA and NAcc.

Interestingly, Charpentier and colleagues (2018) also showed that activity in the mesolimbic dopaminergic system was sensitive to the subjective value of the information – scaling up for desirable information about likely monetary gains, and scaling down for less desirable information about likely losses. However, these results on valence-dependent information seeking were not entirely replicated in other studies. For example, Marvin and Shohamy (2018) found that people were more likely to wait for the answers to trivia questions that they rated as positive or negative than for questions they rated as neutral. Similarly, van Lieshout and colleagues (2021) found that curiosity increased with increasing uncertainty about both expected gains and expected losses in a gambling task. Thus, it seems that although positive information may be preferred to negative information in some contexts (Charpentier et al., 2018), information can be highly attractive regardless of the expected emotional impact of the information.

In summary, curiosity, often defined as an intrinsic motivation to seek information for its own sake, has been associated with activation in reward-related dopaminergic regions. Moreover, information itself has been found to be rewarding, sometimes leading individuals to forgo extrinsic rewards to obtain it. Consequently, it is reasonable to consider that curiosity is closely related to reward and may even interact with other reward dimensions, such as pleasure or learning.

1.3.2 The effect of curiosity on learning and memory

Most of the studies investigating curiosity have also assessed its effect on learning and memory. Evidence reveals that participants are better at remembering answers to questions that elicited high levels of curiosity (Fastrich et al., 2018; Galli et al., 2018; Gruber et al., 2014; Kang et al., 2009; Ligneul et al., 2018; Marvin & Shohamy, 2016; Stare et al., 2018; Wade & Kidd, 2019). Curiosity-related memory enhancements are evident in immediate (Galli et al., 2018; Gruber et al., 2014; Stare et al., 2018; Wade & Kidd, 2019) and delayed (from hours to weeks) (Fastrich et al., 2018; Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016; Stare et al., 2018) memory tests, suggesting that curiosity might enhance both memory encoding and consolidation (Gruber et al., 2014, 2019; Stare et al., 2018).

While it may appear intuitive that individuals are better at learning answers to questions that piqued their curiosity, recent findings suggest that the curiosity-related memory enhancement spreads beyond the target of a person's curiosity. For instance, studies have used a version of the trivia paradigm in which participants were incidentally exposed to faces as they anticipated the answers to trivia questions. Although the faces were irrelevant to the trivia answers, participants exhibited enhanced recognition of faces learned during high-curiosity states compared to those learned during low-curiosity states (Galli et al., 2018; Gruber et al., 2014; Stare et al., 2018).

The beneficial effect of curiosity on learning and memory may be explained by reward anticipation. Research has consistently shown that objects, as well as incidental information, preceded by high-value reward cues are better recognized than those preceded by low-value cues (Adcock et al., 2006; Gruber et al., 2016; Wittmann et al., 2005). These findings are accompanied by neuroimaging data revealing stronger activation of the SN/VTA during the presentation of high- compared to low- monetary reward cues. This increased activity in midbrain areas leads to dopamine release in the hippocampus, enhancing memory formation and consolidation (Lisman et al., 2011). It is worth noting that recent findings suggest that reward anticipation enhances memory formation through an increase in anticipation-related arousal, reflected in dorsal ACC activity, rather than dopaminergic midbrain activity (Gieske & Sommer, 2023). Regardless of the

neural mechanisms, it seems that memory improvements may be driven by the anticipation of a reward, which, in the case of curiosity, would be the information itself (e.g., the answer to a trivia question).

Notably, Marvin & Shohamy (2016) showed that memory enhancements are not only driven by curiosity about information but also by IPEs, that is, the discrepancy between the actual value of the received information and the anticipated value of the information. Specifically, information that is perceived as more interesting than previously expected is associated with a positive IPE and remembered better than information that is less interesting than expected (negative IPE). These findings were further supported by several behavioural studies showing that positive IPEs enhance memory independently of curiosity (Fandakova & Gruber, 2021; Fastrich et al., 2018; Lang et al., 2022).

All these findings were put together in the Prediction errors, Appraisal, Curiosity, and Exploration (PACE) framework (Gruber & Ranganath, 2019). This framework proposes that curiosity is first triggered by significant prediction errors (PEs) that can be either context-based, elicited in response to detection of novel context or unexpected context change and supported by the hippocampus, or information-based, arising from the detection of an information gap due to cognitive conflict and supported by the ACC. PEs trigger an appraisal process supported by the lateral prefrontal cortex during which it is decided whether the current state of uncertainty reflects a potential threat and, if not, whether one has the skills, expertise, and resources needed to resolve the uncertainty. Subsequently, “curiosity enhances memory encoding through increased attention, exploration, and information seeking and enhances the consolidation of information acquired while in a curious state through dopaminergic neuromodulation of the hippocampus” (Gruber & Ranganath, 2019, p. 1014).

Recently, Gruber’s research team investigated whether the extent to which individuals benefit from memory-enhancing effects of curiosity and IPEs could be determined by inter-individual differences in functional connectivity (Eschmann, Valji, et al., 2023). They found a double dissociation: whereas individual differences in functional connectivity between the VTA and the NAcc accounted for curiosity-driven but not IPE-related memory enhancements, individual differences in functional connectivity between the ACC and the hippocampus predicted IPE-driven but not curiosity-related memory benefits. These findings suggest that the PACE framework should be modified to account for the fact that memory enhancements are not always dependent of mesolimbic regions (i.e., VTA and NAcc) but can also be supported by IPE-coding regions (i.e., ACC and hippocampus).

1.3.3 Curiosity and music

Traditionally, studies investigating curiosity have employed discrete and brief pieces of information, such as trivia questions (Gruber et al., 2014; Kang et al., 2009), blurry photos with ambiguous content (Jepma et al., 2012), or lottery trials (Kobayashi et al., 2019; Van Lieshout et al., 2018). However, these experimental designs lead to a rapid satiation and extinction of curiosity, reinforcing Loewenstein's (1994) idea of curiosity being highly transient and failing to account for its temporal component. Hence, the dynamic nature of music offers an appealing alternative for studying the temporal evolution of curiosity. Thus far, only two studies have investigated curiosity in the context of music.

The first study assessed the extent to which listeners' perception of change in music triggered their curiosity as to how the music would unfold (Omigie & Ricci, 2022). Specifically, participants were presented with unfamiliar musical excerpts and asked to provide continuous ratings of their subjective experience of curiosity (i.e., "how curious you are feeling about what will happen next in the music") and their perception of change (i.e., "the extent to which you consider the music to be changing") as the music unfolded. Results showed that for all musical pieces, the perceptual experience of change seemed to precede and cause feelings of curiosity.

In a further study, the same authors investigated whether the information-theoretic properties of music can influence the experience of curiosity during listening (Omigie & Ricci, 2023). Specifically, participants were asked to indicate, when cued, how curious they were about how melodies would continue. Subsequently, a statistical model of melodic expectancy was used to estimate, for each note of the different melodies, information content, a measure of unexpectedness, and entropy, a measure of uncertainty. The researchers observed a positive association between curiosity and information content in low entropy contexts. Conversely, in high entropy contexts, low information content was sometimes associated with greater curiosity. These findings were in line with previous results showing that the interaction between information content and entropy accounted for musical pleasure (Cheung et al., 2019; Gold, Pearce, et al., 2019).

Crucially, this effect was influenced by individual differences in musical expertise and curiosity trait. Specifically, the study revealed that listeners with no music-theory training (and having little to no experience in playing music) were less influenced by musical structure and more driven by judgments of stimulus valence compared to those with music-theory training. In addition, results showed that listeners with different curiosity profiles, as assessed by the Five-Dimensional Curiosity Scale (Kashdan et al., 2018), exhibited variations in their preference for high and low

information content musical events. These results were in line with those reported by Galvan and Omigie (2022), showing how trait curiosity influences appreciation of unfamiliar music.

Despite these relevant studies, music curiosity remains poorly investigated in the music cognition literature. Furthermore, the potential interaction of curiosity with music reward components, such as pleasure, remains unexplored. Considering the temporal nature of both pleasure and curiosity, it would be interesting to assess how they evolve and interact over time. This could reveal different patterns, such as curiosity acting as an anticipatory state for pleasure experience, or the generation of a positive feedback loop that increases pleasure and sustains curiosity.

Research Aims

2 Research Aims

The research work developed in the present dissertation had two main goals. First, we sought to deepen our understanding of musical reward by exploring how it is influenced by two key processes: absorption and curiosity. Second, we investigated the impact of music reward, along with curiosity, on learning and memory. To this end, we established four specific aims.

The **first aim** was to further investigate the effect of the most well-known musical reward component, pleasure, on learning and memory. Previous research had shown a positive effect of musical pleasure on memory for music itself (Ferreri & Rodríguez-Fornells, 2017). However, it remained unexplored whether this effect could extend to simultaneously presented materials (e.g., lists of words). Thus, in our first study, we aimed to **investigate whether musical pleasure had an impact on memory for verbal material** [Study 1, Cardona et al. (2020)]. Additionally, we examined how individual differences in sensitivity to musical reward (i.e., musical hedonia) influenced this effect. With an exploratory purpose, we also tested the penumbra hypothesis, which suggests that memory for events that occur before and after dopamine release (e.g., presentation of word lists) would depend not only on their own properties, but also on whether they fall within the penumbra of a dopamine-releasing stimulus (e.g., music; Lisman et al., 2011). To address these questions, we conducted a behavioural study in which participants encoded words presented in different auditory contexts (highly pleasant classical music, lowly pleasant classical music, and control white noise), played either before and during, or only before the encoding. Twenty-four hours later, participants' verbal episodic memory was tested using an old/new recognition and remember/know paradigm (Yonelinas, 2002). The Barcelona Music Reward Questionnaire (BMRQ, Mas-Herrero et al., 2013) was used to measure participants' musical hedonia. We hypothesized that words encoded while listening to highly pleasant classical music would be better recognized and remembered than those presented with lowly pleasant music or white noise. Furthermore, we expected this effect to be stronger in participants with higher musical hedonia compared to those with lower musical hedonia. Finally, we hypothesized that memory enhancement would be similar whether music was played both before and during the encoding or only before.

The **second aim** of this thesis was to **investigate the potential contribution of absorption to musical reward** [Study 2, Cardona et al. (2022)]. Since peak experiences and flow states are often achieved during active music listening, and considering that absorption is a key aspect of these experiences, it seemed appropriate to study the influence of absorption on musical reward. Accordingly, we conducted a study where participants completed the Absorption in Music Scale

(Sandstrom & Russo, 2013), a questionnaire inspired by the Tellegen Absorption Scale (Tellegen and Atkinson, 1974) that measures individuals' ability and willingness to be drawn into an emotional experience by music, and the Barcelona Music Reward Questionnaire (Mas-Herrero et al., 2013), known for its reliability and robustness in assessing individual differences in music reward sensitivity (i.e., musical hedonia). We hypothesized that, although scores on both questionnaires might be highly correlated, certain absorption-related items could assess a distinct aspect of the musical experience compared to the existing facets. By identifying these items, we aimed to create a more comprehensive version of the BMRQ, which would better characterize individual differences in musical hedonia by accounting for the absorption aspect of the musical experience.

The **third aim** of this thesis was to **investigate the influence of curiosity on musical reward and its impact on memory for music (Study 3)**. Specifically, we sought to determine the value participants assigned to exploring new music and how this subjective value was influenced by curiosity. In other words, we measured participants' willingness to pay for further exploring a song depending on their level of curiosity. Moreover, we examined how musical hedonia modulated this effect. Finally, we assessed the impact of curiosity and musical hedonia on memory for music. To achieve this, we designed a novel exploration/exploitation tradeoff paradigm in which participants chose between listening to new electronic music (which they had pre-listened to for 10 seconds) or their favourite music. Importantly, each option was associated with a monetary reward. Twenty-four hours later, participants' memory for music was tested using an old/new recognition and remember/know paradigm (Yonelinas, 2002), and their musical hedonia was assessed using the extended version of the BMRQ (eBMRQ) developed in Study 2. This paradigm was adapted to be conducted in a naturalistic setting to assess these effects in a real-world context with all its inherent complexity. Our main hypothesis was that curiosity would significantly influence exploratory behaviour, even at a cost. In addition, we expected this effect to be influenced by musical hedonia. Finally, we hypothesized that both curiosity and musical hedonia would positively influence musical memory performance.

Finally, the **fourth aim** of the present thesis consisted in **investigating the temporal evolution and potential interplay of music-induced curiosity and pleasure, as well as their effects on memory for music and information (Study 4)**. Based on the results from Study 3, we assumed curiosity to significantly modulate musical reward and sought to understand how it interacts with pleasure over time. Notably, few studies have explored the temporal dynamics of pleasure, and even fewer have examined curiosity. In this sense, music, as a complex stimulus evolving over time, provided an ideal context for this investigation. With that aim, we performed an experiment

Research Aims

in a music-and-science event. Participants were asked to provide continuous ratings of either pleasure or curiosity during a 10-minutes classical music piece performance. They did it twice, once at the beginning of the event and again at the end, after receiving profuse information about the musical material (i.e., information-learning phase). Twenty-four hours later, participants' memory for the music was tested using an old/new recognition and remember/know paradigm (Yonelinas, 2002), and their memory for the information was assessed using a 10-question multiple-choice test. In addition, they completed a series of questionnaires, including the eBMRQ. We hypothesized that during the first listening, when the piece was unfamiliar, curiosity would be higher than pleasure. Furthermore, we posited that experiencing pleasure would not be possible without experiencing some degree of curiosity first. Thus, we expected curiosity ratings to anticipate subsequent pleasure ratings. Conversely, during the second listening, after participants had received extensive information about the musical piece, we expected pleasure to be higher than curiosity as a result of an increase in pleasure and a decrease in curiosity due to satiation. Regarding memory outcomes, we expected that both curiosity and pleasure ratings would predict memory performance. Finally, we hypothesized that musical hedonia would modulate both the ratings provided by the participants and memory performance.

Study 1

The impact of musical pleasure and musical hedonia on verbal episodic memory

This study corresponds to:

Cardona, G., Rodriguez-Fornells, A., Nye, H., Rifà-Ros, X., & Ferreri, L. (2020). The impact of musical pleasure and musical hedonia on verbal episodic memory. *Scientific Reports*, 10, 16113.
<https://doi.org/10.1038/s41598-020-72772-3>

3 Study 1

The impact of musical pleasure and musical hedonia on verbal episodic memory

3.1 Introduction

Music has a strong emotional power. Accordingly, the most common goal of musical experience is related to music's ability to modulate emotional state in the listeners (Juslin & Västfjäll, 2008). Several studies have shown that, besides recreation, distraction or mood regulation, music-evoked emotions can also drive memory enhancements in both healthy (Aubé et al., 2013; Eschrich et al., 2008; Greene et al., 2010) and clinical (Meilán-García et al., 2011; Samson et al., 2009) populations. Most part of these studies focused on two crucial dimensions of musical emotions, namely arousal and valence (Jäncke, 2008). In the present study, we aimed at studying the link between music, memory and emotion by focusing on a particular aspect of music-induced affective responses (Zatorre & Salimpoor, 2013): *pleasure*. Together with motivational and learning aspects, pleasure constitutes a crucial emotional component of reward processing (Berridge & Kringelbach, 2008). Pleasure is a complex construct, particularly for humans who, in addition to primary (e.g., food) and secondary reinforcers (i.e., a reward with a learned value associated to a primary reinforcer, such as money), can also trigger rewards from internal mental states (e.g., flow and curiosity, Csikszentmihalyi, 1975; Gruber et al., 2014), intrinsic motivational processes (Gottlieb et al., 2013; Ryan & Deci, 2000), and more abstract rewards such as music and aesthetic appreciation (Skov, 2019). Music-induced pleasure is strongly related to increases in physiological arousal, such as skin conductance responses (SCR) or heart rate (Blood & Zatorre, 2001), and to the activity of core reward-related regions within the mesolimbic dopaminergic system (Ferreri et al., 2019; Koelsch, 2014; Mas-Herrero, Dagher, et al., 2018; Menon & Levitin, 2005; Salimpoor et al., 2011, 2013). Interestingly, humans show music-specific hedonia (i.e., individual differences in sensitivity to musical pleasure, efficiently measured through the Barcelona Music Reward Questionnaire, BMRQ, Mas-Herrero et al., 2013). While listening to music, high-musical hedonic individuals, compared to low- or to music anhedonics, report more intense feelings of pleasure. Furthermore, these subjective ratings are associated to higher SCR as well as higher brain activity and increased functional connectivity in several core regions of the human reward and dopaminergic system (Martínez-Molina et al., 2016; Mas-Herrero et al., 2014). Even though music does not provide direct survival advantages, it recruits brain networks similar

to the ones activated by primary rewards, such as food or sex. This raises crucial questions about the nature and the possible implications of music hedonic signals.

Crucially, and in line with a wide range of literature showing the importance of emotional significant experiences in memory (McGaugh, 2018) and learning (Tambini et al., 2017; Tambini & Davachi, 2019), recent research has shown that reward is intimately related to memory processing (Adcock et al., 2006; Gruber et al., 2014; Wittmann et al., 2005; Wolosin et al., 2012). At a behavioural level, information associated to potential external rewards (e.g., money or higher point-values in a task where the goal is to earn a larger score, Adcock et al., 2006; Hennessee et al., 2017; Loftus & Wickens, 1970; Murayama & Kitagami, 2014), internal curiosity states (Gruber et al., 2014) or intrinsic self-regulated learning processes (Ripollés et al., 2016), lead to better memory performance. According to the neoHebbian framework for episodic memory, this positive memory effect might be related to the interaction between midbrain dopaminergic neurons (substantia nigra/ventral tegmental area complex, SN/VTA) and the hippocampus (Goto & Grace, 2005; Lisman et al., 2011; Lisman & Grace, 2005). Reward-motivated activation of midbrain dopamine neurons might indeed result in dopamine release able to strengthen long-term potentiation in the hippocampus, thus enhancing the capacity to store relevant new information into long-term memory (Schultz, 2000) and improving further consolidation processes (Chowdhury et al., 2012; Ripollés et al., 2018). This would in turn lead to an enhanced recollection associated with better quality, higher confidence and more detailed episodic traces (Chowdhury et al., 2012; Tulving, 1985; Yonelinas, 2002). Being music a rewarding stimulus triggering dopamine release (Ferreri et al., 2019) it is possible that its positive effect on memory might be at least partially related to the pleasurable responses it triggers (Ferreri & Verga, 2016). In line with this hypothesis, Ferreri & Rodriguez-Fornells showed that unfamiliar classical music excerpts rated as more pleasant during encoding were significantly better recognized and remembered the next day (Ferreri & Rodriguez-Fornells, 2017). Furthermore, they showed that individual differences in the ability to experience reward from music (as measured via the BMRQ, Mas-Herrero et al., 2013) positively predicted memory performance. Notice however, that this study focused on memory for music itself and it did not explore the possibility of music-related reward responses favouring the consolidation of non-musical material (e.g., verbal information) concurrently present during the encoding process.

The main aim of the present study was, therefore, to determine whether music-driven reward can modulate episodic verbal memory performance for associated items present in the encoding context. To investigate this issue, participants encoded lists of real words in three different auditory contexts: highly pleasant music, lowly pleasant music and white noise. 24 hours later their memory was tested with an old/new recognition paradigm. In addition, and in order to test

whether the music-related reward responses may specifically influence the recollective episodic experience (Chowdhury et al., 2012), we used a remember/know paradigm to differentiate between recollection ('remember' responses) and familiarity ('know' responses) processes (Yonelinas, 2002). Furthermore, we employed the BMRQ to evaluate inter-individual differences in musical reward sensitivity. We would expect that words presented in a highly pleasant musical context would be better recognized and remembered than the ones presented in lowly pleasant music or white noise conditions. Moreover, according to our previous results (Ferreri & Rodriguez-Fornells, 2017), we would expect different memory performance according to inter-individual differences in the ability to experience musical reward. Specifically, participants with a higher musical hedonia might benefit more from a highly pleasant musical context (i.e., better memory performance) than less musical hedonic participants.

In order to further investigate the link between music reward and memory, the second aim of the present study was to determine whether the positive effect of musical pleasure on memory performance persists even when music is not concurrently present during the encoding of target items. According to the Behavioral Tagging hypothesis (BT, Moncada & Viola, 2007), a short-lasting memory induced by a weak event can be consolidated into a long-term memory if paired relatively close in time (usually, within 1 hour before until 2 hours after the weak event (Moncada et al., 2015) with an independent and strong event (e.g., a novel or rewarding stimulus). At a cellular level, the weak stimulation sets a tag to a specific synapse where plasticity-related proteins induced by the strong event are captured. This in turn promotes long-term potentiation and creates a persistent mnemonic trace (Synaptic Tagging and Capture model, Frey & Morris, 1997; Moncada et al., 2015). Considering the importance of dopaminergic release in hippocampal long-term potentiation, the memory for events that occur before and after dopamine release would depend not only on their own properties, but also on whether they fell within the penumbra of a dopamine-releasing stimulus (Lisman et al., 2011). Accordingly, being pleasant music a stimulus triggering dopamine release (Ferreri et al., 2019), it is possible that events occurring not only during, but also after its presentation might result in enhanced memory traces. In order to address this exploratory question, we manipulated the duration of the auditory stimuli during the encoding of verbal material. Half of the participants performed a version of the task in which music was heard before and during the encoding of lists of words ('with auditory background' version) and the other half of the sample completed a version in which music was presented only before the encoding ('without auditory background' version). According to the penumbra-BT hypothesis, we might expect memory performance enhancement driven by music reward to show no significant differences between these two experimental versions.

3.2 Material and Methods

Participants

One hundred and eleven participants (95 female, mean age = 21.1, sd = 2.71), all non-professional musicians (83 non-musicians and 28 amateurs), took part in the study in exchange of university course credits. For each subject, a measure of exposure to classical music (i.e., ‘How often do you listen to classical music?’) was obtained (1-5 scale, from 1: ‘never’ to 5: ‘every time I listen to music, I listen to classical music’). Participants were also asked how much they liked classical music (1-5 scale, from 1: ‘I strongly dislike classical music’ to 5: ‘I love classical music’). All of them were tested with the Physical Anhedonia Scale (PAS; Chapman et al., 1976) and a modified version of the BMRQ (Mas-Herrero et al., 2013), which included 20 items on musical reward (1-5 scale, from 1: ‘I totally disagree’ to 5: ‘I totally agree’) and two additional items selected to assess amusia (item 21 ‘I can barely perceive when someone is singing out-of-tune’ and item 22 ‘I’m usually unable to recognize a very familiar melody without the help of the lyrics’). The BMRQ shows a 0.92 reliability and it comprises five different facets: Musical Seeking, Emotion Evocation, Mood Regulation, Social Reward, and Sensory-Motor (0.89, 0.88, 0.87, 0.78 and 0.93 reliability, respectively). The BMRQ score density curve in our sample was very similar to the one shown by a demographically comparable sample used for exploratory and confirmatory analyses of the questionnaire (Mas-Herrero et al., 2013) (see **Figure 1**).

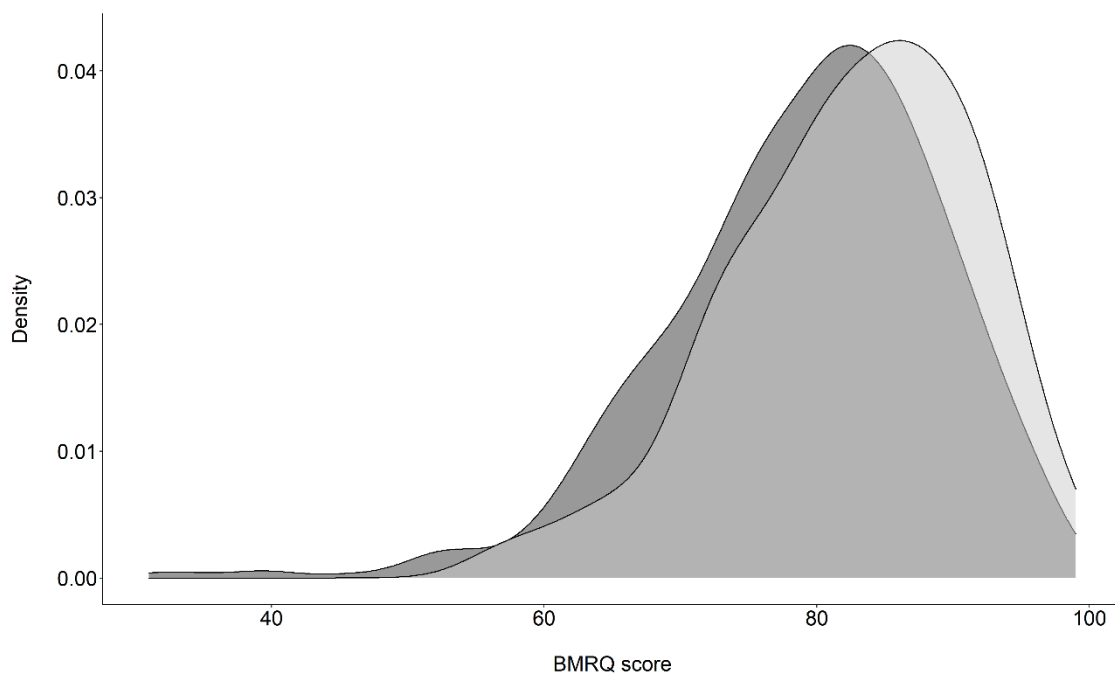


Figure 1. BMRQ score density plots for our sample (light grey, N = 111, 86% female, mean age = 21.1, sd = 2.7) and the sample used in Mas-Herrero et al. (2013) (dark grey, N = 605, 68% female, mean age = 20.5, sd = 3.3).

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From the N=111 sample, two participants reported amusia, five participants resulted general anhedonics and four participants were musical anhedonics. These eleven participants were excluded from the analyses here reported. Thus, the final sample consisted of 100 participants (88 female, mean age = 20.9, sd = 2.57; **see Table 1**).

The present study was approved by the Ethics Committee of the University of Barcelona. It was conducted in accordance with the Declaration of Helsinki and all participants provided written informed consent.

	Age	Classical Music Liking	Classical Music Exposure	PAS score	BMRQ score					
					MS	EE	MR	SM	SR	Overall
<i>M</i>	20.93	3.41	1.95	9.30	14.67	16.75	18	16.12	16.12	83.69
<i>SD</i>	2.57	1.02	1.01	4.30	2.92	2.33	1.69	2.36	2.47	7.57

Table 1. *Descriptive Statistics (N=100).* M = Mean. SD = Standard Deviation. Classical Music Liking and Exposure range from 1 to 5. For the BMRQ, raw mean additive scores of its five facets [Musical Seeking (MS), Emotion Evocation (EE), Mood Regulation (MR), Sensory-Motor (SM), and Social Reward (SR)] and the overall scale are reported. Maximum score for each facet is 20; with higher scores indicating more sensitivity.

Materials

Musical stimuli

Musical stimuli consisted of 10 instrumental classical music excerpts. The selection of these excerpts was twofold. First, we selected the 10 excerpts rated as most pleasant and the 10 excerpts rated as most unpleasant from a list elaborated in a previous study (Ferreri & Rodriguez-Fornells, 2017). Then, these 20 pieces were additionally rated by an independent sample of 24 participants in terms of familiarity (from 1 = completely unfamiliar to 5 = completely familiar), arousal (from 1 = very relaxing to 5 = very arousing), emotional valence (from 1 = very sad to 5 = very happy) and general pleasantness (from 1 = no pleasantness to 5 = very high pleasantness/chills). From these ratings, we selected the 5 excerpts with the highest (mean = 3.23, sd = 0.14) and the 5 excerpts with the lowest pleasantness ratings (mean = 2.16, sd = 0.36). These two groups (high-pleasure vs. low-pleasure) did not differ in terms of arousal, emotional valence and familiarity (all $p_s > 0.05$, two-sample t -tests). Furthermore, we used Spotify's *Sort Your Music* tool to obtain, for each excerpt, the following attributes: tempo (bpm), energy, valence, and popularity (see **Table 2**). No significant differences were found between the two groups of stimuli (all $p_s > 0.05$, two-sample t -tests). In addition to the musical stimuli, white noise (i.e., a random signal with equal power at any frequency in a given bandwidth) was used as control condition.

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Each auditory stimulus (i.e., musical excerpts and white noise) was normalized (-10 dB) and faded (3s in and 3s out) with Audacity software (version 2.1.0, Mazzoni, 1999).

Verbal stimuli

300 Spanish words were selected from EsPal database (Duchon et al., 2013). These words were 3-10 letter, singular and concrete nouns. The frequency was set at 2-6 per million (database mean = 3.60). Words were divided into 30 blocks with 10 words each one so that there were no significant differences between blocks in terms of number of letters, frequency, concreteness, familiarity and imageability (all $p_s > 0.05$, repeated-measures ANOVA with a thirty-level within-subjects factor). In addition, semantic relationships between items in each block were avoided to the extent possible. Blocks were divided into two lists, counterbalanced across subjects, one including the items to be encoded and the other one containing the new items randomly mixed with the target items in the recognition test.

Title	Artist	Key	T	E	V	P	PR
<i>Highly pleasant</i>							
Scherzo capriccioso, Op. 66, B. 131	Antonín Dvořák	B flat major	122	8	6	1	3.46
Scenes de bal, Op. 17: I. Entreées des masques	Jules Massenet	F major	109	7	25	0	3.25
Suite bergamasque: I. Prelude	Claude Debussy	F major	90	7	11	7	3.21
Symphony No. 8 in F Major, Op. 93: I. Allegro vivace e con brio	Ludwig van Beethoven	F major	146	15	18	0	3.17
6 Pieces for Organ: Variation	César Franck	B minor	76	3	17	0	3.08
<i>Lowly pleasant</i>							
Concerto grosso in G Minor, Op. 6 No. 6, HWV 324 (Transc. M. Podeur & O. Bass): V. Allegro	George Frideric Handel	G minor	135	26	79	1	2.54
6 Bagatelles, Op. 126: II. Allegro	Ludwig van Beethoven	G minor	71	16	23	2	2.42
3 Intermezzos, Op. 117: No. 3 in C-Sharp Minor, Andante con moto	Johannes Brahms	C sharp minor	65	1	8	0	2.29
Mikrokosmos, Sz. 107, BB 105, Vol. 6: No. 149. Dance in Bulgarian Rhythm II	Béla Bartók	C major	101	33	47	2	1.79
Symphonic Études, Op. 13: Étude No. 7	Robert Schumann	E major	108	36	9	2	1.75

Table 2. *Musical stimuli.* T = tempo (bpm), E = energy, V = valence, P = popularity. These values were obtained from Spotify's *Sort your music* tool. PR = mean pleasantness ratings provided by the independent sample.

Procedure

On day 1 participants were exposed to 15 encoding blocks (5 highly pleasant music excerpts + 5 lowly pleasant music excerpts + 5 white noise, 10 words for each block). Each block consisted of 40 seconds of a fixation cross followed by 30 seconds during which words appeared at the centre of the screen (10 words, one at a time, 3 seconds each). In the version with auditory background, participants (N=49) listened to the music/white noise during the whole block (i.e., 70 seconds, see **Figure 2**). In the version without auditory background, participants (N=51) only listened to music during the first 40 seconds of each trial (i.e., during the fixation cross, before the encoding) and encoded words in silence (see **Figure 2**). Between blocks, participants were allowed to rest for 5 seconds in silence. Presentation of both lists of words and musical/white noise excerpts were randomized across participants.

24 hours later, all participants were presented with 150 old and 150 new words. For each one, they had to indicate if they had seen it the day before (old/new recognition). If so, they had to commit to one of three additional options (recollection task): remember (R), know (K), or guess (G) (see **Figure 2**). R indicated that they could recollect something specific about the study episode, K indicated that the word was confidently familiar but they had no recollective experience, and G responses were given when unsure whether the word was old or new (R/K paradigm, Yonelinas, 2002).

Auditory stimuli were presented using a headset, and the experiment run on E-Prime software (version 2.0; Psychology Software Tools, Sharpsburg, PA, USA).

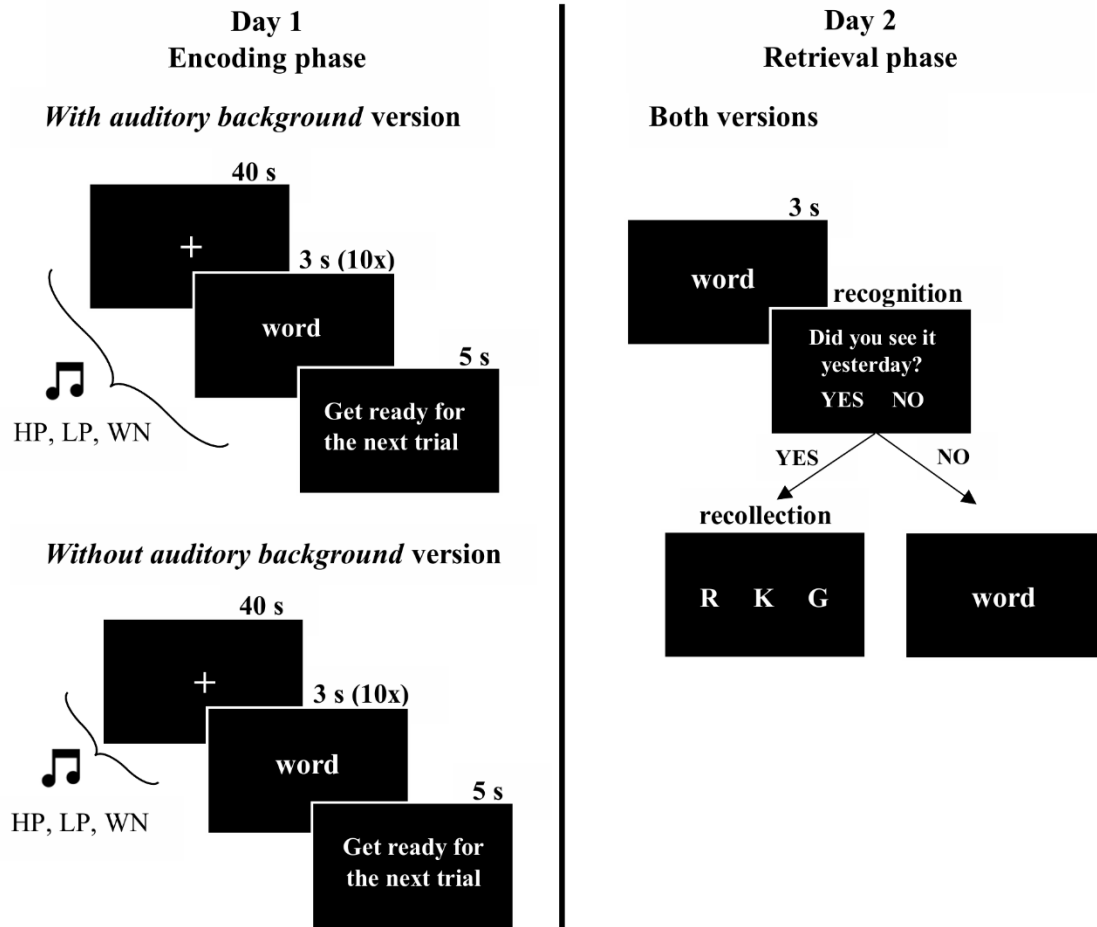


Figure 2. Experimental design. Procedure in day 1 was repeated 15 times corresponding to the 5 excerpts in the three different contexts [Highly pleasant (HP), Lowly pleasant (LP), and White noise (WN)]. Procedure in day 2 was repeated 300 times (150 old words and 150 new words).

Data analysis

We defined as outliers those participants with a d' -prime outside the range $\pm 3sd$. In order to test homogeneity between the groups that completed the different versions (i.e., with or without auditory background) of the task, we ran Student's t -tests for those scales following a normal distribution (i.e., BMRQ), Mann Whitney U tests for ordinal measures and for those scales not following a normal distribution (i.e., classical music liking, classical music exposure and PAS) and Chi-Squared tests for nominal measures (i.e., musical expertise). Bonferroni's correction for multiple comparisons was applied to all statistical significance tests.

In order to test whether different conditions, participants' musical hedonia and/or the presence or absence of an auditory background during the encoding had a significant effect on recognition performance we used a generalized linear mixed model (GLMM) approach on single trials. The dependent variable (whether the old items were correctly recognized, 'YES', or not, 'NO') was

assumed to have a binomial distribution. Therefore, we applied a logit link function. As explanatory variables we used Condition (i.e., highly pleasant music, lowly pleasant music and white noise) as within-subjects factor and BMRQ score and Background (i.e., with or without auditory background) as between-subjects factors. In order to account for the variability on memory performance from one participant to another, random intercepts for participants were included. BMRQ score predictor was grand-mean centred to avoid convergence failures. Laplace approximation was used for parameter estimation.

Backward elimination method was used for model selection, starting with the full model including all fixed effects (and their interaction) and random intercepts for participants. Increases in model fit were assessed using the likelihood ratio test. Marginal and conditional R^2 ($R^2_{(m)}$ and $R^2_{(c)}$, respectively) were used as a measure of goodness-of-fit of the final model. $R^2_{(m)}$ describes the proportion of variance explained by the fixed factors whereas $R^2_{(c)}$ explains the proportion of variance explained by both fixed and random factors (Nakagawa & Schielzeth, 2013). Likelihood ratio tests were performed in order to assess the contribution of the different predictors and their interaction to the response variable. Following a significant interaction, pairwise contrasts were used to test how the effect of the continuous variable on memory varied across conditions.

The same analysis was run to test the possible effect of different conditions, participants' musical hedonia and/or the presence/absence of the auditory stimulus during encoding on recollection performance. In this case, recollection responses were reorganized into two categories ('Remembered', including 'R' responses, and 'Not remembered', including both 'K' and 'G' responses) and a binomial distribution of the response was assumed.

When using this paradigm, 'R' and 'K' responses are the most frequently chosen options. Consequently, analyses performed on these responses usually lead to complementary results. However, given that participants can also choose the 'guess' (i.e., 'G') option, these results could differ. Thus, we performed the analysis for 'K' responses. In this case 'G' responses were excluded, so the response variable represented whether the recognized word had been further classified as 'know' ('K' responses) or 'remember' ('R' responses) and it was assumed to have a binomial distribution.

Analyses were carried out using *lme4* (Bates et al., 2015), *emmeans* (Lenth et al., 2020), and *piecewiseSEM* (Lefcheck et al., 2019) packages in R (version 3.6.0, R Core Team, 2019).

3.3 Results

Memory performance resulted significantly above chance level for both recognition ($t(99) = 10.02, p < 0.001, d = 1.00$, one sample t -test) and recollection ($t(99) = 5.76, p < 0.001, d = 0.57$, one sample t -test; see **Table 3**). No significant differences in memory performance, musical hedonia, general hedonia, classical music liking, classical music exposure or musical expertise (all $p_s > 0.121$) were found between the two groups that performed the different versions of the task (i.e., with vs without auditory background).

		Recognition (hits)			Recollection ('R')			Familiarity ('K')		
		HP	LP	WN	HP	LP	WN	HP	LP	WN
With background group	<i>M</i>	0.65	0.65	0.64	0.41	0.42	0.45	0.33	0.33	0.32
	<i>SD</i>	0.17	0.15	0.17	0.20	0.16	0.18	0.17	0.15	0.14
Without background group	<i>M</i>	0.64	0.65	0.63	0.42	0.40	0.43	0.29	0.30	0.29
	<i>SD</i>	0.16	0.15	0.17	0.19	0.17	0.18	0.11	0.12	0.15

Table 3. *Memory performance.* M = Mean. SD = Standard Deviation. Recognition: proportion of old items correctly recognized (i.e. hits; 50 items per condition). Recollection: proportion of hits further classified as 'remembered'.

Recognition

The full model included Condition, BMRQ score and Background predictors as well as the three double interactions and the triple interaction. Random intercepts for participants were also considered [intra-class correlation coefficient (ICC) = 0.114]. Backward elimination lead to discard all predictors, suggesting that memory performance at the recognition level was not modulated by any of the factors considered in the model.

Recollection

The full model included Condition, BMRQ score and Background predictors as well as the three double interactions and the triple interaction. Random intercepts for participants were also considered (ICC = 0.131). Backward elimination revealed that the best model was the one considering Condition, BMRQ score, and their interaction ($\chi^2(5) = 20.9, p < 0.001, R^2_{(m)} = 0.008, R^2_{(c)} = 0.110$; see **Table 4**). Likelihood ratio tests showed a significant effect of BMRQ score ($\chi^2(1) = 5.54, p = 0.019$) and a significant interaction between Condition and BMRQ score ($\chi^2(2) = 10.24, p = 0.006$). That is, the effect of the different conditions on memory performance was modulated by participants' sensitivity to music-induced reward (see **Figures 3 and 4a**). Post-hoc contrasts

revealed that the effect of BMRQ score on recollection performance was significantly different between highly pleasant and white noise conditions ($Z \text{ ratio} = 3.20, p = 0.004$). However, no significant differences were found between lowly pleasant and white noise conditions ($Z \text{ ratio} = 1.60, p = 0.24$) or between highly and lowly pleasant conditions ($Z \text{ ratio} = 1.63, p = 0.23$). Given the non-significant differences between the two musical conditions (presumably lead by the small difference in pleasantness ratings between the two sets of musical excerpts used as lowly and highly pleasant; mean rate of 2.16 and 3.23, respectively, on a 5 points scale) we conducted a further analysis considering the mean pleasantness ratings reported by the independent sample for each musical excerpt (i.e., rather than classifying musical stimuli into lowly and highly pleasant categories). Thus, we generated a new model including BMRQ score, Pleasantness and their interaction ($\chi^2(3) = 12.5, p = 0.006, R^2_{(m)} = 0.011, R^2_{(c)} = 0.109$). Likelihood ratio tests revealed a significant interaction between BMRQ score and Pleasantness ($\chi^2(1) = 4.07, p = 0.044$). Specifically, for highly hedonic participants, the higher the pleasantness of the excerpt, the greater the probability of remembering the words encoded during/after listening to that excerpt. On the contrary, for less hedonic participants, the higher the excerpt's pleasantness, the lower the probability of remembering the words associated to that excerpt (see **Figure 5**).

In sum, and in line with our hypothesis, episodic memory formation was particularly enhanced when a combination of both highly pleasant musical stimuli and higher sensitivity to experience reward from music were present.

On the other hand, the presence or absence of an auditory background during the encoding did not have a significant effect on recollection performance. Furthermore, the effects of Condition and BMRQ score factors on memory performance were present regardless of the presence or absence of an auditory background, suggesting that music-induced reward favoured the encoding of verbal material not only when it was presented concurrently with the rewarding stimulus, but also when it was presented immediately after.

In light of the essential role of BMRQ score in the predictive capacity of the model, we decided to further investigate this factor. In order to do that, we generated a full model with the five BMRQ facets and their interaction with Condition. Due to the small number of items composing each facet, we used the factor scores estimate instead of the raw addition of items of each subscale (Ferrando, 2012; ten Berge et al., 1999). Random intercepts were also considered in the model. Backward elimination revealed that the best model was the one including only Emotion Evocation ($\chi^2(1) = 9.43, p = 0.002, R^2_{(m)} = 0.010, R^2_{(c)} = 0.107$), suggesting that the effect of BMRQ score on memory performance was mainly driven by the Emotion Evocation facet.

Study 1

Finally, analyses for ‘K’ responses revealed that the best model was the one that only included BMRQ score ($\chi^2(1) = 10.82$, $p = 0.001$, $R^2_{(m)} = 0.012$, $R^2_{(c)} = 0.096$). As expected considering previous analyses, more hedonic participants reported less ‘K’ responses (see **Figure 4b**).

Fixed effects	df	Measures of fit				Likelihood ratio tests		
		AIC _{ci}	Δ AIC _c	w_i AIC _c	LL _i	χ^2	df	p
Cond*BMRQ*Back	13	12,570	9.01	0.01	-6,272			
Cond*BMRQ+Back	8	12,563	1.33	0.32	-6,273	2.34	5	0.801
Cond*BMRQ	7	12,561	0.00	0.63	-6,274	0.67	1	0.412
Cond+BMRQ	5	12,567	6.23	0.03	-6,279	10.24	2	0.006

Table 4. *Model selection.* Tested models for recollection. All models included the Participant variable as random effect. In the formulas, ‘Cond’ = Condition, ‘BMRQ’ = BMRQ score, ‘Back’ = Background, ‘*’ indicates an interaction, and ‘df’ = degrees of freedom. Three different measures of fit are reported: the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), and likelihood (LL). LL ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

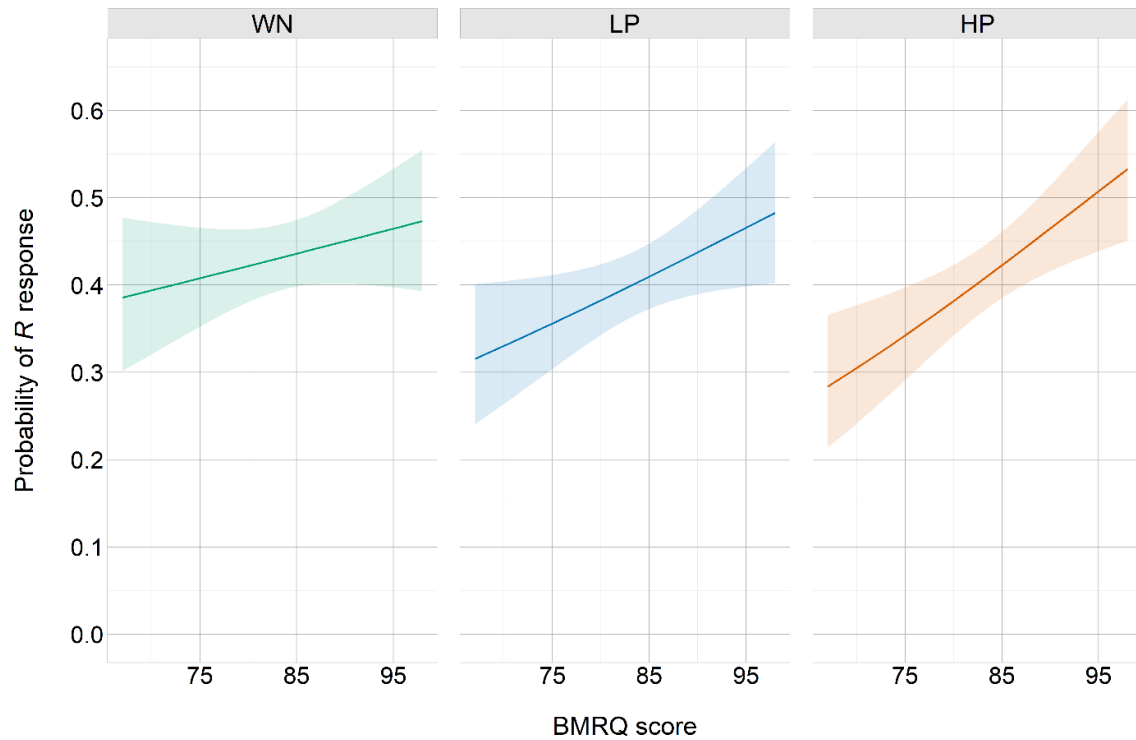


Figure 3. Predicted probability of memory recollection (i.e. ‘R’ response) as a function of participants’ musical hedonia (measured through the BMRQ) in the different conditions [White noise (WN), Lowly pleasant (LP), and Highly pleasant (HP)]. 95% confidence intervals.

Study 1

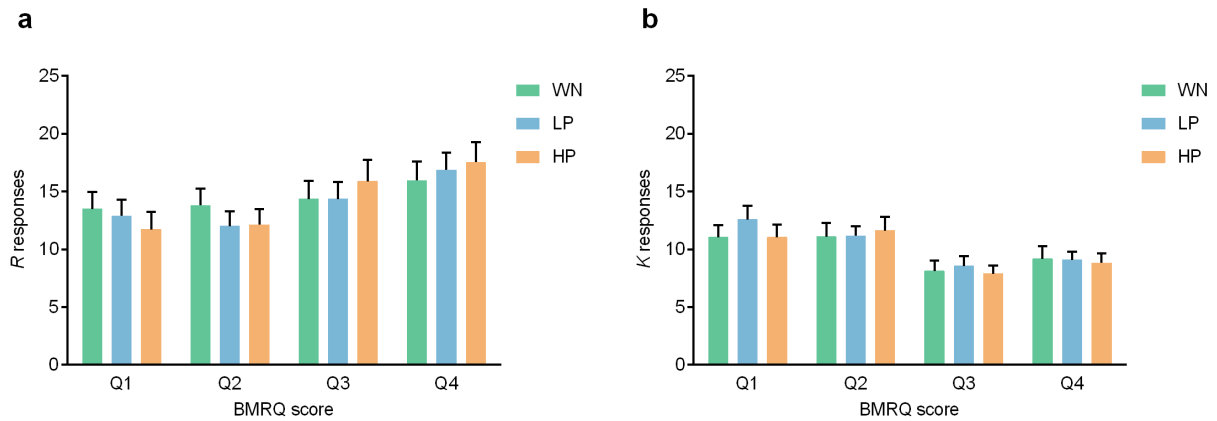


Figure 4. Mean and SEM for total 'R' responses (a) and 'K' responses (b) reported in each condition [White noise (WN), Lowly pleasant (LP), and Highly pleasant (HP)] by participants divided into quartiles according to their BMRQ score.

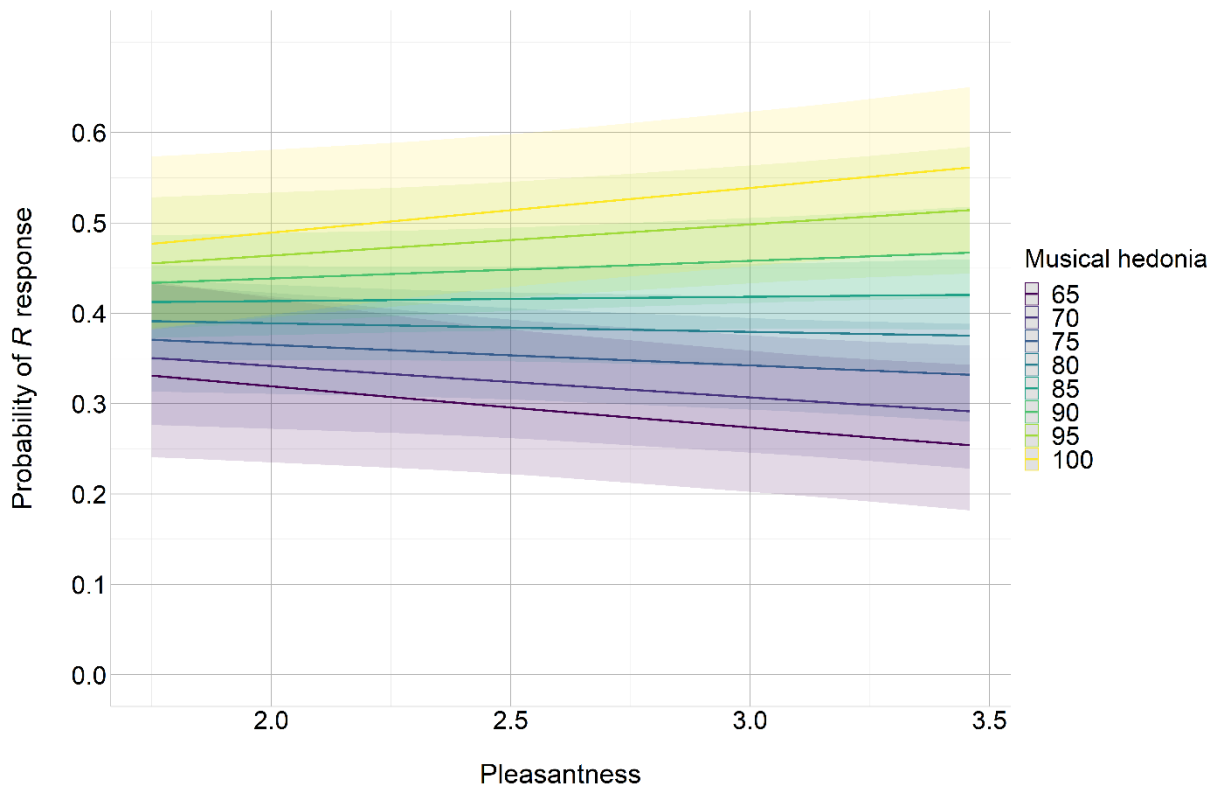


Figure 5. Predicted probability of memory recollection (i.e., 'R' response) as a function of musical excerpts' pleasantness ratings and participants' musical hedonia (measured through the BMRQ). 95% confidence intervals.

3.4 Discussion

In the present study we investigated whether musical reward, and more specifically pleasant musical material and individuals' musical hedonia, modulate verbal long-term memory. Our results showed that participants with a high musical reward sensitivity presented a greater number of episodic memory traces, especially for words encoded in a highly pleasant musical context. This effect was found regardless of the presence/absence of the auditory stimuli during verbal encoding.

This positive effect of musical pleasantness and musical hedonia on memory is in line with several studies reporting that reward, either extrinsic (Adcock et al., 2006; Hennessee et al., 2017; Murayama & Kitagami, 2014; Wolosin et al., 2012) or intrinsic (Gruber et al., 2014; Ripollés et al., 2016), can promote memory for relevant and incident information. Nevertheless, these studies used money, point-values, curiosity or self-monitoring of correct performance as reward-eliciting stimuli. One previous experiment focused on the most iconic human abstract reward, music, and showed the effect of music-related reward on musical memory (Ferreri & Rodriguez-Fornells, 2017). In the present study, by manipulating a crucial component of reward, pleasantness, we showed a transfer effect of music reward on memory for verbal material. This finding concurs with previous studies highlighting the importance of considering emotional states in predicting memory encoding and consolidation (McGaugh, 2018; Tambini & Davachi, 2019) even when the items to be remembered are emotionally neutral (Anderson et al., 2006).

An important finding of our research is that the pleasant component did not modulate memory performance at the recognition level (i.e., hits), but specifically improved recollection processes (i.e., 'R' responses). Traditionally, episodic memory is assumed to rely on two distinct memory processes: recollection and familiarity (Yonelinas, 2002). Whereas recollection entails the retrieval of specific details associated with the study event, familiarity represents the feeling of having previously encountered the item but not being able to retrieve further details. At a neural level, recollection relies on the hippocampus and prefrontal cortex, whereas familiarity relies on regions surrounding the hippocampus (see Yonelinas, 2002, for a review). As the effect of reward on learning and memory is due to an interaction between the reward network and the hippocampus (Lisman et al., 2011), rewarding stimuli should specifically improve hippocampal-dependent recollection processes. The fact that potential reward responses can specifically stimulate episodic memory performance has been previously suggested by several studies using the dopamine precursor levodopa (Apitz & Bunzeck, 2013; Chowdhury et al., 2012; Knecht et al., 2004). For example, Chowdhury and colleagues (2012) showed that levodopa enhanced memory consolidation and led to a dose-dependent long-term persistent episodic memory improvement

(i.e., increase of 'R' responses) for images in older adults. Accordingly, our results revealed that more hedonic participants showed an enhanced recollection (i.e., more 'R' responses), especially when musical excerpts were highly pleasant, with a subsequent decrease in familiarity (i.e., 'K') responses. These results suggest that, for people with a high sensitivity to musical reward, pleasant music constitutes a helpful encoding context that facilitates the retrieval of specific details associated with the study episode. Therefore, it is possible that dopamine-dependent reward responses experienced through pleasant music listening (Ferreri et al., 2019) might facilitate recollective processes for the associated material (i.e., words).

However, although we found that the positive effect of musical hedonia on recollection varied across conditions, post-hoc tests revealed that these differences were mainly driven by the comparison between highly pleasant and control conditions. The non-significant differences between highly and lowly pleasant conditions may be due to the stimuli selection. Indeed, aiming at selecting highly and lowly pleasant stimuli, we avoided the selection of strongly unpleasant stimuli (e.g., dissonant, Blood et al., 1999) that could have led to confounding effects on memory (e.g., due to their salience). The two sets of musical excerpts used as lowly and highly pleasant showed a small difference in terms of subjective pleasure ratings (mean rate of 2.16 and 3.23, respectively, on a 5 points scale). This difference, though statistically significant ($p = 0.001$), might have not been enough to induce significantly different states of pleasure leading to significant differences on memory performance. The non-significant differences between lowly and highly pleasant conditions might have been interpreted as a negative result, suggesting that the enhanced memory performance might be due to the presence of music itself (regardless of its pleasantness) or might be the result of a negative affect derived from listening to white noise. However, our further analyses revealed a significant interaction between excerpts' pleasantness ratings and participants' BMRQ score, thus confirming that musical pleasantness plays a role in modulating recollection memory performance.

It is noteworthy that music-induced reward responses allowing a better memory performance depend on both: music *per se* and individuals' ability to experience reward from music (measured via the BMRQ). Indeed, in line with previous results on musical memory (Ferreri & Rodriguez-Fornells, 2017), we showed that only participants reporting higher sensitivity to musical reward benefited from the presence of the highly pleasant musical context. For less hedonic participants, the presence of highly pleasant music during the encoding lead to a negative effect on memory performance. These findings might be interpreted according to a theoretical approach suggesting that musical pleasure relies on the generation of expectations (Rohrmeier & Koelsch, 2012). Midbrain dopamine neurons encode the degree to which an outcome matches expectations: when outcomes are better than expected, a strong activation, known as positive prediction error

response, is elicited (Cohen et al., 2012; Schultz, 2013; Zhang et al., 2017). As these neurons are also active when experiencing moments of intense musical pleasure (Salimpoor et al., 2011), it has been proposed that this network might encode reward prediction errors (RPEs) during pleasurable music listening (Gebauer et al., 2012; Salimpoor et al., 2015). Accordingly, Gold et al. (2019) provided first new evidences that music elicits RPEs in the nucleus accumbens (NAcc). Interestingly, they also found a significant positive relationship between BMRQ scores and RPE signalling in the right NAcc, with less hedonic participants generally reflecting musical RPEs less reliably. Hence, participants with high BMRQ scores might be better at encoding RPEs, which have been recently proposed to play a role in episodic memory formation (Calderon et al., 2020; Jang et al., 2019). On the contrary, less hedonic participants, although able to predict emotional events as music unfolds, might not experience the expected reward (Martínez-Molina et al., 2016; Mas-Herrero et al., 2014). This could lead to a dopaminergic decrease (Schultz, 1997) that would negatively affect encoding processes. Further studies directly addressing the relationship between musical hedonia, RPEs and memory are needed to disentangle such complex interplay. However, it is important to bear in mind that the musical RPEs responses based on a cortico-striatal model of musical pleasure might constitute only a part of the global picture. As recently proposed by Goupil and Aucouturier (Goupil & Aucouturier, 2019), the pleasurable response to music might be the result of a cooperation between the dopaminergic mesolimbic system and an emotional network involving the amygdala and the dorsolateral prefrontal cortex (DLPFC). Importantly, both the emotional network (Jäncke, 2008) and the DLPFC (Ferreri et al., 2013, 2014, 2015) have been shown to be critical in music-dependent encoding and retrieval of information. In line with these findings, the present study revealed that the participants more prone to get emotionally involved with music showed an enhanced memory performance when an auditory context was present during the encoding of information. It might be therefore possible that highest musical reward responses might promote episodic verbal memory formation via a complex interaction of cortical and subcortical networks, in which both pleasure and emotion mechanisms play a crucial role.

Contradictory results have been reported regarding the effect of background music during the encoding on subsequent verbal memory performance (Ferreri & Verga, 2016). On one hand, some studies suggest that music negatively affects memory performance by attracting participants' attention away from the to-be-remembered information (El Haj et al., 2014; Moussard et al., 2012). On the other hand, several studies speak in favour of a general beneficial effect of music on verbal memory (Ferreri et al., 2013, 2014; Simmons-Stern et al., 2010; Thaut et al., 2005; Wallace, 1994). Different mechanisms have been suggested to be responsible for this effect, including the generation of a temporal scaffolding network that supports sequence learning, changes in

listeners' arousal or mood, induction of emotional states, and activation of the reward system (Ferreri & Verga, 2016). However, so far, no study investigated the effect of experiencing music-related reward during the encoding of non-musical material. The results of the present study suggest that only people with high musical hedonia benefit from the presence of music preceding and accompanying words encoding, especially if the musical stimulus is highly pleasant. Conversely, for less musical hedonic participants, memory performance seems to be better when words are encoded in a white noise context. Therefore, our results suggest that participants' ability to experience reward from music is a crucial aspect to determine whether music will have a positive effect on their memory.

We found that highly pleasant music and participants' musical hedonia had an effect on memory performance not only when the encoding of verbal material was accompanied by an auditory background, but also when it was performed in silence immediately after the auditory stimulus presentation. Importantly, this suggests that music-induced reward generates a penumbra that favours the encoding of non-related material presented in close temporal proximity. Most of the studies showing the reward-related penumbra effect so far have used monetary reward anticipation (Murty & Adcock, 2014) or a state of high curiosity (i.e., intrinsic reward motivation (Gruber et al., 2014)). In these studies, the encoding of target or incidental items was performed during an anticipatory state, that is, before receiving the previously cued reward. In our study, the to-be-encoded verbal material was presented after the rewarding stimulus. Similarly, a previous study from Fenker and colleagues (Fenker et al., 2008) investigated the penumbra effect by asking participants to explore novel or familiar scenes before memorizing familiar words. Through a series of experiments, they provided the first evidence that the effect of novelty-induced dopamine release outlasted the triggering event and facilitated the episodic encoding of non-related material up to 30 minutes later (Fenker et al., 2008). In the same line, a recent study showed that exposure to an extended block of emotion-evoking stimuli enhanced participants' recollection of neutral images encoded 9 to 33 minutes later (Tambini et al., 2017). These results speak in favour of the possible long-lasting influence of emotion-induced states on prospective memory encoding. Accordingly, our findings suggest that exposure to highly pleasant music, which might be inducing reward responses, favoured the consolidation of information presented immediately after, resulting in an enhanced recollection. However, it is worth noting that the penumbra duration for novel, rewarding and emotional events might be different. As proposed by Wittmann et al. (2011), novelty signals are likely to increase the pool of tonically active dopamine neurons, whereas rewards are more likely to induce phasic bursts of dopaminergic activity. Thus, for example, exposure to novelty could lead to a longer period of elevated tonic firing compared to the one produced by exposure to rewards. In addition, the non-significant differences between

with and without background versions reported in the present study and the subsequent interpretation should be taken with caution. Because of the lack of previous experiments studying the penumbra of rewarding stimuli (and particularly music) on memory for weak events, we were not able to perform a power analysis before conducting the present experiment. Therefore, the analyses here reported might be underpowered and, as a result, we might not have been able to detect an effect that was in fact present. Further issues arising from low power and hindering results interpretation include overestimates of effect size and low reproducibility of results (Button et al., 2013). Additional studies are needed to disentangle the duration of the music-driven reward effect on memory.

One possible criticism in the present study concerns the use of white noise as a control condition. Indeed, some authors have reported beneficial effects of white noise on information processing and higher cognitive functions (McDonnell & Ward, 2011; Moss et al., 2004; Usher & Feingold, 2000). Furthermore, this influence of white noise on cognitive performance has been attributed to dopamine release modulation (Rausch et al., 2014; Sikström & Söderlund, 2007). However, in the learning and memory domain, this positive effect has been mainly observed in children with attention-deficit/hyperactivity disorder (ADHD, G. Söderlund et al., 2007; G. B. W. Söderlund et al., 2010), while it has been reported from mild to null when tested on healthy people (Angwin et al., 2017; Helps et al., 2014; Herweg & Bunzeck, 2015; Rausch et al., 2014). Therefore, although results in relation to white noise must be interpreted with caution, the fact that no significant differences in memory performance have been observed between white noise and low-pleasure conditions discards the hypothesis that white noise could have driven a positive effect in this experiment.

Another possible critical point relies on the selection of unfamiliar classical music excerpts. Music-related reward responses can vary depending not only on the inter-individual differences regarding musical hedonia (measured through the BMRQ) but also on musical preferences (Blood & Zatorre, 2001; Montag et al., 2011), which can be strongly modulated by previous exposure (Salimpoor et al., 2015). Although participants reported a general liking of classical music ($M = 3.41$, $sd = 1.02$, on a scale from 1=completely dislike to 5=completely like), our results suggest that, if we had selected participants with a specific preference for classical music, the impact of music on memory performance would have been stronger. Furthermore, it is worth to consider that the stimuli were employed as highly or lowly pleasant based on a preselection. In order to not interfere with the memory encoding, no direct reward subjective ratings were recorded during music listening. Therefore, we cannot guarantee that participants were actually experiencing a pleasant stimulus as such. For this reason, although supported by data on individual musical hedonia scores, the interpretation of the results should be done bearing in

mind this limitation. An enhancement of reward responses might also have been possible by using participants' favourite music²¹. However, in that case, we would not have been able to control for other aspects that are likely to modulate music's effect on memory such as familiarity, emotional valence or arousal.

In conclusion, we have shown that pleasant music contributes to a better encoding of verbal material. We attribute this effect to a greater dopamine release that enhances episodic memory formation thanks to the interaction of the reward networks and the memory circuit. In line with this hypothesis, the positive effect of more pleasant musical context is only observed in those people with the highest ability to experience pleasure from music. Although relevant, these results could constitute only a part of the general picture. In real-life settings, an interplay between changes in arousal and mood, induction of emotional states, and activation of the reward system could jointly contribute to the positive effect of music on memory, and further studies are needed to disentangle such complex interaction.

Taken together, these results might have an important implication for music-based clinical interventions. More specifically, our findings suggest that inter-individual differences in musical reward sensitivity might be a critical predictor of the effectiveness of a music-based treatment for memory stimulation (see also Grau-Sánchez et al., 2018).

The present study showed that musical pleasantness, able to modulate music-related reward responses, and musical hedonia play a crucial role in driving the positive effect of music on verbal episodic memory. In our opinion, this sheds new light on the relationship between music, reward, and memory, thus opening important perspectives about the use of music for the stimulation and rehabilitation of memory processes.

Study 2

The forgotten role of absorption in music reward

This study corresponds to:

Cardona, G., Ferreri, L., Lorenzo-Seva, U., Russo, F. A., & Rodriguez-Fornells, A. (2022). The forgotten role of absorption in music reward. *Annals of the New York Academy of Sciences*, 1514(1), 142-154. <https://doi.org/10.1111/nyas.14790>

4 Study 2

The forgotten role of absorption in music reward

4.1 Introduction

Music has an inherent capacity to evoke a rich and meaningful landscape of emotions and feelings in humans. As such, it is efficiently used across cultures and ages as a powerful mood regulator (DeNora, 1999; Gabrielsson, 2001, 2010; Juslin & Västfjäll, 2008; North et al., 2000; Saarikallio, 2011; Saarikallio & Erkkilä, 2007; Sloboda, 2010; Sloboda & O'Neill, 2001). In special or extraordinary circumstances, people might experience strong peak emotional experiences during music listening and some of them could be associated with transcendence or absorption states (Gabrielsson, 2011). Absorption is usually described as “*an effortless, non-volitional quality of deep involvement with the objects of consciousness*” (Jamieson, 2005), in which attention becomes deeply focused and narrowed, thus lessening awareness of internal states or external conditions (Eisen & Lynn, 2001). In these states, a person might feel like being merged with something bigger (sometimes materialized as an attentional-capture process, harmony/diffusion with the environment or the universe, experiencing joy, peace, ecstasy and more complex emotions) or that goes beyond what is considered an ordinary state of consciousness. These transient mental states and feelings associated with reduced self-consciousness processing (dissolution of body/self-boundaries) and increased feelings of connectedness (beyond the self, including others and one’s environment) have been recently grouped under the umbrella of self-transcendent experiences (Yaden et al., 2017). Historically, diverse forms of music (e.g., Sufi, Tarantella, or Minimalism; see Kirkegaard, 2012), accompanied or not by dance or stimulating drugs (Bachner-Melman et al., 2005; Forstmann et al., 2020; Katz & de Rios, 1971) have been used as a catalyzer for eliciting altered states of consciousness (for a relation between religion, transcendence and music see Becker, 2004; Hills & Argyle, 1998; Miller & Strongman, 2002; Penman & Becker, 2009). Maslow (1971) initially proposed that music might be an easy way of experiencing peak emotional experiences, described as “*moments of highest happiness and fulfilment*” (Maslow, 1968) and characterized by disorientation of time and space, a loss of fear, anxiety and inhibition, and a total absorption by the phenomenon. This type of experience also relates to the concept of *flow* states (Csikszentmihalyi, 1990), shown to be promoted by musical activities (Chirico et al., 2015; Vroegh et al., 2021).

However, while one person could enter into these absorption states through listening to *Spiegel im Spiegel* by Arvo Pärt, others might be more easily absorbed by Springsteen's *Nebraska* album, Rosalía's *El Mal Querer* or Massive Attack's trip hop music. Music-driven transcendence and absorption experiences tend to be highly valued but are not experienced by everybody and might depend on certain individual characteristics (Whaley et al., 2009). For example, Kreutz and colleagues (2008) showed that people high in absorption trait (evaluated using the *Tellegen Absorption Scale*, TAS; Tellegen & Atkinson, 1974) tend to have more intense music emotional reactions (Rhodes et al., 1988). Also, these kind of states of consciousness have been related to previous music exposures (i.e., background musical culture and identity) in special moments of a person's life (Herbert, 2012).

These transcendental experiences are emotionally extraordinary and they might impact and depend on the activation of emotion and reward processing brain networks (Koelsch, 2014). Strong emotional reactions to music are usually accompanied with behavioral (intense feelings of pleasure), psychophysiological (breathing, heart rate and skin conductance changes associated to chills) and neural mesolimbic dopaminergic reward activations (Grewe et al., 2007; Huron & Margulis, 2010; Koelsch, 2014; Salimpoor et al., 2011; Zald & Zatorre, 2011). However, remarkable individual differences exist in music reward sensitivity (Mas-Herrero et al., 2013). The Barcelona Musical Reward Questionnaire (BMRQ; Mas-Herrero et al., 2013) is a self-report questionnaire distinguishing five factors or music-reward facets: musical seeking, emotion evocation, mood regulation, sensory-motor, and social reward. By employing the BMRQ, we found that while some listeners experienced normal to high-pleasure in response to music, others, termed musical anhedonics, reported experiencing musical pleasure to a very small degree or not at all, despite being capable of experiencing other kinds of pleasure (Mas-Herrero et al., 2013, 2014). Subsequent neuroimaging studies showed that musical anhedonia was associated with decreased connectivity between the auditory and reward networks (Martínez-Molina et al., 2016). Therefore, the nature of pleasure decoding abilities in the human brain varies largely across people, and this variability can deeply characterize individuals' relationship with music.

Because of the complex landscape of emotions that characterize music, an interesting question arises about the extent to which individual differences in the susceptibility to experience absorption in music might be associated with the different dimensions of musical reward (Mas-Herrero et al., 2013). Revising the initial large pool of items reflecting activities and situations associated with music-reward and pleasure experiences gathered across musicians and non-musicians and that entered into the initial study for the development of the BMRQ, it is clear that this pool did not reflect the specific content associated to strong peak experiences, transcendence

and absorption in music. This might have limited the capacity of the BMRQ scale to incorporate this absorption construct.

Thus, the present research aims at understanding the relationship between transcendence or absorption states during music listening and individual differences in the susceptibility to experience reward from music. With this purpose, we used the Absorption in Music Scale (AIMS; Sandstrom & Russo, 2013) and the BMRQ (Mas-Herrero et al., 2013). The AIMS is a well-known measure of music absorption that possesses good psychometric properties in terms of internal consistency, test-retest reliability, and convergent validity. These scales present some conceptual overlap but they can also be viewed as unique. For example, one AIMS item states that “It is sometimes possible for me to be completely immersed in music and to feel as if my whole state of consciousness has been temporarily altered”. This item does not appear to fit squarely with any of the BMRQ factors: musical seeking (e.g., “I’m always looking for new music”), emotion evocation (e.g., “I like to listen to music that contains emotion”), mood regulation (“music comforts me”), social reward (“music makes me bond with other people”), or sensory-motor (“music often makes me dance”). This lack of concordance is not surprising as the AIMS was derived from Tellegen & Atkinson’s (1974) concept of absorption as an attentional (cognitive) process, whereas the BMRQ was derived from an individual differences approach that focuses on music reward-related experiences and activities (Mas-Herrero et al., 2013).

Despite the unique derivations of these two scales, we predicted a strong relationship between sensitivity to music-driven absorption and sensitivity to music reward, as they might hijack common neural networks for decoding pleasure states from music. Although this relationship is probably related to the common use of cognitive and neural resources involved in music-reward processing, it is important to notice that absorption states are characterized by altered states of consciousness, attention-capture and mind wandering and are accompanied by emerging mental contents that are clearly not present during standard music listening. Thus, we also predicted that individual differences on the susceptibility to experience absorption states might uniquely contribute to the experience of music-reward and might therefore be considered as a potential new facet of the music-related reward scale.

4.2 Material and Methods

Participants

Nine hundred and twenty participants (64 % women, 29.8 ± 12 years old) took part in the study. Of those, 34% reported some musical training (mean number of years of training, 7.4 ± 4.9). Participants responded to the questionnaires online via Google Forms.

A set of 370 individuals answered the 20 items of BMRQ and 34 items of the AIMS. This sample was used to select the four items of AIMS with the optimal psychometrical proprieties to be added to the 20 items of BMRQ, in order to obtain a 24 items questionnaire that we named Extended Barcelona Music Reward Questionnaire (eBMRQ). Then, 550 participants responded the new eBMRQ. Finally, participants' responses from both samples were mixed to conform the final sample of 920 participants.

The total sample was half-split using Solomon procedure (Lorenzo-Seva, 2021). This procedure aims to find two subsamples in which all the sources of common variance are equally represented. The first subsample was analyzed with an exploratory factor analysis (EFA) using FACTOR software (Ferrando & Lorenzo-Seva, 2017). The second subsample was analyzed with a confirmatory factor analysis (CFA) using LISREL 8.5 (Jöreskog & Sörbom, 2001). The aim of the overall analysis was: (1) to explore in the first subsample if the expected factor model can be fitted in the sample at hand; and (2) to assess using the second subsample whether the factor model explored in the first subsample can be accepted to be the factor model in the population. As both analyses led to the same conclusions, the total sample was used to obtain the factorial loadings, the scales proprieties, and the weights needed to compute scores.

Instruments

The BMRQ (Mas-Herrero et al., 2013) evaluates individual differences in how people experience reward in music-related activities. It includes 20 items representing five different factors: Musical Seeking, Emotion Evocation, Mood Regulation, Social Reward, and Sensory-Motor (0.89, 0.88, 0.87, 0.78 and 0.93 reliability, respectively). The overall test shows a 0.92 reliability. All factors and the overall scale correlated with Feeling and Aesthetics facets and the overall measure Openness to experience (Spanish version of the NEO-PI-R; Costa & McCrae, 1992) as well as Fun seeking, BAS drive, and Reward responsiveness from the BIS/BAS questionnaire (Carver & White, 1994). On the other hand, they were negatively correlated with Physical Anhedonia Scale (PAS; Chapman et al., 1976) In addition, all facets except Musical Seeking positively correlated with the BIS scale.

The AIMS (Sandstrom & Russo, 2013) comprises 34 items designed to measure individuals' ability and willingness to allow music to draw them into an emotional experience. It presents a good internal consistency (Cronbach's alpha ranging 0.92 - 0.94), and strong test-retest reliability (0.86, $p = 0.001$). Convergent validity is supported by its correlation with similar scales such as the Tellegen Absorption Scale (Tellegen & Atkinson, 1974) ($r = 0.76$, $p < 0.01$) and the Musical Involvement Scale (Nagy & Szabó, 2004) ($r = 0.74$, $p < 0.01$). In addition, AIMS showed a positive correlation with the Fantasy subscale of the Interpersonal Reactivity Index (Davis, 1980) ($r = 0.50$, $p < 0.01$).

Items of both tests describe situations that participants could experience in their daily life. Participants were requested to indicate the level of agreement with each statement by using a five-point scale (from 1 "fully disagree" to 5 "fully agree"). Questionnaires were submitted once all the items were answered. There was no time limit imposed on completion of the questionnaire.

Data analysis

Relation between the BMRQ and the AIMS

Pearson's correlation coefficient was used to assess the relationship between BMRQ (the five facets and the overall scale) and AIMS scales. By using the interquartile range (IQR) criterion we found nine participants to be outliers. However, because we wanted to assess the relationship between BMRQ and AIMS across the population, only two participants that were outliers for just one of the variables were removed from the analyses reported here. Therefore, the sample size for these analyses was $N = 368$.

We additionally assessed the correlation between the different eBMRQ facets and the overall scale in the final sample ($N = 918$). In order to compare the set of correlations obtained in the initial sample ($N = 368$) to the one obtained in the total sample ($N = 918$), we computed Root Mean Square of Residuals (RMSR). Harman (1976) proposed a threshold value of 0.05 to conclude that differences between two sets of correlations are low (Harman, 1976).

Selection of four items from the AIMS

Different criteria were used to select a final set of four items out of the overall pool of 34 AIMS items. First, we performed a unidimensional exploratory factor analysis of the 34 AIMS items. In order to assess the goodness-of-fit of the factor model the following indices were inspected: Root Mean Square Error of Approximation (RMSEA; values between 0.050 and 0.080 are considered as *fair*), Comparative Fit Index (CFI; values larger than 0.990 are considered *excellent*), and Goodness of Fit Index (GFI; values larger than 0.990 have been recommended to represent good fit). Three

different criteria were used to perform a preliminary selection of eligible items: 1) having a loading value higher than 0.60, 2) being related to the concept of absorption, and 3) not having a mean too similar to the other items' means. These selection criteria left us with 4 items. Then, we performed a second EFA with these 4 items in order to inspect if the loading values in the reduced set of items were still large. These four items were added to the 20 items from the BMRQ in order to compose the eBMRQ (see *Appendix A* and *B* for the Spanish and English versions of the eBMRQ). In this way, we constituted the new test that we labeled Extended Barcelona Music Reward Questionnaire (eBMRQ) that was composed by 24 items. The analyses described below were carried out with these 24 items.

EFA of the first Solomon subsample

Regarding the development of an extended version of the BMRQ (i.e., eBMRQ), examination of the item scores showed that the distributions were generally skewed. So, the item scores were treated as ordered-categorical variables, and the factor analysis based on the polychoric inter-item correlations was the model chosen to fit the data. This model is an alternative parameterization of the multidimensional IRT graded response model (Ferrando & Lorenzo-Seva, 2013). In order to assess the adequacy of matrix correlation to be factor analyzed, Kaiser-Meyer-Olkin (KMO) Test for Sampling Adequacy was computed (Kaiser & Rice, 1974). Indices Normed-MSA was also inspected for the items in order to decide if some item was not sharing enough communality with the whole set of items: values of Normed-MSA below 0.50 suggest that the item does not measure the same domain as the remaining items in the pool, and so that it should be removed (Lorenzo-Seva & Ferrando, 2021). Next, the factor analysis solution was fitted by using Robust FA based on the Diagonally Weighted Least Squares criterion as implemented in the program FACTOR (Ferrando & Lorenzo-Seva, 2017), and six factor were extracted. The factor solution was rotated using Robust Promin (Lorenzo-Seva & Ferrando, 2019). Again, in order to assess the goodness-of-fit of the factor model the following indices were inspected: RMSEA, CFI, and GFI. In order to assess essential unidimensionality, Unidimensional Congruence (UNICO), Explained Common Variance (ECV), and Mean of Item Residual Absolute Loadings (MIREAL) were inspected (Ferrando & Lorenzo-Seva, 2018). Values of UNICO larger than 0.95, ECV larger than 0.85 and MIREAL lower than 0.30 suggests that data can be treated as essentially unidimensional. Finally, as the indices to assess essential unidimensionality suggested that a single dimension could be interpreted, the unidimensional factor solution was also inspected.

CFA of the second Solomon subsample

In order to study the replicability of the factor structure obtained in the first Solomon subsample, a CFA was carried out on the second Solomon subsample. Unweighted least square estimates were computed from the inter-items polychoric correlation matrix. It was proposed that the model should retain six correlated factors, as suggested by the previous exploratory factor analysis. When personality questionnaires obtained by EFA are tested using CFA, the model proposed is usually rejected, although a series of different exploratory studies have previously replicated the same factorial structure, especially in multidimensional questionnaires (Ferrando & Lorenzo-Seva, 2000). In these cases, a semi-restricted model is more appropriate for testing the model fit in CFA. Taking this into account, we applied this analysis by selecting six marker items. To select these items, we selected the simplest items from the previous EFA.

Factor analysis and psychometric properties of the total sample

Finally, as both previous analyses led to the same conclusions, the total sample was factor analyzed following the same specifications used in the first EFA. Both (the six dimensional and the unidimensional) factor models were computed. In order to estimate factor reliabilities of factor scores, we computed ORION reliability index of factor scores (Ferrando & Lorenzo-Seva, 2016). The quality of the factor solution was inspected using the construct replicability, and the quality of factor scores estimate estimates were assessed with indices H, Sensitivity ratio (SR), and Expected Percentage of True Differences (EPTD; Ferrando & Lorenzo-Seva, 2018). The H index evaluates how well a set of items represents a common factor. It is bounded between 0 and 1 and approaches unity as the magnitude of the factor loadings and/or the number of items increase. High H values (> 0.80) suggest a well-defined latent variable. The SR can be interpreted as the number of different factor levels than can be differentiated on the basis of the factor score estimates. The expected percentage of true differences (EPTD) is the estimated percentage of differences between the observed factor score estimates that are in the same direction as the corresponding true differences. If factor scores are to be used for individual assessment, marginal reliabilities above 0.80, SR above 2, and EPTDs above 90% are recommended.

Age and group differences

As further exploratory analyses, we assessed whether the six factors of the eBMRQ varied according to age and years of musical training through Pearson's correlation. Independent samples t-tests were performed to check for gender-related differences. Non-binary participants ($N = 7$) were excluded from the t-tests.

4.3 Results

Relation between the BMRQ and the AIMS

All BMRQ factors positively correlated with AIMS, $p < 0.001$ (see **Table 1**). In addition, the overall BMRQ score showed a high correlation with AIMS ($r(366) = 0.78$, $p < 0.001$, see **Figure 1**). These results confirmed our first prediction suggesting that a large amount of variance would be shared between both constructs, music-reward and absorption, thus indicating that they are highly related.

Table 1 shows the set of correlations obtained for the total sample ($N=918$). Interestingly, correlations between the Absorption in Music (AM) facet and the rest of the eBMRQ facets were higher in the total sample than in the initial one. This might be related to the order in which items were presented: whereas in the initial sample the 4 AM items were embedded in the 34 AIMS items, in the second sample those 4 AM items were mixed with the rest of the eBMRQ items, thus helping subjects to use the same criteria for all items.

	<i>MS</i>	<i>EE</i>	<i>MR</i>	<i>SM</i>	<i>SR</i>	<i>AM</i>	<i>eBMRQ</i>
Emotion Evocation (EE)	0.44						
Mood Regulation (MR)	0.57	0.60					
Sensory-Motor (SM)	0.37	0.34	0.46				
Social Reward (SR)	0.61	0.47	0.62	0.52			
Absorption in Music (AM)	0.50	0.57	0.65	0.36	0.55		
eBMRQ (overall sum)	0.76	0.73	0.84	0.65	0.82	0.81	
$\bar{X}$	13.8	16.9	17.3	17.2	15.5	14.1	94.8
<i>SD</i>	3.6	3.0	2.9	3.1	3.2	4.0	15.2

Table 1. Pearson correlation values, mean and standard deviation for eBMRQ facets and the overall sum ($N = 918$). All $p < 0.001$. eBMRQ maximum score = 120. MS: *Musical Seeking*; EE: *Emotion Evocation*; MR: *Mood Regulation*; SM: *Sensory-Motor*; SR: *Social Reward*; AM: *Absorption in Music*; eBMRQ: *extended BMRQ (overall sum)*. Facet scores were obtained from the raw addition of participants' responses to the items.

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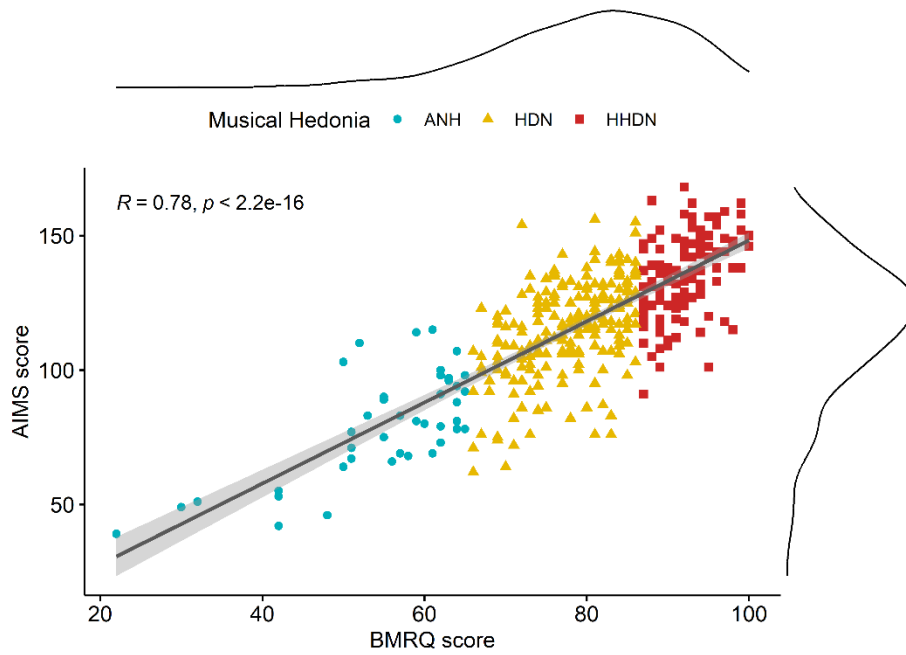


Figure 1. Correlation between BMRQ and AIMS scores. For illustrative purposes, participants are represented in three different colors according to their level of musical hedonia (Martínez-Molina et al., 2016): anhedonics (ANH, BMRQ score ≤ 65), hedonics (HDN, $65 < \text{BMRQ score} < 87$), and hyperhedonics (HHDN, BMRQ score ≥ 87). In the margins, density plots for BMRQ and AIMS scores are shown.

Selection of four items from the AIMS

From the overall pool of AIMS items, selection criteria led us to keep items 3, 13, 15 and 29 (see **Table 2**). A factor analysis of these four items extracting a single factor showed high loading values (i.e., values between 0.727 and 0.873), and the solution reached acceptable goodness-of-fit levels in terms of RMSEA = 0.087, CFI = 0.997, and GFI > 0.999. ORION reliability was 0.889. These values suggested that these four items could be a convenient set of items to be added to the BMRQ in order to conform the eBMRQ.

Item		Response average	Loading value
3	I sometimes feel like I am 'one' with the music.	3.633	0.779
13	While listening to music, I may become so involved that I may forget about myself and my surroundings.	3.683	0.823
15	It is sometimes possible for me to be completely immersed in music and to feel as if my whole state of consciousness has been temporarily altered.	3.520	0.873
29	When listening to great music I sometimes feel as if I am being lifted into the air.	3.308	0.727

Table 2. AIMS items selected to be part of the eBMRQ.

EFA of the first Solomon subsample

The inter-item polychoric correlation matrix had good sample KMO = 0.904. Normed-MSA for items ranged between 0.719 and 0.946. The factor analysis solution reached acceptable goodness-of-fit levels: RMSEA = 0.027, CFI = 0.998, and GFI > 0.999. The rotated solution was inspected in order to assess whether the patterns of items corresponded to the expected solution. While the overall pattern of loadings was as expected, some items have a complex pattern. However, the dimensions were related to a reasonable number of salient loadings (i.e., loadings with absolute value larger than 0.25): between 4 (dimensions MS, SM, and AM) and 6 (dimensions MR and SR). These outcomes support the hypothesis of a six-dimensional solution.

The values of the inter-factor correlation matrix ranged between 0.339 and 0.704. In addition, the values of the indices to assess essential unidimensionality were UNICO = 0.951, ECV = 0.839, and MIREAL = 0.223. These outcomes suggested that a single dimension could also be acceptable for the dataset. To assess it, a second factor analysis with a single factor was computed. The corresponding goodness-of-fit indices were RMSEA = 0.071, CFI = 0.975, and GFI = 0.970. While the fit was worsened, it was still acceptable. The loading values in the single factor ranged from 0.423 to 0.819. Finally, the EAP reliability of the factor was 0.952.

In sum, the EFA indicated that the six factor model was acceptable for the eBMRQ, and that a single factor would also be informative in order to compute an overall score in the questionnaire.

CFA of the second Solomon subsample

To assess if the conclusion reached in the previous EFA could be replicated, the second Solomon subsample was analyzed using CFA. The values of goodness-of-fit indices related to the six factor model were RMSEA = 0.070, CFI > 0.999, and GFI > 0.999. These values suggested an acceptable model fit, and the replication of the six factor model observed in the EFA. The unidimensional model showed a goodness-of-fit indices of RMSEA = 0.140, CFI = 0.970, and GFI = 0.970. Again, and as expected, the fit worsened but still acceptable.

Factor analysis and psychometric properties of the total sample

The polychoric correlation matrix related to the total sample had a KMO value of 0.921, and Normed-MSA for the items ranged from 0.758 to 0.964. The goodness-of-fit indices related to the six factor model were RMSEA = 0.039, CFI = 0.995, and GFI > 0.999. Inter-factor correlation matrix showed values between 0.430 and 0.791. In addition, the values of the indices to assess essential unidimensionality were UNICO = 0.949, ECV = 0.846, and MIREAL = 0.206. Finally, the goodness-of-fit indices related to the one factor model were RMSEA = 0.096, CFI = 0.951, and GFI > 0.999.

Table 3 shows the loading values in the six dimension (MS, EE, MR, SM, SR, and AM) and the single

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factor (eBMRQ) solutions. ORION reliabilities of the six dimensions ranged from 0.836 to 0.932, whereas the ORION reliability of the overall dimension was 0.952. The interfactor-correlation ranged between 0.439 and 0.791.

Item	<i>MS</i>	<i>EE</i>	<i>MR</i>	<i>SM</i>	<i>SR</i>	<i>AM</i>	<i>eBMRQ</i>
13 <i>I'm always looking for new music.</i>	0.553	-0.015	0.281	0.059	-0.119	0.004	0.591
8 <i>I inform myself about music I like.</i>	0.695	0.202	0.045	-0.075	0.065	-0.152	0.592
20 <i>I spend quite a bit of money on music and related items.</i>	0.744	-0.038	-0.188	-0.107	0.283	0.057	0.566
2 <i>In my free time I hardly listen to music.</i>	0.366	-0.107	0.647	0.148	-0.387	0.001	0.537
21 <i>I sometimes feel chills when I hear a melody that I like.</i>	0.196	0.762	-0.033	0.018	-0.293	0.167	0.643
14 <i>I can become tearful or cry when I listen to a melody that I like very much.</i>	-0.045	0.742	-0.093	0.064	-0.009	0.089	0.609
9 <i>I get emotional listening to certain pieces of music.</i>	-0.063	0.894	0.092	-0.066	0.121	-0.116	0.733
3 <i>I like listen to music that contains emotion.</i>	0.005	0.782	0.076	0.023	-0.052	-0.066	0.632
16 <i>Music helps me chill out.</i>	-0.018	-0.078	0.953	-0.052	0.026	0.007	0.777
10 <i>Music calms and relaxes me.</i>	-0.009	0.127	0.730	-0.043	-0.007	-0.040	0.689
22 <i>Music comforts me.</i>	-0.023	0.162	0.413	0.039	0.169	0.161	0.805
4 <i>Music keeps me company when I'm alone.</i>	0.120	0.043	0.672	-0.050	-0.062	0.058	0.692
11 <i>Music often makes me dance.</i>	0.024	0.072	-0.014	0.905	0.026	-0.098	0.658
23 <i>When I hear a tune I like a lot I can't help tapping or moving to its beat.</i>	-0.186	0.060	-0.068	0.775	0.214	0.085	0.672
17 <i>I can't help humming or singing along to music that I like.</i>	-0.177	0.128	0.205	0.354	0.267	-0.121	0.547
5 <i>I don't like to dance, not even with the music I like.</i>	0.137	-0.136	-0.009	1.005	-0.239	0.029	0.522
15 <i>I like to sing or play an instrument with other people.</i>	0.174	-0.047	0.069	0.080	0.386	-0.050	0.505
1 <i>When I share music with someone I feel a special connection with that person.</i>	0.045	-0.146	0.030	-0.003	0.694	0.094	0.626
7 <i>Music makes me bond with other people.</i>	0.030	-0.153	0.056	0.022	0.871	0.030	0.752
19 <i>At a concert I feel connected to the performers and the audience.</i>	0.237	-0.031	-0.061	0.125	0.411	0.115	0.643
6 <i>I sometimes feel like I am 'one' with the music.</i>	0.066	0.021	0.026	0.008	0.055	0.678	0.725
12 <i>While listening to music, I may become so involved that I forget about myself and my surroundings.</i>	-0.070	-0.037	0.226	-0.032	-0.058	0.782	0.719
18 <i>It is sometimes possible for me to be completely immersed in music and to feel as if my whole state of consciousness has been temporarily altered.</i>	-0.047	-0.112	0.068	-0.048	0.021	0.957	0.737
24 <i>When listening to great music I sometimes feel as if I am being lifted into the air.</i>	-0.015	0.223	-0.247	0.040	0.065	0.711	0.644

Table 3. Factor solutions of multidimensional and unidimensional factor analysis related to the total sample. Salient loadings in the multidimensional solution are printed in bold face. Items 2 and 5 were reversed. Items are ordered by facets and, within every facet, the order is the same as in Mas-Herrero et al. (2013) to facilitate further comparisons. MS: *Musical Seeking*; EE: *Emotion Evocation*; MR: *Mood Regulation*; SM: *Sensory-Motor*; SR: *Social Reward*; AM: *Absorption in Music*.

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As observed in Table 3, there are some complex items that show salient loadings not only for the factor they are supposed to represent but also for another factor (see items 13, 20, 2, 21, and 17). Interestingly, for most of these items the other factor is Social Reward. Particularly complex is item 2 (i.e., *'In my free time I hardly listen to music'*), which even though it is informative of Musical Seeking (loading = 0.366) it also gives information about Mood Regulation and Social Reward (loadings of 0.647 and -0.387, respectively).

The indices to assess the quality of the factor solution are showed in **Table 4**. H-Latent assesses how well the factor can be identified by the continuous latent response variables that underlie the observed item scores (i.e., the factor scores estimates), whereas H-Observed assesses how well it can be identified from the observed item scores (i.e., the score obtained from the raw addition of participants' responses to the items). As the values of H-Latent are systematically larger than the corresponding values of H-Observed, factor scores should be computed instead of the simple addition of responses to items. In the supplementary materials, we provide researchers an excel file that computes factor scores from the participants' responses to the items.

The value of the indices show that the six dimensions and the overall dimension show an acceptable quality. The facet that shows a lower quality is MS. In general, the indices related to the unidimensional solution are higher than the ones obtained in the six dimensions. This indicates that the factor score in the overall questionnaire is more reliable and informative than the scores in the six facets that compose the test.

Index	MS	EE	MR	SM	SR	AM	eBMRQ
H-Latent	0.833	0.917	0.917	0.932	0.893	0.918	0.952
H-Observed	0.802	0.801	0.828	0.786	0.830	0.887	0.935
SR	2.257	3.332	3.319	3.712	2.894	3.337	4.440
EPTD	89.9%	93.3%	93.3%	94.2%	92.2%	93.4%	95.4%

Table 4. *Indices to assess the quality of the factor solution related to the total sample. MS: Musical Seeking; EE: Emotion Evocation; MR: Mood Regulation; SM: Sensory-Motor; SR: Social Reward; AM: Absorption in Music; eBMRQ: extended BMRQ.*

Age and group differences

We assessed how these music reward factors are modulated by age, gender, and musical experience.

Four out of six factors were negatively correlated with age: Musical Seeking, $r(916) = -0.111$, $p = 0.001$; Mood Regulation, $r(916) = -0.115$, $p < 0.001$; Sensory-Motor, $r(916) = -0.239$, $p < 0.001$; and Social Reward, $r(916) = -0.105$, $p = 0.001$ (see **Figure 2** and **Figure S1**). Emotion Evocation

and Absorption in Music factors did not show a significant correlation with age [$r(916) = -0.013$, $p = 0.69$; and $r(916) = 0.013$, $p = 0.69$, respectively].

Women presented higher values in Emotion Evocation ($t(909) = 2.36$, $p = 0.019$), Mood Regulation ($t(909) = 3.86$, $p < 0.001$), Sensory-Motor ($t(909) = 9.68$, $p < 0.001$), and Social Reward ($t(909) = 4.29$, $p < 0.001$) factors (see **Figure S2**). However, no differences were reported in Musical Seeking ($t(909) = 0.72$, $p = 0.47$) or Absorption in Music ($t(909) = 1.57$, $p = 0.12$) factors.

Finally, we studied the correlation between years of musical training and the six factors of the eBMRQ. Musical training showed a significant positive correlation with Musical Seeking ($r(916) = 0.177$, $p < 0.001$), Emotion Evocation ($r(916) = 0.095$, $p = 0.004$), Mood Regulation ($r(916) = 0.146$, $p < 0.001$), Social Reward ($r(916) = 0.242$, $p < 0.001$), and Absorption in Music ($r(916) = 0.143$, $p < 0.001$) factors (see **Figure 2** and **Figure S3**). In contrast, no significant correlation was found with the Sensory-Motor ($r(916) = 0.003$, $p = 0.92$) factor.

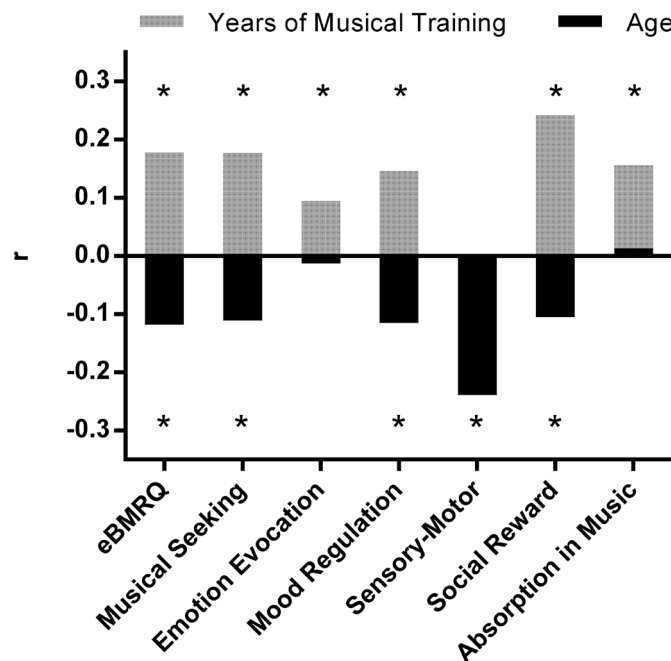


Figure 2. Graphical representation of Pearson's correlation coefficients showing the relationship between years of musical training (gray) or age (black) and eBMRQ's overall sum and its different factors. * represents $p < 0.005$.

4.4 Discussion

The aim of the present study was to investigate the relationship between individuals' susceptibility to experience music-induced transcendence or absorption states and their susceptibility to experience reward and pleasure from music. In order to do that, we evaluated

the relationship between the Absorption in Music Scale (AIMS; Sandstrom & Russo, 2013) and the Barcelona Music Reward Questionnaire (BMRQ; Mas-Herrero et al., 2013). Results showed that the two constructs were highly correlated, suggesting that the individual differences in the susceptibility to experience music-related absorption states and to experience reward from music are intimately related. Although this relation was strong, the amount of unshared variance between both constructs suggested that it might be possible to incorporate an absorption facet to the BMRQ. We believe that the extension of the BMRQ into the domain of absorption/transcendence could improve its capacity to characterize individual differences in the sensitivity to experience music-related reward and pleasure.

Our first result confirmed that a large amount of variance is shared between both constructs, music-reward and absorption. Importantly, the BMRQ facets that correlated the most with AIMS's overall sum were Mood Regulation, Social Reward, and Emotion Evocation ($r = 0.69$, $r = 0.68$, $r = 0.62$, respectively). Accordingly, Kreutz and colleagues (Kreutz et al., 2008) showed that people high in trait absorption had more intense emotional reactions in response to music than those with low absorption trait. Similarly, Sandstrom & Russo (2013) showed that people high in trait absorption were more likely than people low in trait absorption to recover from an acute stressor in the presence of peaceful music. Furthermore, absorption states have been suggested to be linked to an emotional involvement with the attentional object (Roche & McConkey, 1990). In line with the present results, Garrido & Schubert (2011) showed a positive relationship between trait absorption and the enjoyment of evoked negative emotions in response to music (i.e., rating of the item "I like to listen to music which makes me feel sadness or grief"). This relationship was further demonstrated by Hall et al. (2016), who found that people high in trait absorption reported high enjoyment of self-selected music that was strongly evocative of negative emotions. To explain these intriguing results, Schubert (2013) proposed that, because these negative emotions are experienced in an aesthetic context, they can become activated without their unpleasant effect and can be thoroughly enjoyed. This ability to disconnect from the negative aspects of the experience would be enhanced in individuals high in trait absorption, since absorption represents a disconnection from one's surroundings and immersion in internal thoughts. Overall, undergoing these exceptional experiences of absorption triggers a wealth of complex emotions (Maslow, 1971), explaining the high correlation observed between absorption in music and the Emotion Evocation facet.

At a neural level, this marked relationship between transcendence or absorption states and music reward might be explained by partial activation of similar brain networks. For example, one of the characteristics of absorption is that attention becomes deeply focused and narrowed (Eisen & Lynn, 2001). Interestingly, Yacubian & Büchel showed that, when meaningful objects are in the

focus of attention, there are phasic increases in dopamine release. Specifically, as the personal meaning and valence of the object in focus becomes higher, an indirect increase in dopamine release is observed (Yacubian & Büchel, 2009). Complementing this perspective, recent studies have associated self-transcendence experiences (i.e., experiencing *awe* emotions) with temporary disruption of activity in the default mode network associated to self-awareness (Van Elk et al., 2019). This result converges with the attenuated connectivity in the DMN observed in participants after psychedelic drug administration and when experiencing mystic-transcendence experiences (e.g., ego dissolution, feelings of internal and external unity, transcendence of time and space, etc; Tagliazucchi et al., 2016). Previous research has consistently shown the implication of dopaminergic transmission and mesolimbic activation in experiencing music listening as a rewarding activity (Ferreri et al., 2019; Salimpoor et al., 2011). We could therefore expect that, during music-induced absorption states, and because of the meaningful relevance and high reward value of these experiences, increased activation in mesolimbic dopamine networks could be observed together with decreased activation in self-awareness networks (i.e., DMN).

Despite the high correlation between the two constructs, it is important to recognize that 41% of the variance in these constructs was unshared, meaning that the incorporation of an absorption facet to the BMRQ could contribute to better characterizing individual differences in the ability to extract reward from music. Therefore, we selected four AIMS items representing this new facet. In order to do that, we performed a unidimensional exploratory factor analysis and we discarded those items with loading values lower than 0.60. Then, the content and adequacy of the remaining items was subjectively assessed, and four final items were selected. While the first two items (i.e., *'I sometimes feel like I am 'one' with the music'*, and *'While listening to music, I may become so involved that I may forget about myself and my surroundings'*) exclusively represent the concept of absorption, the third and fourth items (i.e., *'It is sometimes possible for me to be completely immersed in music and to feel as if my whole state of consciousness has been temporarily altered'*, and *'When listening to great music I sometimes feel as if I am being lifted into the air'*) could be interpreted as absorption or transcendence. Importantly, these items represent certain aspects that were not contemplated in the previously existing version of the BMRQ. A careful examination of the items that were initially considered to be included in the BMRQ revealed that none of them approached the concept of absorption or transcendence. The only items that could be somehow, though remotely, linked to this concept were related to the usage of music as a means of escaping reality (i.e., *'Music makes me feel free'*, *'Time flies when I listen to music'*, *'Music inspires me'*, and *'Listening to music helps me dreaming and imagining things'*). The lack of transcendence or absorption-related items could be explained by the fact that these are not very common experiences, so they are not easily accessible in our minds (lack of availability) and the probability

of retrieving them in a free recall might be lower than other music activities which are commonly very pleasant (Tversky & Kahneman, 1973). Thus, when people are asked to recall about music-related pleasure experiences, they might report everyday memories and might not access these more complex and unusual events. One might however counter-argue that, because they are novel and highly meaningful, absorption experiences with music might be more salient and might be more accessible to free recall. In this regard, it is interesting to consider that because of the uniqueness of the absorption experiences, they could be associated to clear autobiographical and self-relevant information. The interaction between long-term autobiographical information, and reward-pleasure might be especially relevant for the value we ascribe to these experiences (for a similar theoretical framework in neuroaesthetics see Bara et al., 2020).

Following this line of reasoning, one could even consider the recall of music absorption or transcendence states as a type of flashbulb memory (FBM), created after exceptional events, and that endure for long periods of time, retaining many details that would be easily forgotten in "ordinary" everyday memories (Brown & Kulik, 1977). FBMs depend on the degree of emotional arousal, surprise, importance, consequentiality (e.g., having personal consequences), and rehearsal (Conway, 1995; Conway et al., 1994). Given their emotional impact (in most cases negative), FBM have been linked to emotional encoding brain regions with participation of the amygdala (Metternich et al., 2020) and its interaction with the autobiographical memory encoding system, comprising medial temporal lobe, retrosplenial cortex, medial and prefrontal cortices, as well as the temporoparietal junction (Addis et al., 2012; Maguire, 2001; Martinelli et al., 2013; McCormick et al., 2018; Miró et al., 2020). Accordingly, there could be a difference between the memories of the actual piece of music (i.e., "origin of the event") and the memories of one's own situation at the time of experiencing these states (i.e., "reception event") (Brewer, 1992; Conway et al., 1994). In the future, it might be interesting to observe the impact of music absorption states in both dimensions, memory for music (i.e., factual information) and memory for the personal situation experienced at that moment (i.e., autobiographical information), as well as the implication of reward-processing networks during the recall of these events and personal narratives (Janata, 2009). Finally, note that the potential impact of FBM depends on its consequences, especially on one's own life (Brown & Kulik, 1977). Similarly, absorption and self-transcendence states seem to have clear impact on people's narratives, being sometimes reported as some of the most important experiences in life (Griffiths et al., 2008; Hood et al., 2009).

Interestingly, the four items selected to constitute eBMRQ's Absorption in Music facet do not evaluate specific emotional correlates. Indeed, the selected items describe some aspects previously associated to peak emotional experiences (Maslow, 1962; Whaley et al., 2009) (i.e. being merged/fused with the music (item 3), being captured and fully involved (item 15), "loss of

self" (item 13), and experiencing altered states of consciousness (item 15) and physical changes (e.g., being lifted, item 29)) but they are not specially associated to the emotions and feelings induced by music listening (Grewe et al., 2007). This apparent dissociation between absorption states and the affective dimension is interesting and needs further exploration. However, it is important to remind that the original concept of peak experience, as proposed by Maslow (1962), comprises a complex phenomenon characterized by absorption states including emotional aspects [see for example how the concept of 'peak experience' was presented to Maslow's participants: "(...) the most wonderful experience of your life, happiest moments, ecstatic moments, moments of rapture, perhaps from being in love, or from listening to music, or suddenly 'being hit' by a book or painting, or from some great creative moment"; Maslow, 1968; Whaley et al., 2009]. Interestingly, Maslow also pointed to the different time-course development of some phenomenological experiences both during and after the event. Subsequent work on peak emotional experiences (Gabrielsson, 2001, 2010; Lamont, 2011; Laski, 1961; Panzarella, 1980; Whaley et al., 2009) revealed different components associated to these experiences and, in most of the cases, both (i) absorption/transcendental (ecstatic) states (associated to cognitive aspects such as perceptual narrowing, becoming merged, object capture and fusion with the medium), and (ii) emotional changes (associated to physical aspects such as tears, heart beat changes, floating sensation, and feelings of joy, happiness, tenderness, calm, peace, etc.) were present. Similarly, Panzarella (1980) commented on the three possible temporal stages of the peak experience: (i) cognitive responses to the feeling of "loss of self", (ii) climax phase with "loss of self" and motor-physical reactions, and (iii) ending with emotional responses and self-transformations. Thus, overall, music-induced peak experiences contain perceptual, cognitive, physical, and emotional components which could have different time courses during the full experience (Whaley et al., 2009). It would be interesting to further study the time-course of these complex experiences. Importantly, individual differences might play a role on the intensity and valence of emotions during absorption-transcendental experiences. In this regard, Vroegh (2019) found that highly susceptible individuals are clustered in two different types of absorption (labeled as zoning-in and tuning-in), showing unique bondings of imagery and emotions with other dimensions of consciousness. Specifically, whereas subjects who were tuned-in clearly experienced positive affect and were consciously aware of their altered consciousness, individuals zoning in had mixed emotions and were more self-forgetful. Interestingly, these findings were in line with the idea that connections between affect and cognition are common in ordinary states consciousness, but they tend to decouple in trance-related experiences (Vroegh, 2019).

It is worth noting that not all individuals are equally prone to these types of exceptional experiences. Some elements of personality, specially flexibility and openness to experience, seem

to encourage them (Whaley et al., 2009). Interestingly, absorption (measured through the TAS; Tellegen & Atkinson, 1974) has been shown to be highly correlated with specific aspects of openness to experience (measured through the Coan's Experience Inventory, CEI (Coan, 1972), and the Openness to Experience subscale of the NEO Personality Inventory, NEO-OE; Costa & McCrae, 1985) related to aesthetic sensitivity, unusual perceptions and associations, fantasy and dreams, unconventional views of reality, and awareness of inner feelings (Glisky et al., 1991). Similarly, it has been shown that people higher in openness to experience trait get chills from music more often (Colver & El-Alayli, 2016; Nusbaum & Silvia, 2011). Therefore, it may be possible that people who are high in trait absorption tend to experience greater levels of music-related reward. Consistent with this view, Loxton and colleagues (2016) found that AIMS correlated positively with reward sensitivity as well as involvement in music as assessed by a series of questions concerning musical activities. Moreover, AIMS was found to mediate the association between reward sensitivity and involvement in music.

Regarding the relationship between age and the different eBMRQ factors, we found that Musical Seeking, Social Reward, Sensory-Motor, and Mood Regulation factors were negatively correlated with age. These results seem reasonable given that, while music plays an essential role during adolescence (e.g., it helps developing an individual and cultural identity, it contributes to socialization and integration with peers, it constitutes a coping strategy, etc.; Miranda, 2013) as we get older our relationship with music changes (e.g., our musical preferences have already been established and we are usually reticent to look for new music, as well as we cannot go clubbing every Saturday night and dance to the music with our friends, etc.). Note that, in line with the results reported by Sandstrom & Russo (2013), the Absorption in Music factor was not significantly correlated with age. Interestingly, and contrary to the results reported in Mas-Herrero et al. (2013), the correlation between age and Emotion Evocation was not significant, suggesting that music's ability to elicit emotions persists over time. Accordingly, a recent study (Belfi et al., 2021) found no significant relationship between age and the Aesthetic Experience Scale in Music (AES-M; Sloboda, 1991). These findings may be related to the fact that music often evokes autobiographical memories that are strongly emotional (Janata et al., 2007) and that persist even in persons with significant memory impairments (El Haj et al., 2012). Therefore, when we get old, music might help to remember episodes of our life that trigger intense emotions.

It is worth noting that the present study is a cross-sectional study and, consequently, the significant correlations between age and the different eBMRQ factors could be possibly due to a cohort effect rather than a true effect of age. In addition, in the collected sample of participants, ages were not equally represented and, therefore, the correlations here reported cannot be definitively explained by maturation effects. Similarly, results showing that women presented

higher scores than men in all factors except in Musical Seeking (in line with Mas-Herrero et al., 2013), need to be interpreted with caution since the sample was not gender-balanced (i.e., 64% female).

Regarding musical training, we observed a positive correlation between years of training and Musical Seeking, Emotion Evocation, Mood Regulation, Social Reward, and Absorption in Music. In the original paper on BMRQ, Mas-Herrero et al. (2013) reported higher scores in professional musicians and musically trained participants than in untrained participants only for Musical Seeking and Emotion Evocation subscales. For the Absorption in Music facet, and contrary to Sandstrom & Russo (2013), we found a significant correlation between absorption and musical training. Such discrepancies could be related to differences in the distribution of music training across the studies. In the present study, only 34% of participants reported to have musical training and we did not fully assess it (e.g., we did not ask if they received group or private instruction, or if they were autodidacts, etc.). Thus, further studies are needed in order to disentangle the relationship between musical training and individual differences in the experience of music-related reward and absorption.

It is also interesting to specifically focus on participants who could have been considered musical anhedonics ($N=43$) (following previous criteria; Martínez-Molina et al., 2016). The scatterplot (Figure 1) highlighted the presence of seven unquestionably anhedonic participants with really low BMRQ scores, who also showed very low scores in music absorption. On the other hand, it was also possible to observe five participants with less extreme musical anhedonia reporting AIMS scores close to the mean score of the whole sample. In line with what we previously discussed, this would suggest that, although musical absorption is strictly related to musical reward, some aspects of music-driven absorption states exist independently from the pleasure derived while listening to music. This might be the case, for example, of music driving specific emotional states via its strong ritual efficacy (Patel, 2010), e.g. during meditation sessions evoking mental imageries (Taruffi & Küssner, 2019) or religious rituals promoting associative conditioning (Juslin & Västfjäll, 2008). Further research specifically addressing musical anhedonia and absorption states is needed to clarify these interesting findings.

The present study presents some limitations. First, we employed BMRQ and the AIMS questionnaires, but we did not request participants to complete other questionnaires related to hedonia or absorption, such as the BIS/BAS (Carver & White, 1994), the Physical Anhedonia Scale (Chapman et al., 1976), or Tellegen's Absorption Scale (Tellegen & Atkinson, 1974). Therefore, external validity of the eBMRQ remains to be assessed. Second, and as previously mentioned, we did not specifically control our sample for age, gender, or musical training. Thus, further studies

would be needed to investigate how these variables influence the different ways of deriving pleasure from music.

It is worth mentioning that this study was never aimed at extracting the most representative items from AIMS to obtain a reduced scale. Rather, our aim was to enrich the BMRQ by adding a new facet accounting for the absorption construct. Thus, researchers looking for a measure of absorption in music should use the AIMS (Sandstrom & Russo, 2013).

Importantly, the identification of this new Absorption in Music facet could contribute to a better characterization of individual differences in the ability to experience reward from music. Several studies have provided evidences of the beneficial effects of music in both patients and healthy participants (Altenmüller & Schlaug, 2013; Stegemann et al., 2019). Of particular interest is the use of music for rehabilitation. It has been shown that music-supported rehabilitation programs for stroke patients lead to significant improvements at both cognitive and emotional levels (Rodriguez-Fornells et al., 2012; Rojo et al., 2011; Särkämö et al., 2008). Other studies have also reported improvements in cognitive function, as well as quality of life and depressive symptoms in patients with dementia and Alzheimer's disease (Fang et al., 2017; Moreno-Morales et al., 2020). Crucially, several studies have shown that musical reward and its different facets can predict music-related benefits on cognition and well-being (Cardona et al., 2020; Ferreri, Mas-Herrero, et al., 2021; Ferreri, Singer, et al., 2021; Ferreri & Rodriguez-Fornells, 2017; Grau-Sánchez et al., 2018). A better characterization of subjects' relationship with music by means of the eBMRQ might help therefore to predict the effectiveness of music-based treatments at an individual level.

Overall, in the present study we showed that there is a close relationship between individual differences in the susceptibility to experience music-related absorption states and in the ability to experience reward from music. Accordingly, we constructed and validated an extended version of the BMRQ including an absorption/transcendence facet. Using this eBMRQ could contribute to a better characterization of individual differences in the sensitivity to experience music-related reward and pleasure.

4.5 Supplementary information

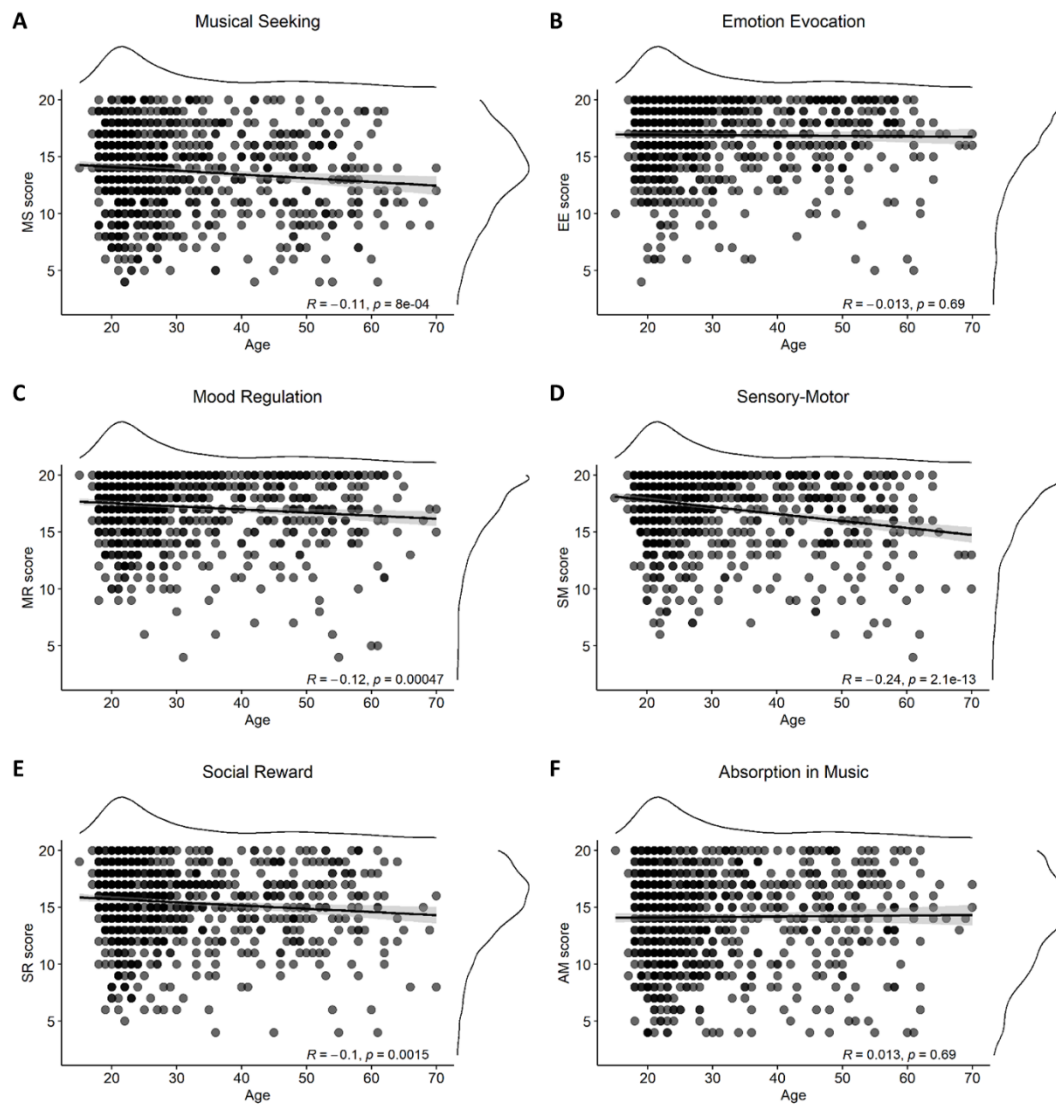


Figure S1. Correlation between age and each of the eBMRQ's factors. In the margins, density plots for age and the corresponding eBMRQ factor are shown.

Study 2

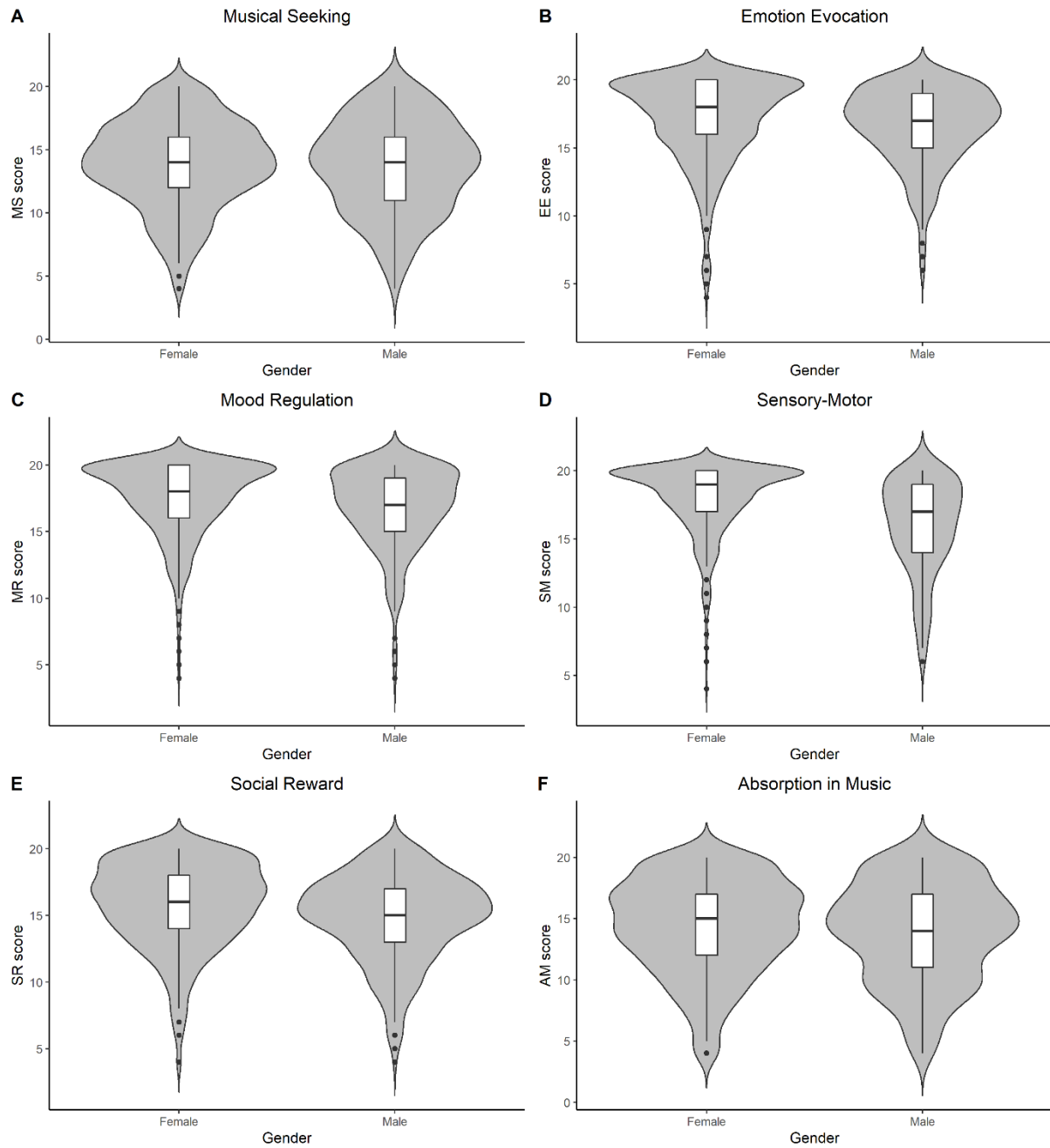


Figure S2. Distribution of each of the eBMRQ's factors as a function of gender.

Study 2

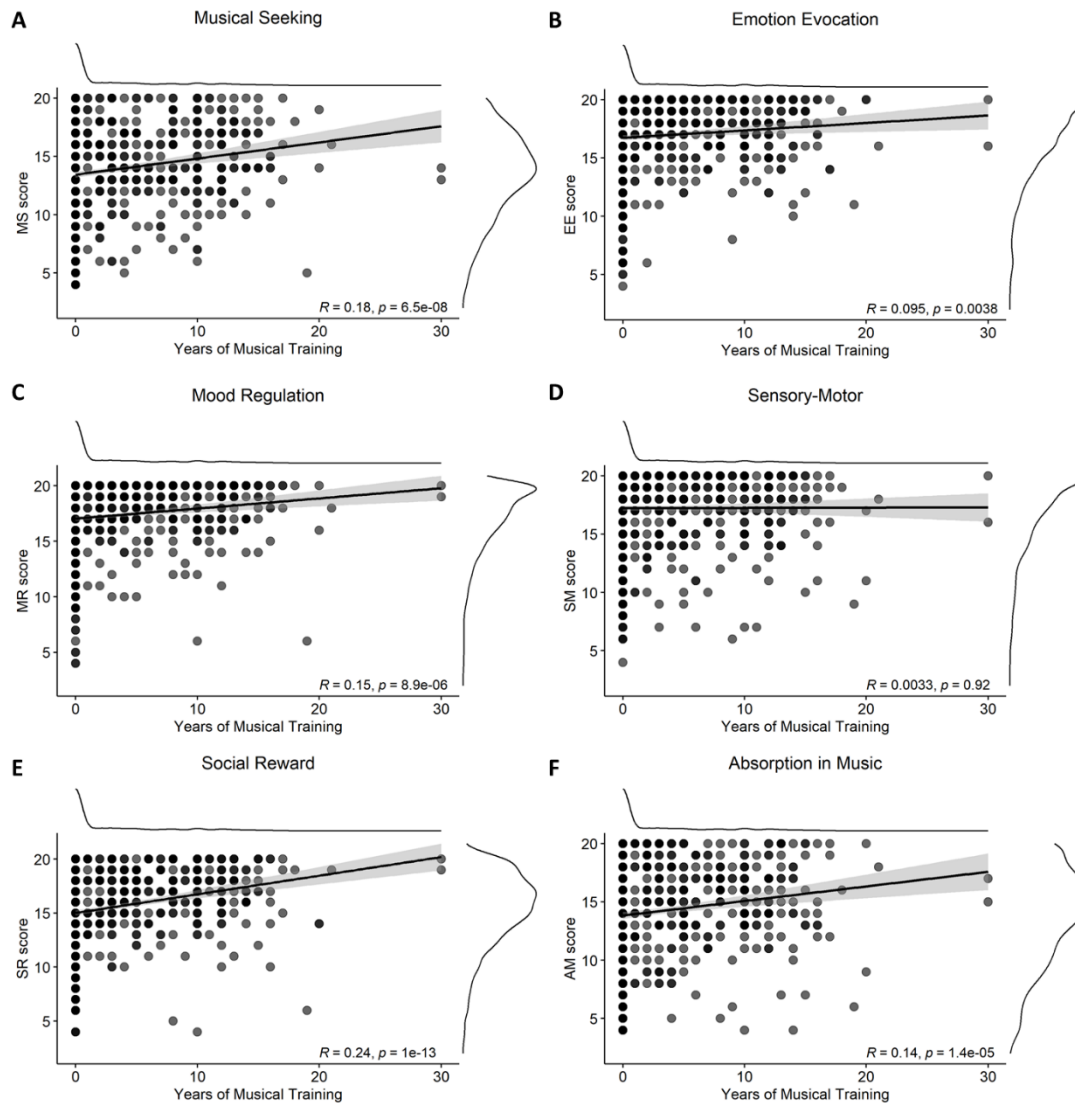


Figure S3. Correlation between years of musical training and each of the eBMRQ's factors. In the margins, density plots for years of musical training and the corresponding eBMRQ factor are shown.

Study 2

Appendix A. eBMRQ Spanish version

El siguiente cuestionario hace preguntas sobre tus actitudes en relación a la música. Cada ítem de este cuestionario es una afirmación con la que se puede estar de acuerdo o en desacuerdo. Para cada ítem, indica en qué grado estás de acuerdo o en desacuerdo con lo que dice el ítem. Por favor, responde a todos los ítems y no dejes ninguno en blanco. Escoge sólo una respuesta para cada afirmación. Por favor, intenta ser lo más preciso y honesto, respondiendo a cada ítem como si fuera el único. Es decir, no te preocupes en ser “consistente” en tus respuestas. Escoge entre las siguientes opciones:

[1] - completamente en desacuerdo; [2] - en desacuerdo; [3] - ni de acuerdo ni en desacuerdo; [4] - de acuerdo; [5] - completamente de acuerdo.

1. Cuando comparto música con alguien siento una complicidad especial con aquella persona.
2. En mi tiempo libre apenas escucho música.
3. Algunas canciones me ponen los pelos de punta.
4. La música me hace compañía cuando estoy solo.
5. No me apetece bailar ni con la música que más me gusta.
6. A veces siento como si la música y yo fuéramos uno solo.
7. La música me hace conectar con la gente.
8. Me informo sobre la música que me gusta.
9. Me emociono escuchando ciertas canciones.
10. La música me tranquiliza y me relaja.
11. La música me hace bailar.
12. Mientras escucho música puedo llegar a involucrarme tanto que me olvido de mí mismo y de mi entorno.
13. Busco novedades musicales continuamente.
14. Puedo llorar cuando escucho algunas melodías que me gustan mucho.
15. Me gusta cantar o tocar un instrumento con más gente.
16. La música me ayuda a desconectar.
17. No puedo evitar tararear las canciones que me gustan cuando las escucho.
18. A veces soy capaz de sumergirme completamente en la música y sentir como si mi estado de consciencia se hubiera visto alterado temporalmente.
19. En los conciertos me siento en sintonía con los artistas y el público.
20. Me gasto bastante dinero en música y cosas relacionadas con la música.
21. Siento escalofríos cuando escucho una melodía que me gusta.
22. Con la música me puedo desahogar.
23. Cuando escucho una melodía que me gusta mucho no puedo evitar mover el cuerpo.
24. Cuando escucho buena música a veces siento como si me elevara en el aire.

Study 2

Appendix B. eBMRQ English version

Each item of this questionnaire is a statement that a person may either agree with or disagree with. For each item, indicate how much you agree or disagree with what the item says. Please respond to all the items; do not leave any blank. Choose only one response to each statement. Please be as accurate and honest as you can be. Respond to each item as if it were the only item. That is, do not worry about being consistent in your responses. Choose from completely disagree (left) to completely agree (right) one of the five options:

[1] - Completely disagree; [2] - disagree; [3] - Neither agree nor disagree; [4] - agree; [5] Completely agree.

1. When I share music with someone I feel a special connection with that person.
2. In my free time I hardly listen to music.
3. I like listen to music that contains emotion.
4. Music keeps me company when I'm alone.
5. I don't like to dance, not even with music I like.
6. I sometimes feel like I am 'one' with the music.
7. Music makes me bond with other people.
8. I inform myself about music I like.
9. I get emotional listening to certain pieces of music.
10. Music calms and relaxes me.
11. Music often makes me dance.
12. While listening to music, I may become so involved that I may forget about myself and my surroundings.
13. I'm always looking for new music.
14. I can become tearful or cry when I listen to a melody that I like very much.
15. I like to sing or play an instrument with other people.
16. Music helps me chill out.
17. I can't help humming or singing along to music that I like.
18. It is sometimes possible for me to be completely immersed in music and to feel as if my whole state of consciousness has been temporarily altered.
19. At a concert I feel connected to the performers and the audience.
20. I spend quite a bit of money on music and related items.
21. I sometimes feel chills when I hear a melody that I like.
22. Music comforts me.
23. When I hear a tune I like a lot I can't help tapping or moving to its beat.
24. When listening to great music I sometimes feel as if I am being lifted into the air.

Study 3

**The cost of music curiosity and its
impact on memory: evidence from
laboratory and natural settings**

5 Study 3

The cost of music curiosity and its impact on memory: evidence from laboratory and natural settings

5.1 Introduction

Curiosity, often defined as the need or desire to know (Gottlieb et al., 2013; Sharot & Sunstein, 2020), constitutes a fundamental drive in human behavior. It enhances organisms' cognition by promoting non-instrumental information seeking and enriching internal models of the world, which can be crucial for their biological fitness. Recent research has shown that curiosity states elicit activation of reward-related mesolimbic dopaminergic pathways (Gruber et al., 2014; Van Lieshout et al., 2020), likely reinforcing non-instrumental information seeking activities and motivated-learning. The activation of these regions boosts consolidation processes in the hippocampus, ultimately improving the encoding of new information into long-term memory (Adcock et al., 2006; Gruber et al., 2014; Wittmann et al., 2005). This reward-motivated component of curiosity is necessary for attributing value to new information (Bromberg-Martin & Hikosaka, 2009), which is essential for refining internal models and improving prediction and action control.

Curiosity, however, comes with a cost, as the intrinsic motivation to learn and to seek for new information usually requires a “curious mind” to allocate attention, energy, time, and/or money in the absence of foreseeable extrinsic benefits (Kang et al., 2009; Van Lieshout et al., 2020). This effortful process is sometimes sustained over long timescales, such as when developing specific interests or skills. Understanding how curiosity is triggered and maintained over time and how it varies across individuals constitutes therefore an important – yet largely unexplored – question (Kashdan et al., 2018; Kobayashi et al., 2019), especially in natural contexts. This is particularly relevant when considering that we are living in the so-called “information age” (Simon et al., 1971), where curiosity and attention are constantly hijacked by new and often irrelevant or non-beneficial information.

Music is considered as one of the most rewarding activities for humans, eliciting strong emotions and passions. However, large individual differences are observed in music curiosity and interests, with information-seeking being one of the main facets characterizing individual differences in music reward sensitivity (the so-called musical hedonia; Mas-Herrero et al., 2013). Because of its

hedonic properties, music serves as a highly effective mood regulator, being controlled by dopaminergic and opioid neurotransmission systems (Ferreri et al., 2019; Laeng et al., 2021; Mas-Herrero et al., 2023). Humans usually take advantage from this, so that we could conceive music as a *low-hanging fruit*, used for inducing swift and deeply pleasurable experiences. Nevertheless, this easy access to emotional regulation and hedonic experiences (e.g., via preferred music) may also, conversely, mitigate the inclination to invest in more demanding exploration of new music and related information. Thus, music presents the same explore-exploit dilemma usually encountered in decision-making, either exploiting known options for immediate reward (e.g., listening to favorite music) or incurring into a costly exploration that could end-up with a surprising new source of pleasure (Cohen et al., 2007; Wilson et al., 2021).

Relevant for the present research, music differs from other stimuli commonly used in curiosity research. While curiosity studies typically employ discrete, brief pieces of information (e.g., ambiguous images or trivia questions) that quickly satisfy curiosity (Gruber et al., 2014; Jepma et al., 2012; Loewenstein, 1994), musical structures are more complex and unfold over time, modulating listener's expectations and predictions through dynamic rhythmic, melodic, or harmonic changes, thus continuously influencing the on-going emotional experience. This inherent complexity, in turn, might increase curiosity and exploration (Berlyne, 1970), making music more resistant to hedonic adaptation (i.e. the decline of enjoyment with repeated exposures) and satiation compared to other stimuli like food taste (Kahneman & Snell, 1992; O'Brien, 2021). Accordingly, individuals often engage in repetitive listening of preferred songs or albums in a constant search for resolution and satisfaction. Therefore, music provides a compelling domain for investigating curiosity and the associated desire for exploration.

In the present study, we aimed to: (i) investigate music curiosity and its ignition, as well as its influence on exploratory behavior and memory outcomes, and (ii) extend, for the first time, the study of curiosity to a natural setting (within an electronic music DJ session), considering the inherent complexities of real-world environments. In this sense, music constitutes an ideal stimulus allowing to investigate cognitive mechanisms in natural settings, such as live performances. To these aims, we conducted two experiments (Exp. 1 and Exp. 2) where we investigated curiosity states during music listening (using self-reported measures) and assessed the extent to which participants might be incurring in some costs for engaging in exploratory behaviors. In Exp. 1, we implemented a new laboratory exploration/exploitation tradeoff paradigm inspired by previous animal studies (Blanchard et al., 2015; Deaner et al., 2005) and a language learning tradeoff task (Rodriguez-Fornells et al., under review). Besides providing subjective curiosity ratings, participants were allowed to decide to what extent they were "willing

to pay” to continue exploring a new music piece to which they were briefly pre-exposed. Alternatively, participants could decide not to explore the new song and listening to their favorite songs instead. Thus, our paradigm combined both subjective and objective measures of curiosity. In Exp. 2, we adapted this paradigm to be carried out in a natural setting. During an electronic music DJ session in a concert hall, we measured exploratory behavior by asking participants whether they would be “willing to pay” to get access a given excerpt or related information.

We defined logistic regression models to measure the predictive power of curiosity ratings on exploratory behaviors (Rosenfeld & Kraus, 2018; Tonetti & Sanz, 2019; see also Harper, 2005; Zare et al., 2016; Zavadskas & Turskis, 2011). Additionally, we used machine learning techniques to predict laboratory and naturalistic data, and further explored whether models trained on laboratory outcomes could predict decision-making in a natural setting with a different sample. We expected the curiosity elicited during music listening to predict whether participants would explore new music/information despite a possible monetary cost (i.e., the higher the curiosity, the higher the willingness to pay - WTP). Critically, and in order to investigate the potential effect of music-related individual differences on exploratory behavior, we took into account in both experiments individual music preferences (with particular focus on the electronic music genre here employed) and sensitivity to music reward (through the extended version of the Barcelona Music Reward Questionnaire, eBMRQ; Cardona et al., 2022; Mas-Herrero et al., 2013). Furthermore, in both experiments, we investigated the possible impact of curiosity on learning (i.e., memory for music pieces) by using a surprise memory task the following day (Cardona et al., 2020; Ferreri, Mas-Herrero, et al., 2021; Ferreri & Rodriguez-Fornells, 2022). We expected that the higher the curiosity experienced during music listening, the higher the dopaminergic transmission boosting consolidation processes in the hippocampus, and the better the memory outcomes.

5.2 Material and Methods

5.2.1 Experiment 1. Laboratory Setting

Procedure

The experiment was structured in two sessions occurring on two consecutive days and it was conducted onsite at the Psychology and Medicine Faculties of the University of Barcelona. The first day, participants completed a *music curiosity tradeoff task*. Twenty-four hours later, participants

went back to the lab to perform two surprise memory tasks and fill in a set of questionnaires. All tasks were ran on Psychopy software (Peirce et al., 2019; version 2021.2.3).

Participants

Sixty-three undergraduate students (mean age = 20.6 ± 2.4 y.o., 58 women, 5 men) took part in this experiment. A total of three participants were removed from the analyses: two who did not understand the task (see details below), and one who did not complete the experiment. Therefore, the final sample included sixty participants (mean age = 20.4 ± 2.1 y.o., 55 women, 5 men). Participants received monetary compensation according to their choices during the task, and they provided informed consent for their participation in the study, which was approved by the Bellvitge University Hospital's Ethics Committee (PR335/21).

Stimuli

Musical stimuli consisted of 70 experimenter-selected unfamiliar electronic music tracks, from which excerpts of 50 s were extracted. All the excerpts were split into a preview (the first 10 s) and a continuation (the next 40 s). Electronic stimuli did not contain lyrics nor highly salient features (e.g. a single instrument leading the melody, highly noticeable audio distortions, sounds resembling human voices) to avoid a facilitatory effect on subsequent memory tasks. The selected pieces were rated by an independent sample of 20 undergraduate students (mean age = 20.9 ± 1.8 y.o., 17 women, 3 men) in terms of pleasure, arousal, familiarity, and valence. Subsequently, the excerpts were divided into two balanced lists showing no significant differences regarding these ratings ($ps > 0.6$, two-sample t tests of equal variances). These two lists were counterbalanced across subjects, one including the excerpts to be used in the curiosity tradeoff task (i.e., the old stimuli in the memory task), and the other one containing new excerpts to be randomly mixed with the old items in the subsequent memory task.

In addition, each participant was asked to provide a list including the 20 favorite songs they had listened to the most during the last year. From each song of that list, the first 40 s were extracted.

All stimuli were automatically normalized and faded (2.5 s in and 2.5 s out) using the *pydub* library from Python (Robert et al., 2018). Stimuli were presented using headphones and participants were able to adjust the volume at the beginning of the tasks.

Tasks

Music curiosity tradeoff task (laboratory setting)

The experiment was carried out in two consecutive days (see **Figure 1**). On Day 1, participants were exposed to 35 trials (i.e., one of the two lists). In each trial, participants listened to the preview of an electronic music excerpt while a black note was displayed on the screen. Then, participants rated their *curiosity* (i.e., “How curious are you about this excerpt?”) using a 7-point Likert scale (from 1=Not curious at all, to 7=Very curious). Subsequently, participants could choose between listening to the continuation of the electronic excerpt (i.e., electronic option) or listening to one of the songs they included in their own list (i.e., favorite option). To make possible the participants' choice, two long-plays (LPs) with the words “favorite” and “electronic” written at the top of them were displayed on the screen. Importantly, each option was associated to a monetary gamble stake ranging from one to ten euros, which was represented by a 10-slices pie chart displayed at the center of each LP (each colored slice represented a euro). The difference between the stakes associated to electronic and favorite options defined the differential value (see Analyses section), being possible values equal to $\{-5, -2, -1, 0, 1, 2, \text{ or } 5\}$ (see **Table 1**). For each subject, a total of five trials for each differential value was presented. Negative values indicated that the participant could lose money if he/she chose the electronic option, while positive ones indicated that he/she could earn money if the electronic option was chosen. The participants who aimed to maximize their earnings, always chose the option associated with the higher reward (i.e., more pie slices). The presentation side of the LPs was counterbalanced across participants, and the monetary rewards were presented pseudorandomly.

Once the choice was made, each participant listened to the chosen 40 s of music (i.e., the electronic music continuation or one of their favorites), and an associated colored note (i.e., blue, green, red, or yellow) was displayed on the screen. The colors were chosen to minimize their brightness differences, and their pseudorandom presentation was balanced across the two music conditions (i.e., electronic and favorite). The aim of changing the note's color across trials was to measure incidental encoding (see *source memory task* below). Thus, the meaning of the colored note was not explained to the participants until the end of the study. In order to ensure that participants saw the color of the note, they were explicitly encouraged to look at the center of the screen during the whole task. After this phase, participants were asked to rate in a 7-point Likert scale: 1) liking (i.e., “How much did you like the song?”, from 1=I didn't like it at all, to 7=I liked it a lot); 2) surprise (i.e., “How much did the song surprise you?”, from 1=No surprise at all, to 7=High surprise). Participants were instructed to report the absolute value of this rating, without regard to whether the surprise was positive (the continuation ended up being better than expected) or negative

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(they were disappointed by its unfolding); and 3) absorption (i.e., “How much absorption did you experience during the song?”, from 1=No absorption at all, to 7=A lot of absorption). In order to understand this construct, participants were asked to “think of a situation in which you have let yourself be carried away by the music and have ended up so immersed in it that you have come to forget yourself and your surroundings, as if the music and you had merged into one” (see Cardona et al., 2022).

Finally, at the end of the experiment, following a lottery procedure, three trials were randomly selected. Participants won the money associated with the selected option in each of these trials (the underlying code was arranged so that the total reward was between 15 and 25 euros).

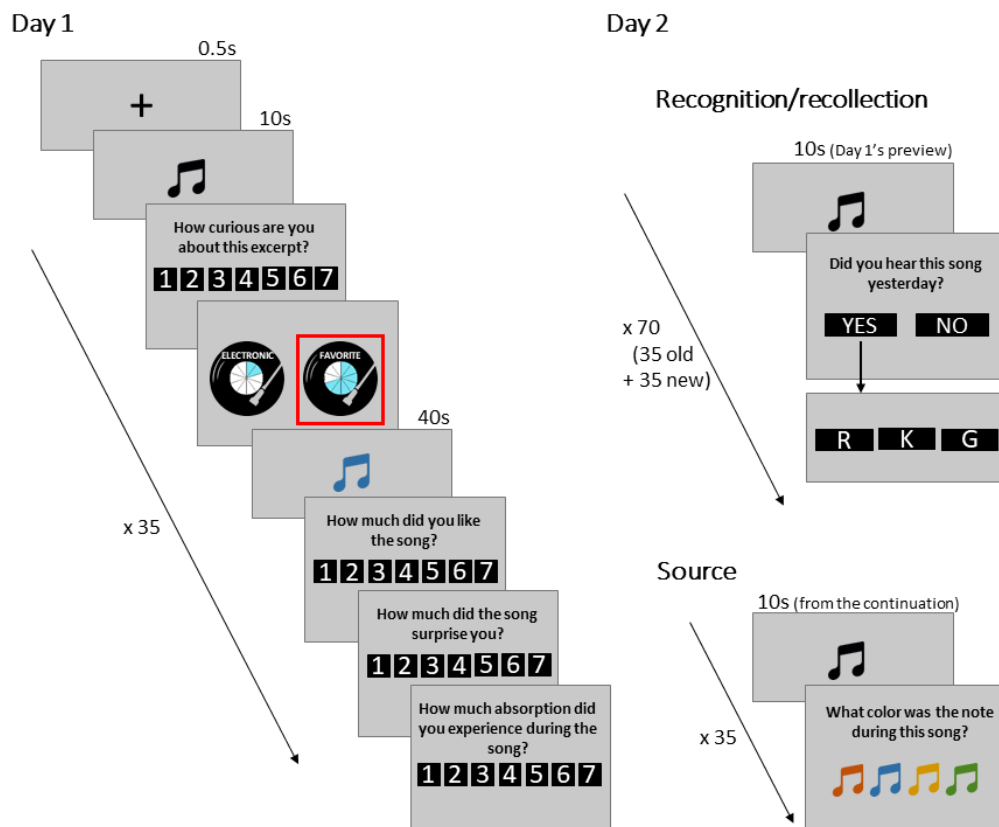


Figure 1. Experiment 1 procedure (Laboratory Setting). The experiment was conducted in two separate days in laboratory settings. On **Day 1**, participants listened to the electronic preview (10 s) and rated the elicited curiosity. Then, they had to choose between listening to the continuation of the track (LP with the word “electronic” written on it; electronic option), or listening to an excerpt of a favorite music they provided (LP with the word “favorite” written on it; favorite option). Each option was associated with a monetary reward represented by a 10-slices pie chart in the middle of the LP (one colored slice = one euro). After the choice, music played for 40 s while a colored note was displayed on the screen. On **Day 2**, participants performed two surprise memory tasks. First, they completed a recognition/recollection task where they listened to a 10 s preview and had to indicate whether it was played the day before (old stimulus) or not (new stimulus; recognition phase). If the participant said “yes”, he/she needed to commit to one of the three additional options (recollection phase): Remember (R), Know (K) or Guess (G). Second, participants performed a source memory task where, after listening to 10 s extracted from the continuation of the song (either electronic or favorite depending on their choice on Day 1) participants had to indicate the color of the note presented during that song.

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<i>Value [-5]</i>	[1,6]	[2,7]	[3,8]	[4,9]	[5,10]
<i>Value [-2]</i>	[1,3]	[2,4]	[4,6]	[7,9]	[8,10]
<i>Value [-1]</i>	[1,2]	[2,3]	[4,5]	[7,8]	[8,9]
<i>Value [0]</i>	[1,1]	[2,2]	[5,5]	[9,9]	[10,10]
<i>Value [+1]</i>	[2,1]	[3,2]	[5,4]	[8,7]	[9,8]
<i>Value [+2]</i>	[3,1]	[4,2]	[6,4]	[9,7]	[10,8]
<i>Value [+5]</i>	[6,1]	[7,2]	[8,3]	[9,4]	[10,5]

Table 1. Reward conditions [*Electronic/Favorite*] presented in the music curiosity tradeoff task.

Memory tasks

Twenty-four hours later (i.e., Day 2), participants went back to the laboratory and performed a two-phase surprise memory task. First, they completed a *recognition/recollection task* (Yonelinas, 2002) (see refs. Cardona et al., 2020; Ferreri, Mas-Herrero, et al., 2021; Ferreri & Rodriguez-Fornells, 2022). Thirty-five old (i.e., from the list they listened to on Day 1) and 35 new (i.e., from the unused list) electronic music previews were presented to the participants. For each preview, they had to indicate whether they had listened to it the day before (old/new recognition). If they indicated they had, they needed to commit to one of the three additional options (recollection task): Remember (R), Know (K) or Guess (G). R indicated that they were able to recollect something specific about the episode; K indicated that they were confident that they had heard it but they had no specific memory associated with it; and G indicated that they were unsure about whether the excerpt was indeed heard the day before. Then, they performed a *source memory task*. Participants were presented with 35 ten-seconds excerpts extracted from the 40 s excerpts they chose to listen to (either the electronic continuation or the favorite song). For each excerpt, participants had to indicate which of the four possible colored musical notes was showed during the presentation of that excerpt. To avoid any bias in the responses, the order of the colored notes was counterbalanced across subjects.

Demographics, questionnaires and music-related information

After the memory tasks, participants completed questionnaires including the extended Barcelona Music Reward Questionnaire (*eBMRQ*; Cardona et al., 2022), the Beck Depression Inventory's anhedonia subscale (*AnhedoniaBeck*; Beck et al., 1996), the Diversive subscale from the Perceptual Curiosity Scale (*DiversivePC*; Collins et al., 2004), the Diversive subscale from the Epistemic Curiosity Scale (*DiversiveEC*; Litman & Spielberger, 2003)), the Absorption subscale

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from the Curiosity and Exploration Inventory (*AbsorptionCEI*; Kashdan et al., 2004), and two items to assess *amusia* (i.e., ‘I can barely perceive when someone is singing out-of-tune’, and ‘I’m usually unable to recognize a very familiar melody without the help of the lyrics’; the mean of the two items was employed). In addition, participants were asked to provide some information including age, gender, education level, musical training (*Music Training*, i.e., whether they had ever received musical training or not), and musical preferences (i.e., 7-point Likert scale for classical, jazz, pop, rock, and electronic music; see **Figure 2** for a summary).

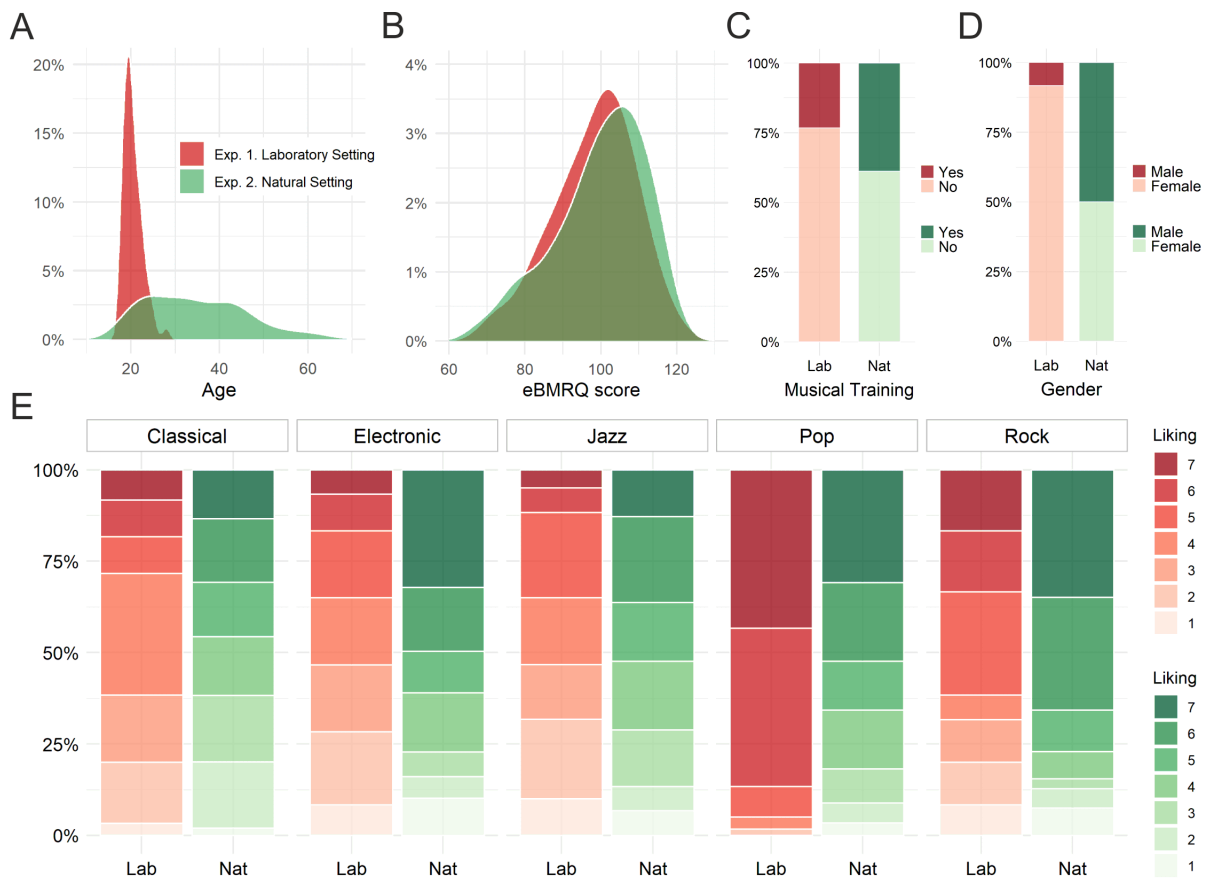


Figure 2. **A and B.** Density plots showing the distribution of Age and eBMRQ score, respectively, in the samples from both Laboratory (orange) and Natural (green) settings. **C and D.** Barplots showing the percentage of musically trained participants and gender distribution in both experiments. **E.** Liking ratings reported for each musical genre (classical, electronic, jazz, pop, and rock music) in both samples.

Analyses

Modeling participants' choices

First, we discarded the data from two (out of the sixty-three total) participants who did not respond to monetary incentives (that is, those who were insensitive to the differential value) since

this reflected inattention to the task or to the initial instructions, thus hindering interpretation of their curiosity behavior. Then, we used maximum-likelihood estimation to fit individual participants' choices with a two-parameter logit model (see Kobayashi et al., 2019):

$$P(\text{choice}) = \frac{1}{1 + \exp(-(w_0 + w_{\Delta MR} * \Delta MR))}$$

in which w_0 and $w_{\Delta MR}$ were free parameters, $P(\text{choice})$ was the probability of choosing the electronic option, and ΔMR (i.e., the differential value) was the monetary reward associated with the electronic option minus the monetary reward associated with the favorite one.

Subsequently, we assessed whether participants' choices (represented by the psychometric function) were modulated by elicited curiosity. To that aim, we built a logistic regression mixed model where the response variable was whether the participant chose the electronic option or not, and the fixed effects included the interaction between the differential value (i.e., ΔMR) and the curiosity rating reported for each electronic music preview. Thus, the fixed effects of the model were: $\Delta MR * \text{Curiosity}$. Random intercepts for participants were considered.

For each curiosity rating a logistic function was fitted, and the points of subjective equality (PSE) were calculated (Yarrow, 2018). These points indicated the ΔMR where the probability of choosing the electronic option was equal to 50%. In other words, the point where participants chose randomly between the two given alternatives (electronic-new and favorite options). Therefore, negative and positive PSEs indicated a willingness to pay for electronic-new or favorite options, respectively. A PSE equal to zero would indicate that the participant was interested in the monetary reward only, because he/she always chose the more rewarding option, unless for $\Delta MR = 0$ (no reward difference between choosing either electronic or favorite), where he/she chose whatever he/she desired. If the exploration is guided by the elicited internal curiosity, we expected to observe a preference for exploiting in low curiosity ratings (paying money was not worthy), and a preference for exploring in high curiosity ratings. Therefore, we expected to observe higher PSE values for low curiosity ratings than for high ones. Significant differences between PSEs for the different curiosity levels were assessed using the Tukey HSD post-hoc test.

Finally, we assessed whether the addition of reward-related individual differences measures to the model would better predict participants' choices. To that aim, we generated a new logistic regression mixed model including the interaction between the ΔMR , Curiosity, and the subject's preference for electronic music (Electronic Liking), as well as the interaction between the ΔMR , Curiosity, and the subject's sensitivity to music-induced reward (eBMRQ score). We also included the main effect of Gender to take into account the prevalence of women in our sample. This led to

the following model: $\Delta MR * Curiosity * Electronic\ Liking + \Delta MR * Curiosity * eBMRQ\ score + Gender$. Random intercepts for participants were included. The variance inflation factor (VIF) was used to detect multicollinearity. According to the rule of thumb, VIFs lower than 1 indicate no correlation between the predictors, VIFs between 1 and 5 indicate moderate correlation, and VIFs higher than 5 indicate high correlation. Backward elimination method was used for model selection. Likelihood ratio tests were used to assess increases in model fit as well as the contribution of the different predictors and their interaction to the response variable. eBMRQ score was scaled to avoid convergence failures. Bobyqa optimizer with 10000 iterations was used to fit the models.

Predicting participants' choices

We measured the capability of a model including the interaction between the ΔMR and the elicited curiosity to predict the decision of exploring or exploiting. To assess this predictive power, regardless of participants variability, we built a predictive model (logistic regression model, *sklearn* library in Python) using 70% of the data ($N_{train} = 1470$). Then, this model was used to predict the remaining 30% of the data ($N_{test} = 630$). That is, based on the ΔMR and the curiosity elicited during the preview, the model predicted whether the participant chose to listen to the continuation (exploration) or to listen to his/her favorite song (exploitation). This prediction was carried out for each test instance. To measure how well the results were predicted, the accuracy of the model, the ROC curve and the f1-score for each class were reported.

Regression models for memory performance

For the recognition/recollection memory task, we used logistic regression mixed models to predict both recognition and recollection responses. In the case of recognition, we aimed to predict whether the old stimuli were correctly recognized (or not) as a function of the interaction between *Curiosity* and *Electronic Liking*, the interaction between *Curiosity* and the subject's sensitivity to music reward (*eBMRQ score*), and the main effect of whether the subject had chosen to explore the newly presented electronic excerpt and thus had listened to it for a longer period of time or not (*Choosing exploration*). We also included the main effect of *Gender* to take into account the prevalence of women in our sample. Thus, the full model was: $Curiosity * Electronic\ Liking + Curiosity * eBMRQ\ score + Choosing\ exploration + Gender$. Random intercepts for participants were included. In the case of recollection, correctly recognized items (hits) were reorganized into two categories ('Remembered', including 'R' responses, and 'Not remembered', including 'K', 'G') and the fixed and random effects structure was the same as for recognition. VIF was used to detect multicollinearity.

In the second memory task (source memory), our main interest was to assess whether an incongruence between the curiosity elicited by the preview and the pleasure derived from the continuation facilitated incidental encoding of the colored note presented on the screen. However, results showed that participants' memory performance in this task was below chance level ($\bar{X} = 0.238$, $sd = 0.109$), suggesting that the task was too difficult. Thus, data from this task were no further analyzed.

5.2.2 Experiment 2. Natural Setting

Procedure

Together with Sonar+D (<https://sonarplusd.com>), we organized a DJ set hosted by the internationally renowned DJ Alicia Carrera at the Centre de Cultura Contemporània de Barcelona (CCCB) on October 29, 2021. The same DJ set was repeated the next day at Sala Salamandra (SS) in L'Hospitalet de Llobregat, following exactly the same procedure. Both DJ sets were held in locations specifically designed for organizing this type of event and all anti-COVID measures required by the competent authorities at the time of the concert were applied. Additionally, the organization broadcasted the concert for free on its website, allowing people to take part in the experiment online. The DJ sets were advertised on the Sónar and SS official websites and social media as a unique real-life experiment. The advertisement informed participants that the experiment consisted of two phases, the live event and a follow-up questionnaire to be completed online the following day. In addition, it specified that they would be asked to use their smartphones to answer some questions during the live event. Tickets were distributed free of charge until they were sold out.

On the day of the concert (i.e., Day 1), participants accessed the event site upon presentation of the ticket. Once all participants entered the room, and before the concert began, the researchers explained the mechanics of the experiment with the help of a visual presentation projected on a big screen. Then, participants were asked to use their smartphones to access Mentimeter (Mentimeter AB (publ), Stockholm, Sweden), an online interactive presentation software that we used to collect the data. Before the beginning of the experiment, participants were able to select the preferred language (i.e., English or Spanish). Before starting the data collection, all the information regarding the experiment and the data protection policy was explained by the researchers and presented both on the big screen and the participants' smartphones. Participants then provided informed consent for their participation in the study, which was approved by the Bellvitge University Hospital's Ethics Committee (PR335/21).

The following day (i.e., Day 2) participants received an email to participate in an online surprise memory task. Participation in this second phase was encouraged with the raffle of 20 double tickets for Sonar Day 2022 among all those who completed the task. Two days after the concert, those who completed the second phase received an email indicating whether they had won a double ticket or not. In addition, they all received a link to Alicia Carrera's Soundcloud, where she posted the recording of the concert including tags with the titles of the songs and names of the authors. Therefore, participants, if interested, were able to further explore the personal profiles of these artists and listen to the songs again.

Participants

From the total of 150 participants (mean age = 34 ± 11 y.o., 63 men, 78 women, 3 non-binary, 1 preferred not to respond, and 5 missing values), 94 people attended the concert at CCCB, and 56 at SS. Almost all the participants attended in person (138 in person, 6 online and 6 that did not fill in this field), and only 8 people chose the English version of the questions. Some participants had to be excluded from the analyses due to their missing data (see **Figure 3**).

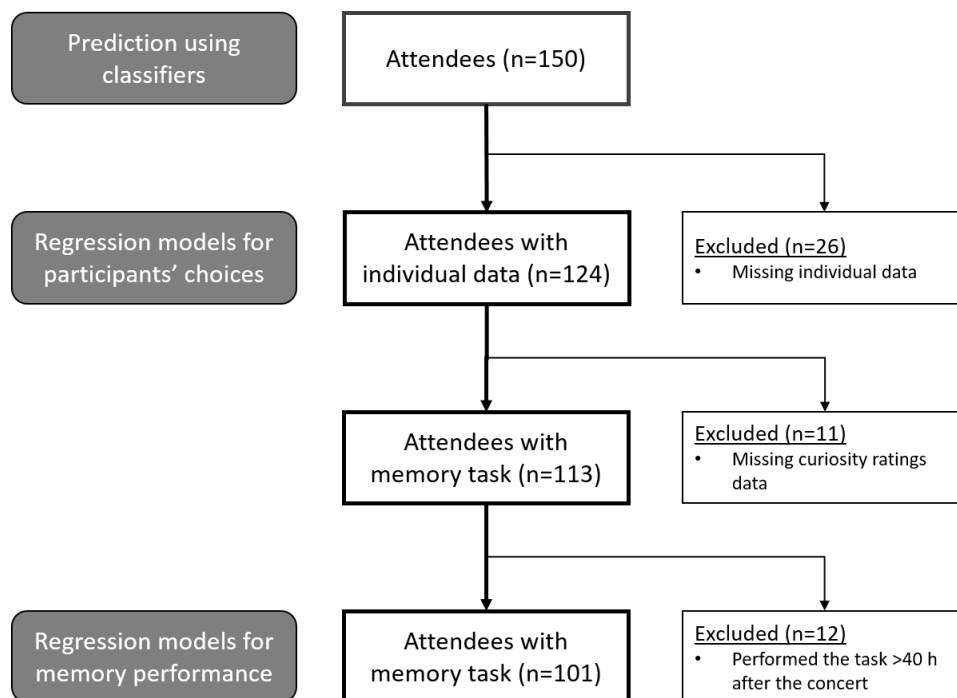


Figure 3. In total, 150 participants attended the organized concerts. However, some participants were removed from some analyses due to missing data.

Stimuli

The DJ set lasted one hour and consisted of 20 unpublished electronic music tracks specifically selected for this event. The 20 tracks were presented in a continuous stream, with soft transitions between one track and the following one. Twenty additional tracks with similar style and tempo were selected by the DJ to be used in the memory task.

Tasks

Music curiosity task (concert setting)

For each trial (i.e., each of the 20 tracks that composed the DJ set) participants answered a set of four questions, which were triggered when the track was approximately in the middle of its duration (mean time = 78.05 ± 27.08 s). This was done in order to allow participants to focus on the first part of the song before answering, thus avoiding possible distractions coming from the task itself and mimicking the previews of Exp. 1, and to answer while the song was still playing, thus avoiding possible interferences coming from the following song. In the first three questions, and as for Exp. 1, participants were asked to rate (7-point Likert scale) the degree of curiosity, pleasure, and absorption they had experienced during the excerpt (i.e., ‘How curious are you about this song?’, ‘How much pleasure have you experienced with this song?’, and ‘How much absorption have you experienced during the song?’). Finally, they were asked whether they were willing to spend Sonar coins (digital coins specifically designed for this experiment) to obtain song-related information (i.e., exclusive information about the song and the artist that would be sent to their email the following day, at a cost of 1 Sonar coin), the song itself (i.e., the song would be included in a personalized playlist to be sent by email the next day, at a cost of 1 Sonar coin), both (cost of 2 Sonar coins) or none (cost of 0 coins, see **Figure 4**). Participants were told that, at the end of the concert, all those songs and information they had invested for would be considered in a lottery. In this lottery, items would be selected randomly until spending a total of ten Sonar coins for each participant. The aim of this lottery design was that participants considered each song independently, without regarding the Sonar coins spent in previous trials. In order to warn participants that they needed to look at their smartphones and answer the questions, we used the color of the ambient lights (red during the listening phase, and green for the answering phase). In addition, the transition between questions was cued by changing the image projected on the big screen. Timings for each question varied depending on how long took the participants to answer (i.e. the number of responses was monitored in real time and we triggered the subsequent question when at least 80% of the participants had answered, with a limit of 30 s). On average participants had 20 s per question to provide their responses.

Memory task

Twenty-two hours after the concert, participants received a link to participate in an online surprise memory task (recognition/recollection paradigm; Yonelinas, 2002, see Figure 3). In this case, participants were presented with 20 old excerpts (extracted from each of the 20 pieces played during the concert) and 20 new excerpts (extracted from similar electronic and unpublished pieces chosen by the DJ). These excerpts had a 10 s duration and were randomly presented to the participants. Memory data were obtained from 75% of the concert attendees (N = 113).

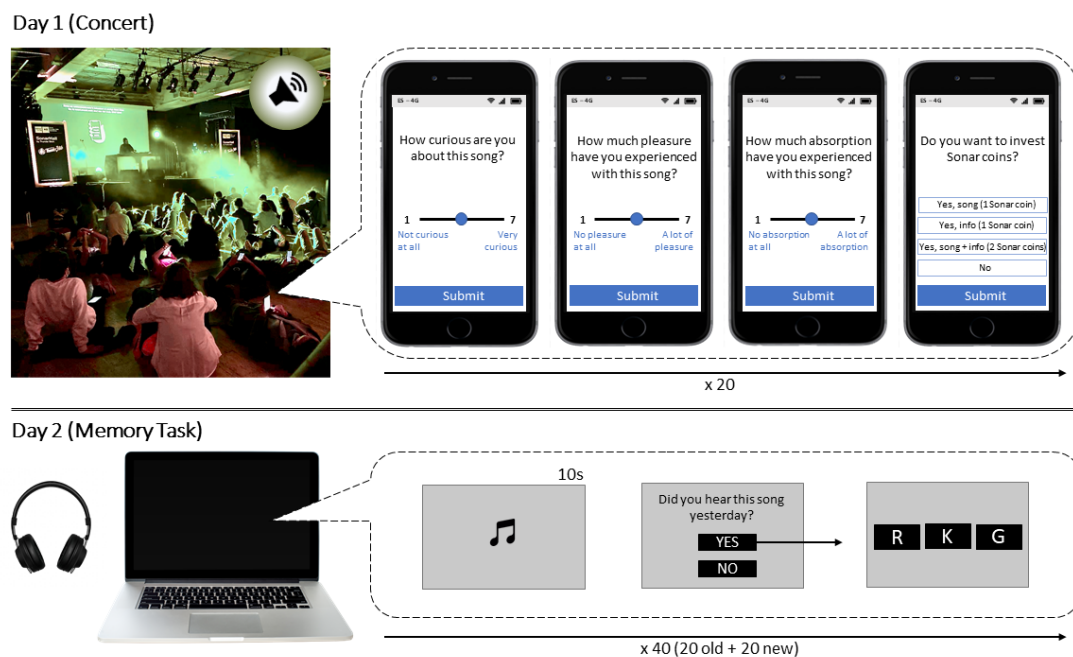


Figure 4. Experiment 2 procedure (Natural Setting). The experiment was conducted in two separate days. On Day 1, participants attended an electronic music DJ set consisting of 20 different tracks. After ~78s of listening to each track, participants had to rate curiosity, pleasure, and absorption in a 7-point Likert scale. They were also asked whether they were willing to spend Sonar coins (digital coins specifically designed for this experiment) to obtain song-related information, the song itself, both or none. Twenty-two hours after the concert, participants received a link to participate in an online surprise recognition/recollection memory task. Participants were presented with 20 old and 20 new excerpts and they had to report whether they had listened to it the day before or not. If they think they had, they had to commit to one of the three options (Remember, Know, or Guess) assessing episodic memory.

Demographics, questionnaires and music-related information

On Day 1, after accepting the informed consent, participants were asked to provide some information including age, gender, education level, musical training (i.e., whether they had ever received musical training or not), and musical preferences (i.e., 7-point Likert scale for classical, jazz, pop, rock, and electronic music; see Figure 2). On Day 2, after the memory task, participants completed the same questionnaires as in Exp. 1.

Analyses

Modeling participants' choices

The main focus of the study was on the triggering of curiosity and its impact on the WTP. Given that the ratings of pleasure and absorption were compromised due to the sequentiality of the responses, we decided not to use these ratings in any of the analyses here reported.

Following the same rationale as for Exp. 1, we first used logistic regression mixed models to assess the effect of curiosity on participants' WTP (i.e., investing a Sonar coin). The four levels of the response variable (i.e., investing for getting song-related information, the song itself, both or neither) were collapsed into two (i.e., whether the participant had decided to invest on something or not). Therefore, the dependent variable was assumed to have a binomial distribution and a logit link function was used. In this model we also included the effect of *Place* (i.e., CCCB or SS) to take into account possible differences between the two samples. Thus, the full model was: *Curiosity + Place*. Random intercepts for both participants and songs were also included.

Subsequently, we assessed how demographic data and individual differences measures affected the effect of curiosity on WTP. In this case, and taking as a reference the model used for Exp. 1, the full model was: *Curiosity*Electronic Liking + Curiosity*eBMRQ score + Place*. Again, random intercepts for both participants and songs were included. In all models *eBMRQ score* was scaled to avoid convergence failures. Nelder Mead optimizer with 10000 iterations was used to fit the models. In those cases in which the model did not converge, we created the same model using *nloptwrap* optimizer and compared the outcomes. If results were similar, we proceeded with the backward elimination process. VIF was used to detect multicollinearity. These models were performed with a sample of 124 participants since 26 participants needed to be excluded due to missing individual differences data (see Figure 2).

Predicting participants' choices

We assessed the predictive power of a model using the curiosity elicited during the concert to predict the participants' WTP (i.e., their choice to spend Sonar coins). This monetary cost had to be paid in order to explore new knowledge about the track. Using the 70% of the data obtained in the natural setting ($N_{\text{train}} = 1999$), a logistic regression model was fitted, and it was used to predict the remaining 30% of the data ($N_{\text{test}} = 858$). For each test instance, the model only considered the elicited curiosity during the excerpt to predict whether the participant spent at least one Sonar coin or not (binary decision) to explore new information about the track. The performance of the model was measured by the accuracy, the ROC curve, and the f1-score for each class.

Regression models for memory performance

The same methodology as in Exp. 1 was used to assess the effects of *Curiosity*, *Electronic Liking*, and *eBMRQ score* on memory performance at both, recognition and recollection levels. Thus, the full model was: *Curiosity*Electronic Liking +Curiosity*eBMRQ score*. Random intercepts for participants were included. VIF was used to detect multicollinearity. Participants that performed the memory task later than 40 hours after the concert (i.e., more than one night of sleep had passed between the concert and the test) were removed from these analyses, ending up with 101 participants.

Using classifiers to predict Exp. 2 results from Exp. 1 data

Both experiments shared an exploration condition, namely, a condition where participants could pay money (or Sonar coins) to keep listening to the unknown electronic music (or to get unknown information about the song). Accordingly, as final analysis, a logistic regression model was fitted using the data obtained in Exp. 1 to predict the data obtained in Exp. 2. To make both datasets comparable, we performed a domain adaptation considering only the data of negative differential values from the laboratory, where participants could pay (or not) money to explore new information (i.e., keep listening to unknown tracks). Since this subset was highly unbalanced ($N_{\text{explore}} = 59$ and $N_{\text{exploit}} = 841$), we applied techniques to balance the two classes (explore and exploit). We randomly selected 59 instances of the exploit class to have a balanced dataset, and therefore to be able to build the predictive model. Once the model was fitted, the elicited curiosity in the concert was used to predict whether the participants spent the Sonar coins to explore more information about the track ($N_{\text{eco}} = 2857$). To avoid a bias due to the random selection of the exploit class during the training of the model, this procedure was repeated 1,000 times. The accuracy of the model and the ROC curve were reported to measure the performance.

5.3 Results

5.3.1 Experiment 1. Laboratory Setting

Modeling participants' choices

Elicited curiosity modulates participants' WTP for exploring new music. Participants' explorative behavior was represented with psychometric choice functions that showed the probability of exploring unfamiliar electronic music as a function of the ΔMR (i.e., the difference between the monetary rewards associated with electronic and favorite options) and the curiosity elicited by

the new song. As expected, results showed that ΔMR strongly influenced participants' tendency to explore/exploit. Specifically, participants tended to choose the most rewarding option (i.e., the option associated to the highest amount of money), especially when the difference between the two options was large. Importantly for our design, we observed that curiosity influenced participants' behavior: the higher the curiosity, the more the money participants were willing to pay (see **Figure 5A**). This effect was clearly visible when computing the point of subjective equality (PSE) for each curiosity rating. The PSE represents the point where participants chose randomly between the two given alternatives (electronic and favorite options), thus indicating the monetary value participants assign to an excerpt that has elicited a particular level of curiosity. In this case, we observed that the value of the PSE decreased as the elicited curiosity increased ($F(6,2093) = 38.11$; Tukey HSD post-hoc test: $p_{\text{adj}} < 0.05$ represented in **Figure 5B**), indicating that *participants were willing to pay more money for exploring new music when they experienced high curiosity*. For example, when participants reported the highest curiosity (curiosity rating = 7) they were willing to pay 1.26 euros on average to explore the new excerpt. Interestingly, when they did not feel curious at all (curiosity rating = 1), participants were even willing to pay an average of 0.99 euros for listening to their favorite music.

Importantly, the impact of curiosity on exploration seemed to be different across ΔMR (see **Figure 5C**), pointing to an interacting effect between these factors (see below for statistical analysis). To visualize this effect more clearly, we computed the difference on the probability of exploring between the highest and the lowest curiosity ratings (7 and 1, respectively) across the seven possible differential values (see **Figure 5D**). Curiosity affected exploration behavior differently when comparing the gains and losses domains (i.e., positive and negative differential values, respectively): when exploring involved gaining money (positive ΔMR values), curiosity did not affect exploration behavior [i.e., participants systematically chose to explore, regardless of the elicited curiosity, especially when the differential value was large (ΔMR 2 and 5)]. On the other hand, when exploration entailed a monetary cost (negative ΔMR), participants were willing to pay to explore the excerpts for which they felt very curious about (see ΔMR -2 and -1).

In order to statistically assess these effects, we created a logistic regression mixed model with choice of electronic music as the dependent variable and the interaction between ΔMR and the curiosity rating as predictors. The final model ($\chi^2(3) = 1,628$, $p < 0.001$; AIC = 1,274, LL = -632) showed that, indeed, there was a main effect of ΔMR ($\chi^2(1) = 147.2$, $p < 0.001$), a main effect of Curiosity ($\chi^2(1) = 88.5$, $p < 0.001$), and a significant interaction between the two predictors ($\chi^2(1) = 27.4$, $p < 0.001$).

Preference for electronic music and sensitivity to music-induced reward (eBMRQ) modulate the explorative behavior. In order to account for the impact of individual differences on the cost for exploring new music, we assessed if participants' preference for electronic music and music reward sensitivity (eBMRQ) modulated the explorative behavior. To that aim, we simulated the choices of a participant who does not like electronic music (electronic liking = 1) as a function of ΔMR and Curiosity. Then, we did the same for a hypothetical participant who really likes electronic music (electronic liking = 7, see **Figure 5E**). Finally, we computed the percentage increase of exploration due to curiosity (see **Figure 5F**). Afterwards, we followed the same procedure to assess differences between participants with low and high sensitivity to musical reward (simulations of participants with eBMRQ score = 80 and 120, respectively, see **Figures 5G** and **5H**). Overall, Figures 5F and 5H, show a clear effect of individual differences in electronic music preference and music reward sensitivity, respectively, in the effect of curiosity across the different ΔMR . In both cases, those participants who liked more electronic music or were more sensitive to music reward, showed stronger impact of curiosity (larger exploration for high curiosity states compared to low ones, i.e. larger curiosity gradient), being this effect largely noticeable in both group analyses in the monetary gains (ΔMR values 1 and 2).

In order to statistically assess these effects, we proceeded to model selection. First, we tested the predictors to be included in the model for multicollinearity. VIFs ranged from 1.02 to 1.22, indicating a slight correlation amongst the predictors but not so high as to compromise the model's results. Therefore, we proceeded to generate a new logistic regression mixed model: $\Delta MR * Curiosity * Electronic\ Liking + \Delta MR * Curiosity * eBMRQ\ score + Gender$. Backward elimination process led to the final model including: $\Delta MR * Curiosity * Electronic\ Liking + \Delta MR * eBMRQ\ score$ ($\chi^2(9) = 1,654$, $p < 0.001$; see **Table 2** for measures of fit of the different models as well as likelihood ratio tests results used for model selection). Significant effects in this model included: a main effect of ΔMR ($\chi^2(1) = 34.22$, $p < 0.001$), a main effect of Curiosity ($\chi^2(1) = 5.48$, $p = 0.019$), a double interaction between ΔMR and Curiosity ($\chi^2(1) = 18.75$, $p < 0.001$), a double interaction between ΔMR and eBMRQ score ($\chi^2(1) = 8.66$, $p = 0.003$), and a triple interaction between ΔMR , Curiosity, and Electronic Liking ($\chi^2(1) = 5.08$, $p = 0.024$).

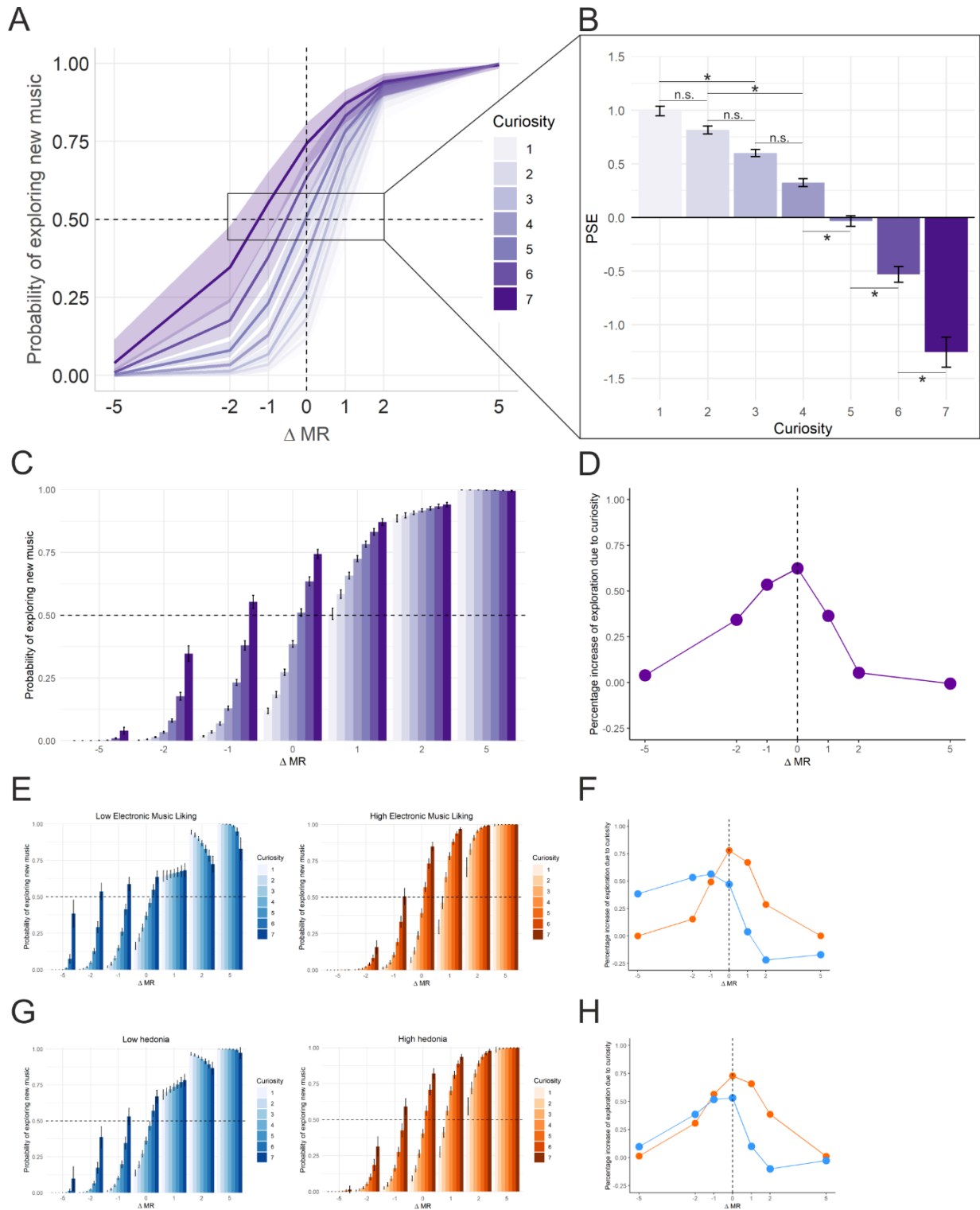


Figure 5. **A.** Graphical representation of the interaction between Δ MR and the curiosity rating, suggesting that high curiosity leads to a higher willingness to pay (WTP) for exploring new music. **B.** PSE and standard error of means (SEM) for each value of curiosity. **C.** Probability of exploring new music for each Δ MR as a function of curiosity. **D.** Difference on the probability of exploring between the highest and the lowest curiosity ratings (7 and 1, respectively) across the seven possible differential values to assess the effect of curiosity on exploration behavior. **E.** Probability of exploring new music for each Δ MR as a function of curiosity depending on participants' preference for electronic music (low: simulation of the choices a participant with a reported Electronic Liking of 1 out of 7 would make; high: simulation of a participant with a reported Electronic Liking of 7 out of 7). **F.** Difference on the probability of exploring between the highest

and the lowest curiosity ratings across the seven possible differential values for participants with low (blue) and high (orange) electronic liking based on the simulation described in panel E. **G.** Probability of exploring new music for each ΔMR as a function of curiosity depending on participants' music reward sensitivity (low: simulation of the choices a participant with an eBMRQ score = 80 would make; high: simulation of a participant with an eBMRQ score = 120). **H.** Difference on the probability of exploring between the highest and the lowest curiosity ratings across the seven possible differential values for participants with low (blue) and high (orange) music reward sensitivity based on the simulation described in panel G.

Predicting participants' choices

The differential value and the elicited curiosity predict participants' intention to explore or exploit. Given that the interaction between ΔMR and the elicited curiosity had a significant effect on WTP, we decided to measure its predictive power. For that purpose, we used 70% of the data to train a logistic regression model including the interaction between the differential value and the elicited curiosity that would predict whether the participant chose to listen to the continuation (exploration) or to listen to his/her favorite song (exploitation). This model was then used to predict the remaining 30% of the data. Since there were only two options (exploration/exploitation) the chance level was 50%. The accuracy of the fitted model was 90% (see red ROC curve in **Figure 6**), and the f1-scores were 0.89 and 0.91 for the exploration and exploitation classes, respectively.

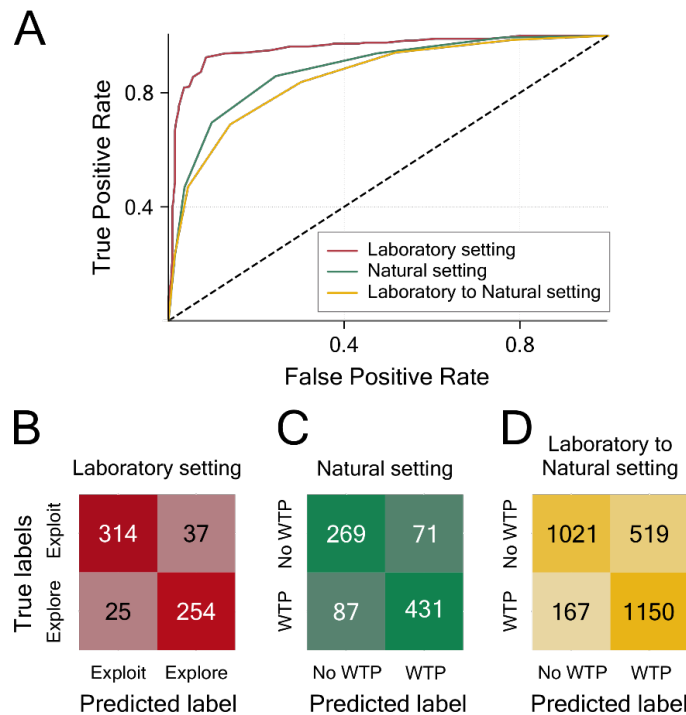


Figure 6. A. ROC curves for different classifiers. The red line shows the performance of the classifier that used 70% of the laboratory data to predict the remaining 30% of data. The green line shows the ROC curve for the model that used 70% of the naturalistic data to predict the remaining 30% of data. The yellow line shows the averaged ROC curve (1000 repetitions) of the classifier trained using the domain adapted laboratory data to predict the naturalistic data. **B, C and D.** Confusion matrices for the different test subsets evaluated by the defined classifiers. These matrices illustrate the models' performance, i.e., the number of correctly (true positives and true negatives; top-left and bottom-right cells), and incorrectly (false positives and false negatives; top-right and bottom-left cells) classified trials.

Regression models for memory performance

Elicited curiosity predicts successful recognition. We first assessed whether *Curiosity*, *Electronic Liking*, the subject's musical reward sensitivity (*eBMRQ*), and his/her decision to explore the new song (*Choosing exploration*) would help us predict a successful recognition of old stimuli. VIFs ranged from 1.00 to 1.17. Thus, we proceeded to build the full model considering: *Curiosity*Electronic Liking + Curiosity*eBMRQ score + Choosing exploration + Gender*. Backward elimination led us to a final model ($\chi^2(2) = 92.14$, $p < 0.001$) including the main effects of *Curiosity* ($\chi^2(1) = 29.69$, $p < 0.001$) and *Choosing exploration* ($\chi^2(1) = 52.83$, $p < 0.001$, see **Figure 7A**), indicating that: 1) the more curiosity, the better the recognition; and 2) the longer participants listen to the song, the better they recognize it (see **Table 3** for measures of fit of the different models as well as likelihood ratio tests results used for model selection).

Elicited curiosity predicts successful recollection. In the case of recollection, we started again with the full model *Curiosity*Electronic Liking + Curiosity*eBMRQ score + Choosing exploration + Gender*. VIFs ranged from 1.01 to 1.13. Backward elimination led us, again, to a final model ($\chi^2(2) = 32.9$, $p < 0.001$) including the main effects of *Curiosity* ($\chi^2(1) = 19.34$, $p < 0.001$, see **Figure 7B**) and *Choosing exploration* ($\chi^2(1) = 10.61$, $p < 0.001$; see **Table 3** for measures of fit of the different models as well as likelihood ratio tests results used for model selection), suggesting that these factors not only enhance familiarity for the musical excerpt (i.e., recognition) but they also promote richer and more detailed memories about the music-related episode.

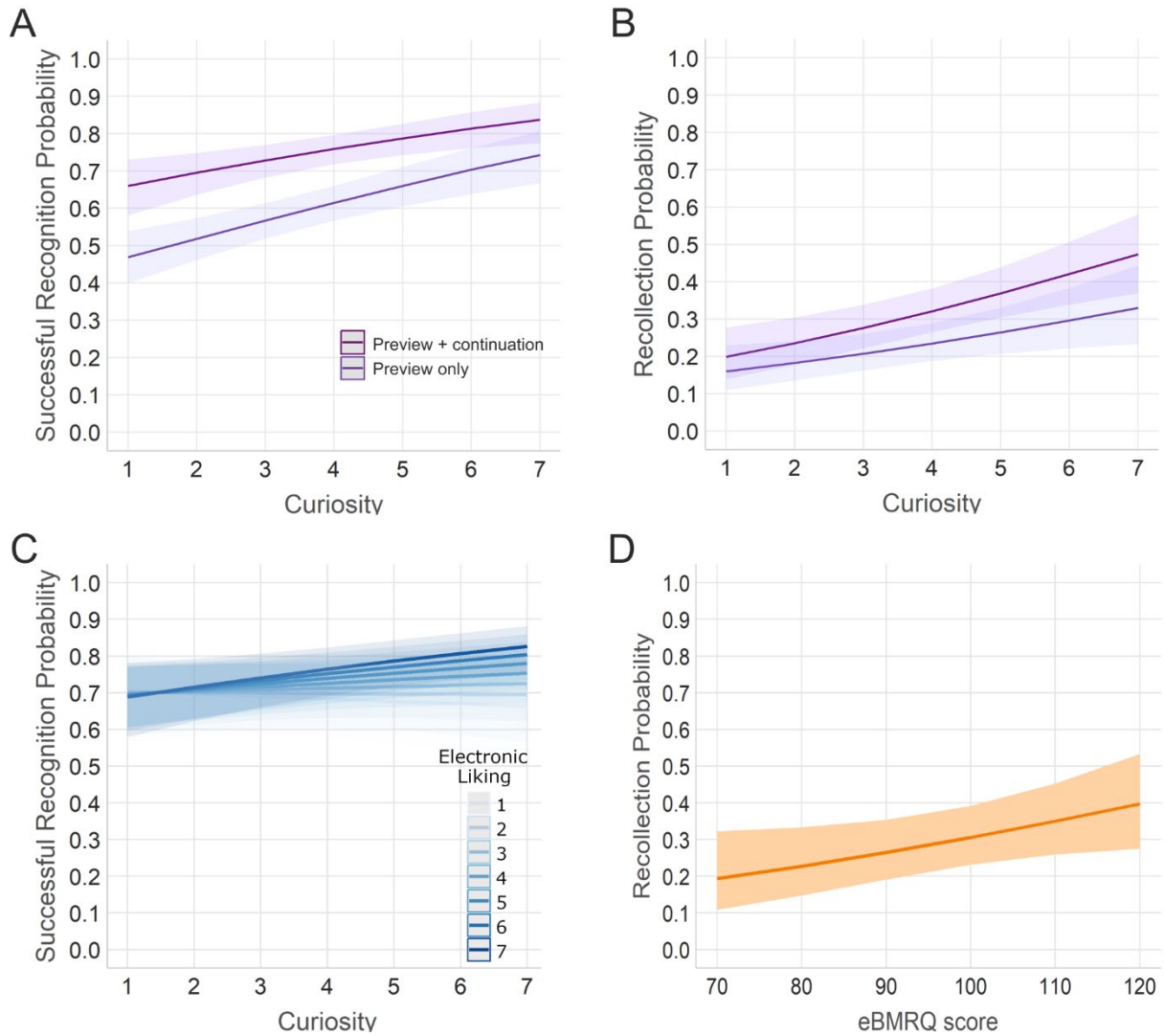


Figure 7. Exp. 1. **A.** Main effects of *Curiosity* and *Choosing exploration* on recognition. **B.** Main effects of *Curiosity* and *Choosing exploration* on recollection. *Preview only* indicates that participants chose the favorite option and, therefore, only listened to the 10-sec preview of the electronic music song. *Preview + continuation* indicated that participants chose the electronic option, thus listening to the electronic piece for a total of 50 seconds. **Exp 2. C.** Double interaction between *Curiosity* and *Electronic Liking* suggesting that when curiosity is low, memory is not affected by whether participants like electronic music or not. On the other hand, when curiosity is high, participants who like electronic music show a higher probability to recognize the song. **D.** Main effect of *eBMRQ score* on recollection, suggesting that more hedonic participants create more episodic memories than less hedonic ones.

5.3.2 Experiment 2. Natural Setting

Modeling participants' choices

Elicited curiosity determines participants' WTP. Following the same rationale as in Exp. 1, we first tested how participants' curiosity for a particular song affected their willingness to pay for it. The full and final model was: *Curiosity + Place* ($\chi^2(2) = 1,151.7$, $p < 0.001$; AIC = 2,445.7, LL = -1,217.9), with significant main effects of *Curiosity* ($\chi^2(1) = 555.4$, $p < 0.001$) and *Place* ($\chi^2(1) = 5.5$, $p =$

0.019), suggesting that the curiosity elicited by a particular song determines whether participants will be willing to invest limited resources on it or not (see **Figure 8**).

Individual differences do not modulate the effect of elicited curiosity on WTP. Subsequently, we assessed how demographic data and individual differences measures influenced the effect of curiosity on WTP. In this case, the full model was: *Curiosity*Electronic Liking + Curiosity*eBMRQ score + Place*. We tested the predictors for multicollinearity and VIFs (ranging from 1.04 to 1.11) indicated a slight correlation amongst the predictors but not so high as to compromise the model's results. Therefore, we proceeded to the backward elimination process which led to a final model including: *Curiosity + Place* ($\chi^2(2) = 988.6$, $p < 0.001$; AIC = 2,040.4, LL = -1,015.2; see **Table 4**), being Curiosity ($\chi^2(1) = 463.3$, $p < 0.001$) and Place ($\chi^2(1) = 8.3$, $p = 0.004$) the only significant main effects.

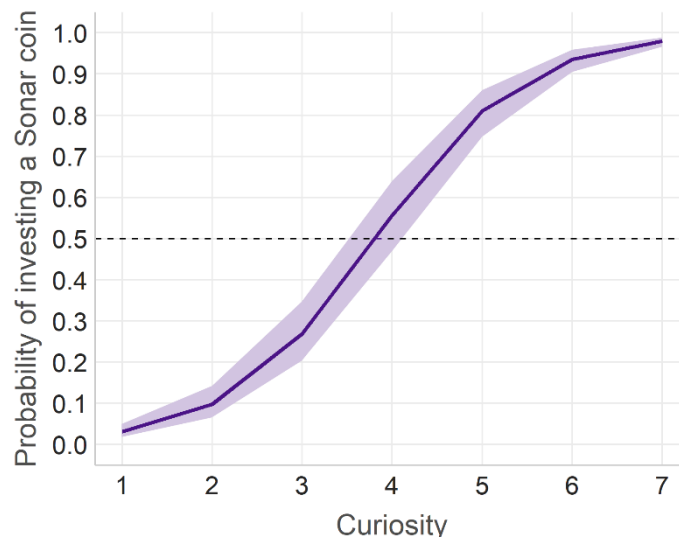


Figure 8. Main effect of Curiosity on WTP (i.e., the probability of investing a limited resource such as a Sonar coin). The higher the curiosity, the higher the WTP.

Predicting participants' choices

The elicited curiosity predicts participants' WTP. Similar to Exp. 1, a logistic regression classifier was trained using 70% of the naturalistic data, and it was used to predict the remaining 30%. In this case, the classifier only considered the elicited curiosity to predict whether the participant was willing to pay at least one Sonar coin or not. The chance level was set to 50% again, and the accuracy of the classifier was 82% (see green ROC curve in **Figure 6**), with the f1-scores being 0.85 and 0.77 for WTP and not-WTP, respectively.

Regression models for memory performance

The interaction between elicited curiosity and electronic liking predicts successful recognition.

We first assessed whether *Curiosity*, *Electronic Liking*, and the subject's musical reward sensitivity (*eBMRQ*) would help us predict a successful recognition of old stimuli. VIFs ranged from 1.03 to 1.09. Thus, we proceeded to build the full model considering: *Curiosity*Electronic Liking + Curiosity*eBMRQ score*. Backward elimination led us to a final model ($\chi^2(2) = 11.86$, $p = 0.008$) consisting of an interaction between *Curiosity* and *Electronic Liking* ($\chi^2(1) = 4.38$, $p = 0.036$, see **Figure 7C**), suggesting that people who like electronic music better recognize those songs they were curious about (see **Table 5** for measures of fit of the different models as well as likelihood ratio tests results used for model selection).

The ability to extract pleasure from music predicts successful recollection. In the case of recollection, we started again with the full model *Curiosity*Electronic Liking + Curiosity*eBMRQ score*. VIFs ranged from 1.02 to 1.10. Backward elimination led us to a final model ($\chi^2(2) = 5.45$, $p = 0.020$) including the main effect of *eBMRQ* ($\chi^2(1) = 5.60$, $p = 0.018$; see **Figure 7D**; see **Table 5** for measures of fit of the different models as well as likelihood ratio tests results used for model selection), suggesting that people with a higher sensitivity to music reward show an increased episodic memory for all songs regardless of the elicited curiosity.

Using classifiers to predict Exp. 2 (Natural Setting) results from Exp. 1 (Laboratory Setting) data

A model trained on the Laboratory Setting predicts the outcome of the Natural Setting with a high accuracy. Finally, we used the data from the Laboratory Setting to predict the results of the Natural Setting. This classifier, which was trained using a subset of the Laboratory data (see Methods), considered the curiosity rating reported in the Natural Setting to predict the WTP of the attendees to the Sonar concert (i.e., whether the participant spent a Sonar coin or not). This procedure was repeated 1,000 times to minimize the bias of the balancing method, and the averaged accuracy was $76 \pm 1.02 \times 10^{-14} \%$ (see averaged, yellow ROC curve in **Figure 6**). The accuracy of the classifier was almost the same across the different repetitions because the curiosity ratings were discrete measures (7-point Likert scale), and the PSE of the fitted logistic regression classifiers showed a low variability (averaged PSE = 4.35 ± 0.10).

Study 3

Fixed effects	df	Measures of fit				Likelihood ratio tests		
		AIC _{ci}	Δ_i AIC _c	w _i AIC _c	LL _i	χ^2	df	p
Δ MR*Cur*ElectLike + Δ MR*Cur*eBMRQ + Gender	14	1,261.0	1.62	0.14	-616.4			
Δ MR*Cur*ElectLike + Δ MR*eBMRQ + Cur*eBMRQ + Gender	13	1,260.3	0.91	0.19	-617.1	1.32	1	0.251
Δ MR*Cur*ElectLike + Δ MR*eBMRQ + Gender	12	1,259.4	0.03	0.30	-617.6	1.14	1	0.285
Δ MR*Cur*ElectLike + Δ MR*eBMRQ	11	1,259.4	0.00	0.31	-618.6	1.99	1	0.158
Δ MR*Cur + Δ MR*ElectLike + Cur*ElectLike + Δ MR*eBMRQ	10	1,262.6	3.18	0.06	-621.2	5.20	1	0.023

Table 2. *Tested structures for modelling participants' choices in Experiment 1.* All models included the Participant variable as random effect. In the formulas, ' Δ MR' = reward condition, 'Cur' = Curiosity, 'ElectLike' = Electronic Liking, 'eBMRQ' = eBMRQ score, '*' indicates an interaction, and 'df' = degrees of freedom. AIC_{ci} = corrected Akaike Information Criterion. Δ_i (AIC_c) = difference between AIC_c for model i and best model's AIC_c. w_i(AIC_c) = Akaike weight measuring the level of support in favour of model i being the most parsimonious among the candidate model set. LL_i = natural logarithm of the maximum likelihood for model i. Likelihood ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

Study 3

		Measures of fit				Likelihood ratio tests		
Fixed effects	df	AIC _{ci}	Δ _i AIC _c	w _i AIC _c	LL _i	χ^2	df	<i>p</i>
Recognition								
Cur*eBMRQ + Cur*ElectLike + Choosing Exploration + Gender	9	2,582.3	8.17	0.01	-1,282.1			
Cur*eBMRQ + Cur*ElectLike + Choosing Exploration	8	2,580.3	6.19	0.02	-1,282.1	0.03	1	0.857
Cur*eBMRQ + ElectLike + Choosing Exploration	7	2,578.6	4.54	0.05	-1,282.3	0.37	1	0.543
Cur*eBMRQ + Choosing Exploration	6	2,576.7	2.56	0.14	-1,282.3	0.03	1	0.861
Cur + eBMRQ + Choosing Exploration	5	2,575.2	1.07	0.29	-1,282.6	0.52	1	0.473
Cur + Choosing Exploration	4	2,574.1	0.00	0.49	-1,283.0	0.94	1	0.331
Choosing Exploration	3	2,602.3	28.2	0.00	-1,298.2	30.2	1	< 0.001
Recollection								
Cur*eBMRQ + Cur*ElectLike + Choosing Exploration + Gender	9	1,570.7	3.48	0.05	-776.3			
eBMRQ + Cur*ElectLike + Choosing Exploration + Gender	8	1,568.8	1.56	0.13	-776.4	0.11	1	0.736
eBMRQ + Cur*ElectLike + Choosing Exploration	7	1,568.1	0.83	0.18	-777.0	1.29	1	0.256
Cur*ElectLike + Choosing Exploration	6	1,567.8	0.55	0.21	-777.9	1.73	1	0.188
Cur + ElectLike + Choosing Exploration	5	1,568.6	1.34	0.14	-779.3	2.81	1	0.094
Cur + Choosing Exploration	4	1,567.3	0.00	0.28	-779.6	0.67	1	0.411
Cur	3	1,575.8	8.57	0.00	-784.9	10.6	1	< 0.001

Table 3. Tested structures for modelling participants' memory performance in Experiment 1. All models included the Participant variable as random effect. In the formulas, 'Cur' = Curiosity, 'ElectLike' = Electronic Liking, 'eBMRQ' = eBMRQ score, '*' indicates an interaction, and 'df' = degrees of freedom. AIC_{ci} = corrected Akaike Information Criterion. Δ_i (AIC_c) = difference between AIC_c for model i and best model's AIC_c. w_i(AIC_c) = Akaike weight measuring the level of support in favour of model i being the most parsimonious among the candidate model set. LL_i = natural logarithm of the maximum likelihood for model i. Likelihood ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

Study 3

Fixed effects	df	Measures of fit				Likelihood ratio tests		
		AIC _{ci}	Δ_i AIC _c	w _i AIC _c	LL _i	χ^2	df	p
Cur*ElectLike + Cur*eBMRQ + Place	9	2,044.7	4.83	0.03	-1,013.4			
ElectLike + Cur*eBMRQ + Place	8	2,042.7	2.83	0.09	-1,013.4	0.02	1	0.900
ElectLike + Cur + eBMRQ + Place	7	2,041.2	1.32	0.19	-1,013.6	0.50	1	0.481
Cur + eBMRQ + Place	6	2,039.9	0.00	0.37	-1,014.0	0.69	1	0.405
Cur + Place	5	2,040.4	0.43	0.30	-1,015.2	2.44	1	0.118
Cur	4	2,046.4	6.48	0.01	-1,019.2	8.06	1	0.005

Table 4. *Tested structures for modelling participants' willingness to pay in Experiment 2.* All models included the Participant and Song variables as random effect. In the formulas, 'Cur' = Curiosity, 'ElectLike' = Electronic Liking, 'eBMRQ' = eBMRQ score, '*' indicates an interaction, and 'df' = degrees of freedom. AIC_{ci} = corrected Akaike Information Criterion. Δ_i (AIC_c) = difference between AIC_c for model i and best model's AIC_c. w_i(AIC_c) = Akaike weight measuring the level of support in favour of model i being the most parsimonious among the candidate model set. LL_i = natural logarithm of the maximum likelihood for model i. Likelihood ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

Study 3

		Measures of fit				Likelihood ratio tests		
Fixed effects	df	AIC _{ci}	Δ _i AIC _c	w _i AIC _c	LL _i	χ^2	df	p
Recognition								
Cur*eBMRQ + Cur*ElectLike	8	2,203.1	3.17	0.10	-1,093.5			
eBMRQ + Cur*ElectLike	7	2,201.2	1.35	0.25	-1,093.6	0.20	1	0.656
Cur*ElecLike	6	2,199.9	0	0.49	-1,093.9	0.66	1	0.415
Cur + ElecLike	5	2,202.2	2.31	0.16	-1,096.1	4.33	1	0.038
Recollection								
Cur*eBMRQ + Cur*ElectLike	8	1,654.2	2.02	0.11	-819.0			
eBMRQ + Cur*ElectLike	7	1,653.5	1.31	0.16	-819.7	1.31	1	0.252
eBMRQ + Cur + ElectLike	6	1,653.3	1.17	0.17	-820.6	1.88	1	0.171
eBMRQ + Cur	5	1,652.2	0.00	0.31	-821.1	0.85	1	0.356
eBMRQ	4	1,652.6	0.45	0.25	-822.3	2.47	1	0.116

Table 5. *Tested structures for modelling participants' memory performance in Experiment 2.* All models included the Participant and Song variables as random effect. In the formulas, 'Cur' = Curiosity, 'ElectLike' = Electronic Liking, 'eBMRQ' = eBMRQ score, '*' indicates an interaction, and 'df' = degrees of freedom. AIC_{ci} = corrected Akaike Information Criterion. Δ_i (AIC_c) = difference between AIC_c for model i and best model's AIC_c. w_i(AIC_c) = Akaike weight measuring the level of support in favour of model i being the most parsimonious among the candidate model set. LL_i = natural logarithm of the maximum likelihood for model i. Likelihood ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

5.4 Discussion

The present study aimed at investigating curiosity and its influence on information seeking behavior and memory outcomes in laboratory and natural settings. Our results revealed that music-driven curiosity predicts individuals' willingness to pay (WTP) for exploring new music, both in controlled laboratory and real-world context. Furthermore, we developed a classifier trained on laboratory data that accurately predicted participants' WTP based on their subjective curiosity ratings in a natural setting. Interestingly, in the laboratory setting, we also observed how individual differences in familiarity with the musical genre and sensitivity to music reward modulated exploratory behavior. Finally, we showed a main effect of curiosity on long-term memory performance, extending previous findings in the laboratory to natural conditions.

In the laboratory setting (Exp. 1) we developed a new paradigm partly inspired on previous tradeoff reward-curiosity tasks (Blanchard et al., 2015; Deaner et al., 2005) and assessing the extent to which individuals are willing to sacrifice resources (expressed as willingness to pay, WTP) to access new information. This paradigm could be considered a version of the exploration-exploitation dilemma (E/E-dilemma; Daw et al., 2006; Sutton & Barto, 2014; Wilson et al., 2014), where participants had to decide whether to explore and listen to the new song or to exploit and listen to one of their favorite songs. E/E-dilemmas are usually studied using k-arm bandit tasks in which participants are faced with a series of choices between stochastic rewards. Our design included a novel aspect: a 10-second pre-exposure to music which allowed participants to prospectively estimate the potential inherent value of the new song (experienced afterwards).

Using psychometric functions and the point of subjective equality (PSE), we observed a significant effect of curiosity on the amount of money the participants were willing to pay for exploration: the higher the curiosity triggered during the pre-exposure to new, unfamiliar music, the higher the WTP for keeping listening to it. Specifically, whereas participants needed to earn €0.99 to listen to the unfamiliar music when having low curiosity (curiosity rating = 1), they were willing to pay €1.26 to listen to it when being in high curiosity states (curiosity rating = 7; see Figs. 4A and 4B). Interestingly, the impact of curiosity on WTP was valence-dependent, being stronger when considering monetary losses (i.e., negative ΔMR , as shown in Figs. 4C and 4D). In other words, when exploration incurred costs (but not earnings), participants' decisions were strongly influenced by their curiosity levels. This robust effect of both ΔMR and curiosity on WTP was further confirmed by a machine learning classifier, which achieved a 90% accuracy in predicting participants' choices using two key features: curiosity ratings and ΔMR .

This larger impact of curiosity on exploration in the loss domain is reminiscent of previous ideas on the larger psychological impact of monetary losses than gains, usually described as loss aversion phenomena (Kahneman & Tversky, 1979). Several studies have observed different physiological effects for losses compared to gains, related to enhanced autonomic response system responses (Burke et al., 2018; Hochman & Yechiam, 2011; Margittai et al., 2018; Sokol-Hessner et al., 2009; Yechiam et al., 2015) or neural responses (Canessa et al., 2013; Sokol-Hessner et al., 2013; Tom et al., 2007). In face of potential losses, humans invest more effort in exploring and foraging (Lejarraga & Hertwig, 2017) and show increased vigilance (Yechiam & Hochman, 2013a, 2013b, 2014), most possibly reflecting a coping mechanism in front of potential negative events that could be more threatening in terms of life adaptation (Krueger et al., 2017; Lejarraga et al., 2012, 2019; Yechiam et al., 2015). From this point of view, the valence-dependent effect of curiosity observed here might reflect an important mechanism that facilitates fine-tuning exploration and decision making in front of potential negative events or potential information loss. Thus, in the presence of losses, participants seem more motivated to draw on curiosity signals to decide if it might be worth to explore the new music piece, most probably based on their anticipated value to be obtained from music listening. Thus, if curiosity is high, the cost of losing money for continuing hearing the new song could be compensated by the anticipated reward expected from the new song. This might also reflect the fact that losing the opportunity of rehearing the new song impacts (information loss) largely than monetary losses, pointing also the potential characterization of curiosity as a loss-aversion phenomena (losing the possibility to get more information or in this case, the opportunity to re-experience the new song). As music exploration is aligned to extrinsic rewards in the domain of monetary gains, there is no incongruence between potential outcomes and participants choose to explore and not sacrificing money for exploiting their favorite songs. This means that when monetary gains are aligned to exploration, curiosity signals remain silent for decision making.

These findings also suggest that exploring new music of potential interest carries an intrinsic reward value that compensates for monetary sacrifices. Previous studies focusing on the role of music reward on motivation behavior found that pleasurable responses to preferred music (lasting around 45-60 sec) influenced participants' WTP via the activation of the dopaminergic reward system (Ferrerri et al., 2019; Salimpoor et al., 2013). Here, we extend this previous research showing that information-seeking behavior for unfamiliar, and even non-preferred, musical excerpts can be modulated by the curiosity experienced during the first 10 seconds of music listening. Reliable estimations of aesthetic judgements of a piece of music (i.e., liking ratings) have been obtained with very short presentations (i.e., 750 ms, with the effect becoming more reliable at 3 s (Belfi et al., 2018; see also Filipic et al., 2010). In a similar vein, visual aesthetic

studies showed that liking evaluations occur after few seconds from images exposition (Brielmann et al., 2017; Pelowski et al., 2017). Accordingly, participants might forecast future pleasures for new music drawing on their fast ability to reliably estimate aesthetic value from short exposures. In this sense, electronic music might prompt even faster evaluations (when compared, for example, to jazz; Belfi et al., 2018), probably due to its repetitive structures. Furthermore, research indicates that slower tempo excerpts and lower instrumental density yield more reliable emotional judgments, even within milliseconds (Filipic et al., 2010). Thus, subjective judgments of experienced curiosity in our study might have occurred particularly fast for the slow tempo, electronic pieces presented in our research.

The key question, however, revolves around the specific computations in which participants engage to balance exploration and exploitation within the current paradigm. According to many psychological and economic theories, decision-making is based on value maximization: individuals assess the subjective value of each option and opt for the one with the highest subjective value. Thus, subjective value might serve as a “common currency”, allowing complex and qualitatively different alternatives to be compared on a common scale (Kahneman & Tversky, 1979; Samuelson, 1937). In our study, participants likely integrated the two dimensions of each option, (i) the potential reward associated to music listening (i.e., the anticipated reward derived from listening to a new excerpt or from exploiting a well-known favorite song) and (ii) the potential amount of monetary reward, and compared the subjective value of these two options in order to make the actual choice. Interestingly, the initial judgement over the new song could be conceived as anticipatory subjective value, creating savoring effects that might influence the desire to prolong exposure to the new music. Accordingly, it has been observed that subjective value could be obtained from savoring advanced information on a future potentially rewarding event (Iigaya et al., 2016; Loewenstein, 1987; Zhu et al., 2017). In this sense, the curiosity modulating participants’ subjective value in our study could be conceived as an internal cognitive-affective conscious signature that provides information about the potential positive outcome if exploration is pursued (Golman & Loewenstein, 2018).

At a neural level, this might rely on dopaminergic signaling. Interestingly, exploration and information seeking have been associated to increased levels of tonic dopamine, indirectly affecting the regulation of effort and energy expenditure (Addicott et al., 2017; Beeler et al., 2012; Salamone et al., 2006). In this line, methamphetamine-dependent individuals, with chronic attenuation of dopamine functioning, showed reduced exploration resulting in impaired learning and updating of knowledge (Harlé et al., 2015) (see also similar results for participants with alcohol use disorder, Morris et al., 2016). Reduced exploration has also been associated to psychiatric disorders such as schizophrenia, anxiety, and depression (Blanco et al., 2013;

Browning et al., 2015; Strauss et al., 2011). The hypodopaminergic states that characterize these disorders might result in increased anhedonia and decreased sensitivity to potential rewards, favoring energy conservation and exploitation (Volkow et al., 2010). Accordingly, several studies have linked curiosity states to activity in the dopaminergic mesolimbic reward circuitry (Eschmann, Pereira, et al., 2023; Gruber et al., 2014; Gruber & Ranganath, 2019; Lau et al., 2020; Oosterwijk et al., 2020). Notably, dopaminergic reward circuitry also plays a main role in regulating musical pleasure (Ferreri et al., 2019; Salimpoor et al., 2011, 2013), with high musical hedonics showing higher mesolimbic activity than low hedonic individuals (Martínez-Molina et al., 2016). Taking all this evidence together, we could hypothesize that, in the present study, the early evaluation of a potential reward after listening to the first 10 s of a music piece might be upregulated through dopaminergic signaling thus affecting the anticipated utility of the explorative option. Accordingly, our results showed that curiosity specifically affected exploration behavior in high musical hedonics, allowing them to be more selective in their decisions. Indeed, this group opted to exploit rather than explore when curiosity was low, potentially sacrificing a larger monetary reward. This effect might be explained by an increased capacity in this group to decode pleasure from music, allowing them to be more selective in their decisions of exploration or exploitation.

In a similar vein, we found that the impact of curiosity on participants' choice was further modulated by individual differences in music preference. Participants with a higher preference for electronic music exhibited a stronger effect of curiosity on exploration behavior. For example, for small monetary gain ($\Delta MR = 1$), those who appreciate electronic music may opt to not to explore when they lack curiosity. Conversely, those without strong interest in the genre tend to explore even when curiosity is lacking. This supports the crucial role of a priori information in determining curiosity (Bonawitz et al., 2012; Wade & Kidd, 2019): while individuals who appreciate electronic music may have prior knowledge of the genre, enabling them to prospectively evaluate the anticipated reward of a new piece, those lacking such familiarity remain uncertain following brief exposure. Consequently, individuals with a strong prior knowledge of electronic music tend to be highly selective and choose to explore only when curiosity or potential monetary gain are high.

In our second experiment (Exp. 2), participants rated their curiosity after listening to unfamiliar musical excerpts during a live dj-set, and successively reported their WTP for obtaining the excerpt or related information. In line with Exp. 1, results in the natural setting showed that the higher the curiosity for a particular song, the higher the participants' WTP for obtaining new information about it. Again, this robust effect was further supported by a machine learning classifier, which utilized the curiosity ratings to predict WTP, achieving an accuracy rate of 82%.

Although over the last years several studies reported the effect of curiosity on information-seeking and encoding processes (Gruber et al., 2014; Ripollés et al., 2016), these effects have never been reported in natural occurring circumstances. Recently, the debate about the importance of real-life ecological settings has strongly increased in psychology and neuroscience research. This becomes particularly relevant when considering the complexity of the musical experience (Sloboda & O'Neill, 2001; Tervaniemi, 2023), which is strongly influenced by the context in which the musical listening takes place (Czepiel et al., 2023), with concerts offering a perfect setting for monitoring an all-embracing affective experience (Chabin et al., 2022; Waldfuhrmann et al., 2021). To the best of our knowledge, this is the first study showing how music-driven curiosity responses influence exploration behavior and memory outcomes in natural, real-life settings.

Differently from Exp. 1, in Exp. 2 individual differences in electronic liking and sensitivity to music reward did not significantly modulate the curiosity-driven effect on participants' choices. Note that, in Exp. 1, participants rated their curiosity and took the exploration/exploitation choice after the pre-exposure phase. Thus, it is likely that participants' subjective ratings and exploration behavior were strongly influenced by their prior knowledge and general relationship with music (e.g., musical hedonia). In contrast, in Exp. 2, participants rated the music after listening to the whole excerpt played by the DJ, thus providing a retrospective judgement. In this case, the exposure to the specific excerpts and their evolution over time might have played a main role in influencing participants' a-posteriori choice, thus reducing the impact of subjective prior knowledge and predictions (see also Omigie & Ricci, 2022).

Crucially, despite the differences between the two experiments, it was possible to train a classifier using laboratory data (Exp. 1) to predict, with an accuracy of 76%, the participants' behavior in the natural setting (Exp. 2) – specifically, whether they spent a Sonar coin or not. Importantly, this classifier considered the subjective curiosity ratings in the natural setting to inform its predictions. This relevant finding not only indicates the comparability between the two experiments of this study, both converging in the same direction, but also strengthens the potential for laboratory observations to predict human behaviors in real-world (natural) settings (Levitt & List, 2007).

A final important finding of the present study concerns the influence of curiosity state on memory outcomes. In the realm of curiosity research, previous studies showed that high curiosity states promote the encoding of information people are curious about, as well of associated incidental material (Gruber et al., 2014). Over the last years, research on music reward highlighted that the pleasure elicited through music is modulated by midbrain dopaminergic signalling (Ferreri et al.,

2019; Martínez-Molina et al., 2016; Salimpoor et al., 2011), and linked to improved memory performance for the music itself and non-musical associated information (Cardona et al., 2020; Ferreri, Mas-Herrero, et al., 2021; Ferreri & Rodriguez-Fornells, 2017; Ferreri & Rodriguez-Fornells, 2022). However, the dopaminergic-mediated effect of music reward on memory outcomes has been mainly investigated through the manipulation of musical pleasure, while the role of music curiosity on motivated learning remained almost unexplored. Here, we consistently observed in both laboratory and natural settings that the curiosity felt during music listening promoted the encoding of the information, in turn improving the recognition and recollection of the excerpts 24 hours later. The ignited curiosity during music listening might therefore promote attention, exploration and information seeking mechanisms likely to enhance the consolidation of the musical information through dopaminergic neuromodulation in the hippocampus (Gruber & Ranganath, 2019; J. Lisman et al., 2011). Further research investigating reward system and/or dopaminergic activity during music-driven curiosity states would be needed to confirm this hypothesis. Nevertheless, the observed modulation of both information-seeking and encoding processes by music curiosity states support curiosity as an efficient endogenous reward likely to strongly modulate human cognitive processes.

Overall, the present study shed new light on how music-induced curiosity influences exploration behavior and willingness to pay and proposed a new paradigm to determine the subjective value humans assign to a particular stimulus. Furthermore, it showed that results obtained in the laboratory setting mimicked those collected in a natural, more complex setting. Finally, it provided further evidence regarding the effect of curiosity on long-term memory, thus reinforcing the idea that it is crucial to ignite curiosity in educational settings to boost memory and learning performance even in complex, real-life environments.

Study 4

**Unveiling the temporal dynamics and
interplay of curiosity and pleasure:
evidence from a live orchestra
listening experience**

6 Study 4

Unveiling the temporal dynamics and interplay of curiosity and pleasure: evidence from a live orchestra listening experience

6.1 Introduction

Curiosity is a fundamental motivator of human behavior, driving individuals to seek new experiences and information (Berlyne, 1966; Litman et al., 2005), thereby promoting learning and memory processes (Gruber et al., 2014; Kang et al., 2009). This intrinsic drive for knowledge (Gottlieb et al., 2013; Sharot & Sunstein, 2020), considered as the noblest of human drives, plays a critical role in cognitive development, decision-making processes, and well-being. However and despite its pervasiveness, several key questions about its underlying mechanisms, purposes, and basis remain unanswered (Kidd & Hayden, 2015).

Historically, curiosity has been viewed as a transient and easily satisfied behavior (Loewenstein, 1994), often described as an anticipatory state of reward or pleasure related to closing potential knowledge gaps (Marvin & Shohamy, 2016). While pivotal, this line of research examines curiosity as a short-term phenomenon, focusing on immediate satisfaction after information gain, such as resolving ambiguous images or providing the answer to trivia questions (Gruber et al., 2014; Jepma et al., 2012). Thus, this research approach overlooks more complex forms of curiosity as well as its temporal dynamics, leaving the intriguing relationship between curiosity and pleasure largely unexplored.

Consider, for example, the scenario of entering a music store to find a new song by a specific artist. Driven by specific curiosity, this continuous and effortful exploration can lead to pleasurable emotional states upon finding and enjoying the song. Over time, the intensity of curiosity presumably diminishes as it is satisfied, and the desire to continue exploring wanes. In this case, the evolution of pleasure relies on curiosity satisfaction during information-seeking activities, where initial curiosity is transformed into pleasure, accompanied by a rapid decay of curiosity (Gruber et al., 2014; Jepma et al., 2012; Kang et al., 2009; Kobayashi et al., 2019; Loewenstein, 1994; Van Lieshout et al., 2018). Nevertheless, we could conceive the opposite scenario: partial internal models, such as prior knowledge of the artist or familiarity with previous artist's songs, might modulate curiosity by allowing predictions and anticipation of potential rewards (Loewenstein, 1994). In this scenario, curiosity is ignited by previously experienced rewards,

suggesting a different pattern where initial pleasure evolves into a curiosity drive. Furthermore and crucially, curiosity may persist longer, continuing exploration even after finding a particular song. This perspective considers curiosity fluctuations to be more stable and resistant to satiation, based on the idea that curiosity acts as an internal metacognitive representation that sets information-seeking goals and prompts self-monitoring of learning satisfaction (Kaplan & Oudeyer, 2007). Indeed, the *learning progress* hypothesis also posits that learning elicits an internal reward signal that reinforces curiosity, allowing to sustain in time information-seeking activities (Gottlieb & Oudeyer, 2018; Oudeyer et al., 2007; Schmidhuber, 1991).

The musical example is particularly apt, as music provides an ideal framework for exploring the dynamic interplay between curiosity and pleasure (Mencke et al., 2022; Schubert, 2010). Musical compositions unfold gradually, altering listeners' expectations through changes in rhythm, melody, or harmony, continuously shaping their emotional experiences (Belfi et al., 2018). In this context, curiosity arises from the desire to explore something new or unfamiliar (Gottlieb et al., 2013), manifesting as interest in exploring melodies or genres (Omigie & Ricci, 2022). Similarly, musical pleasure often stems from fulfilling expectations triggered by musical structure (Gold, Pearce, et al., 2019; Zatorre, 2024). High states of both music pleasure and curiosity drive motivational behaviors (Cardona et al., under review; Salimpoor et al., 2013) and activate the dopaminergic reward system, although with individual differences in sensitivity to music reward (the so-called *musical hedonia*; Martínez-Molina et al., 2016, 2019; Mas-Herrero et al., 2013). Via the activation of the reward system, both pleasure and curiosity have been shown to promote learning and memory processes (Cardona et al., 2020, under review; Ferreri & Rodriguez-Fornells, 2017, 2022; Gruber & Ranganath, 2019; see also Gruber et al., 2014; Kang et al., 2009; Lisman et al., 2011). Nevertheless, curiosity and pleasure may operate on different psychological mechanisms, each playing unique roles in the musical experience. Investigating their temporal interplay during music listening is crucial for understanding their impact on musical engagement, and more generally, on human exploratory behavior.

Recently, research into music affective processes has increasingly moved beyond controlled laboratory settings, embracing more naturalistic and ecologically valid approaches (Tervaniemi, 2023). This shift is evidenced by studies investigating affective responses (McAdams et al., 2004), physiological responses (Czepiel et al., 2023), body movements (Cameron et al., 2022), and interpersonal neural synchronization in audiences (Chabin et al., 2022) during live concerts. Such approaches provide a unique perspective on music's affective experience by capturing its emotional impact in the complex, social context of live performances, which traditional lab settings often fail to replicate.

Based on this evidence, the present study aimed to investigate the temporal dynamics and potential interdependence of curiosity and pleasure within the context of a large music event. We organized a conference-concert featuring the Milan Symphonic Orchestra at the Auditorium di Milano Fondazione Cariplo in Milan, Italy. This event, part of the *Musica e Scienza (Music and Science)* series—a project promoting dialogue between music and science while bridging the gap between research and society—engaged 660 volunteers. Participants used their smartphones to connect to an online testing platform and were randomly divided into curiosity or pleasure groups. They continuously reported their feelings of curiosity or pleasure while listening to a 10-minute minimalist, highly unfamiliar piece, *Fratres* by Arvo Pärt, performed live by the Orchestra. Following the performance, an information-learning phase provided insights into the piece's structure, composition, and the neuroscience of music. Participants then listened to the piece a second time, rating their curiosity or pleasure again. The day after the event, we measured – among other traits– participants' sensitivity to music reward (i.e., musical hedonia) through the extended version of the Barcelona Music Reward Questionnaire (eBMRQ; Cardona et al., 2022; Mas-Herrero et al., 2013). To further explore potential influence of pleasure and curiosity on memory and formation, participants were also asked to take surprise memory tests for both learned information and music (recognition/recollection paradigm; Yonelinas, 2002).

6.2 Material and methods

Participants

Participation in the experiment was strictly voluntary, and participants provided their informed consent before accessing the experimental online platform. The study has been approved by the local Ethical Committee (Department of Brain and Behavioral Sciences, University of Pavia). The study was anonymous and followed the Helsinki Declaration, Convention of the Council of Europe on Human Rights and Biomedicine.

During the event, 682 persons among those present in the audience logged into the task in order to take part to the experiment. Based on the information gathered the following day, underage participants ($N = 10$) and potential amusics ($N = 12$) were removed from all the analyses. This led to include in the analyses 660 logged-in participants (see **Figure 1**). One hundred twenty-two participants were not able to reach the experimental task, likely because of connectivity or technical issues. 117 individuals were further discarded from the analyses due to disengagement from the task (i.e., they provided less than 10 continuous Pleasure/Curiosity ratings during the 10-minutes continuous rating). Thus, we ended up with 421 participants providing valid data in

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the first continuous rating task (i.e. Play 1); 211 from the Curiosity group (age = 44.6 ± 15.2 , liking for classical music = 5.48 ± 1.24 , familiarity with *Fratres* = 1.64 ± 1.39 , curiosity for music-related information = 6.14 ± 1.03 , curiosity for neuroscience-related information = 6.59 ± 0.80 ; 129 women, 80 men, 2 other; 108 non-musicians, 90 amateur, and 13 professional musicians) and 210 from the Pleasure group (age = 45.6 ± 14.4 , liking for classical music = 5.64 ± 1.31 , familiarity with *Fratres* = 1.79 ± 1.55 , curiosity for music-related information = 6.21 ± 1.07 , curiosity for neuroscience-related information = 6.60 ± 0.78 ; 122 women, 84 men, 4 other; 111 non-musicians, 79 amateur, and 20 professional musicians). These two groups showed no significant differences in any of the reported demographic variables. From the 211 and 210 participants in the curiosity and pleasure groups, 135 and 151, respectively, actively engaged in the second continuous rating (i.e. Play 2). The next day (i.e., Day 2), 358 people participated in the follow-up task (Curiosity group: N = 180, eBMRQ score = 93.7 ± 13.4 , diversivePCS = 16.9 ± 2.52 , diversiveECS = 17.4 ± 2.31 , flowCEI = 11.2 ± 2.33 ; Pleasure group: N = 178, eBMRQ score = 91.1 ± 14.0 , diversivePCS = 16.9 ± 2.54 , diversiveECS = 17.3 ± 2.42 , flowCEI = 10.9 ± 2.47 ; no significant differences between the two groups in any of the questionnaires). From those participants, the ones who reported high familiarity with the piece before the event started (i.e., values higher than 4 in a Likert-scale from 1 = “I have never heard it before”, to 7 = “I know the piece very well”) were excluded from subsequent analyses. Therefore, for the memory analyses we ended up with a sample of 362 participants (161 for each group).

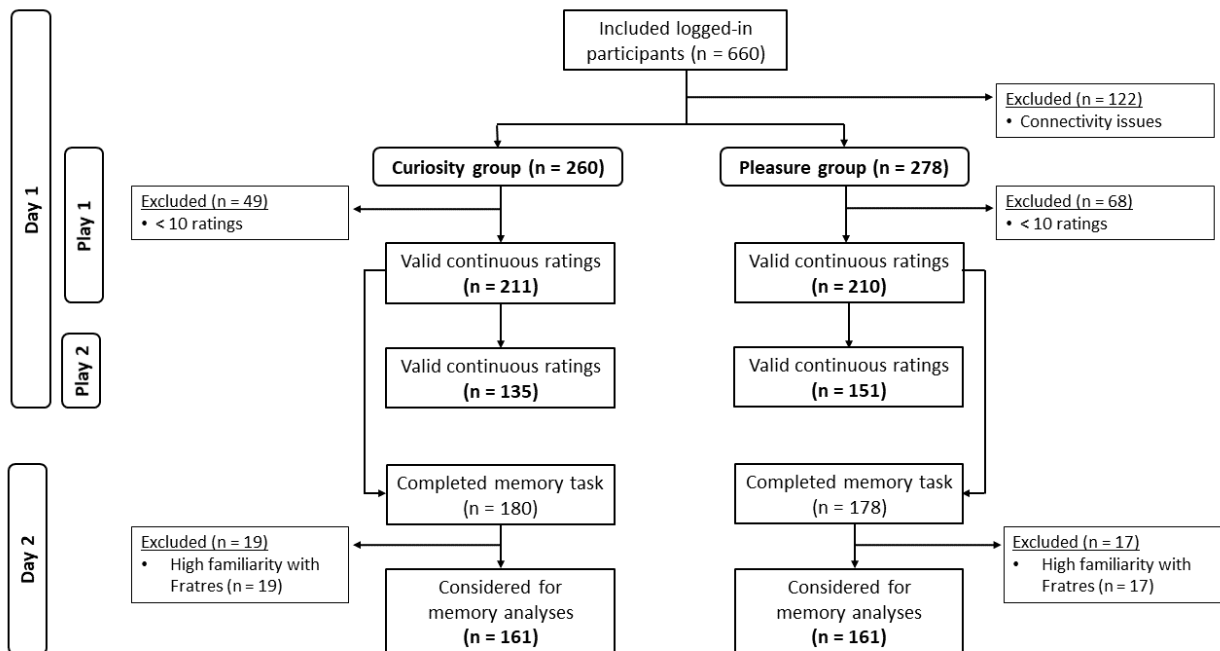


Figure 1. Number of individuals that participated in each phase of the experiment.

Experimental design

Stimuli

In 1977, Arvo Pärt composed *Fratres*, a ten-minute, three-part composition including two melodic lines moving stepwise and the central *tintinnabuli* voice moving on the notes of minor triad. There exist some variations of this piece including a solo instrument. For the event, we selected a version for orchestral strings including a violin solo. This piece constitutes one of the first examples of *tintinnabuli* (from Latin *tintinnabulum* meaning “little bell”) music, a style Arvo Pärt created after studying early polyphony and Gregorian chant for many years. Structurally, *Fratres* consists of a set of nine movements separated by a recurring percussion motif. Throughout the composition, the listener can hear a recurrent theme that starts each time in a different octave.

The selection of *Fratres* was done by the orchestra’s conductor, Ruben Jais, and one of the authors, LF, following some criteria such as: (1) low familiarity, even among regular attendees to classical music events; (2) the presence of novel, salient, surprising, and emotional elements to ensure curiosity and pleasure elicitation; and (3) the possibility to easily explain these elements from a music theory perspective, and to link them with the neuroscience of music concepts presented during the event.

Tasks and Procedure

The experiment was conducted in two consecutive days (see **Figure 2**). The first day (on January 14, 2023), participants attended an event entitled *Esperimenti Neurosinfonici (Neurosymphonic Experiments)* at Auditorium di Milano Fondazione Cariplo, which was part of the programme *Musica e Scienza (Music and Science)* a scientific dissemination project aiming to bridge science and society by creating a dialogue between music and science. This dialogue was hosted by Ruben Jais, the conductor of the Orchestra, and LF, neuroscientist among the authors of the present study. A large screen placed on the scenario, behind the orchestra, and clearly visible from all seats, was used as a visual support for experiment- and neuroscience-related explanations.

Attendees purchased tickets to the event, knowing it would be an experience where great symphonic music would coexist with explanations of cognitive neuroscience. They were informed that if they wished they could actively participate in a unique experiment, allowing them to uncover the secrets of the musical brain.

The day of the event, attendees gathered at the entrance of the Auditorium. When the doors opened, and while their tickets were being scanned, participants randomly received a card

containing a QR code together with a unique, four-number participant ID that allowed them to access the task through their smartphones.

The event started by welcoming the audience providing them instructions about how to enter in the online experimental platform through the scanning of the QR code and the insertion of their personal ID code. After receiving detailed instructions of the event, volunteers gave informant consent and acceded to the experiment. In the first screen of the experimental platform, participants had to provide some demographic information including age, gender, level of education, musical expertise (non-musician, amateur, or professional musician), liking for classical music (Likert scale from 1 = “I don’t like it at all”, to 7 = “I love it”), familiarity with *Fratres* (from 1 = “I have never heard it before”, to 7 = “I know the piece very well”), curiosity for music-related information (from 1 = “no curiosity at all”, to 7 = “a lot of curiosity”), and curiosity for neuroscience-related information (from 1 = “no curiosity at all”, to 7 = “a lot of curiosity”) (see *Participants* section for detailed scores in the two experimental groups).

Next, a horizontal sliding bar ranging from 0 to 100 appeared on participants' smartphone screens. Approximately half of the sample (participants with even IDs for the Curiosity group) was directed to a version of the experiment where they continuously reported their level of curiosity about the unfolding music using the slider. They were instructed that 0 meant “I feel no curiosity at all; if the musicians stopped playing, I wouldn’t mind,” while 100 meant “I feel very curious; I really want to know what happens next and am willing to invest time and energy to find out.” The other half of the sample (participants with odd IDs for the Pleasure group) used the same slider but rated their pleasure instead. For this group, 0 indicated “I am not experiencing any pleasure,” and 100 indicated “I am feeling intense pleasure, including chills or goosebumps.” Participants were given a few seconds to familiarize themselves with the slider by moving it left and right before starting the experiments. Participants were also reminded that continuous ratings were crucial to the experiment. While it might be challenging to explicitly monitor their feelings during the music, it was important to report even slight changes throughout the entire performance. The orchestra then began playing *Fratres*, and all participants listened while providing their ratings (Play 1). Continuous ratings were recorded at a rate of 1 Hz.

After the performance, participants were asked to put away their smartphones and enjoy a dialogue between the orchestra director and LF. This segment, designed as a public dissemination conference, included discussions on both music theory and the neuroscience of music. The music theory content covered Arvo Pärt’s compositional style, the structure of *Fratres*, and how the composer’s choices created expectations and surprises throughout the piece. The neuroscience

content addressed the brain mechanisms underlying pleasure and curiosity, including the activation of the dopaminergic reward system, and explored how these relate to musical structure based on key neuroscientific studies. The content was presented in an accessible manner to engage a non-expert audience with clear and straightforward information.

Following the conference segment, *Fratres* was performed again (Play 2), and participants were asked to rate their levels of curiosity or pleasure once more (i.e., the Pleasure group rated their pleasure, while the Curiosity group rated their curiosity for the second time)

To conclude the dissemination segment, LF presented preliminary results computed backstage during the dialogue. These results included demographic information about the audience (such as gender, musical expertise, enjoyment of classical music, and familiarity with *Fratres*) and the mean ratings of curiosity and pleasure for Play 1 and Play 2. Additionally, to encourage participation in the second part of the experiment, participants were told that they would have the opportunity to view further results if they completed the next part of the experiment at home the following day. The whole event lasted about an hour and a half.

The following day (i.e., around 16 hours after the event), participants received a link at the email address they provided during the event to complete the second part of the experiment. Participants were instructed to access the task on their smartphones and recommended using headphones for an enhanced listening experience with the provided excerpts. This task consisted of three parts. First, participants were asked to complete several questionnaires including the extended Barcelona Music Reward Questionnaire (eBMRQ, Cardona et al., 2022), the Diverive subscale from the Perceptual Curiosity Scale (Collins et al., 2004), the Diverive subscale from the Epistemic Curiosity Scale (Litman & Spielberger, 2003), the Absorption subscale from the Curiosity and Exploration Inventory (Kashdan et al., 2004), and two items to screen for amusia (i.e., 'I can barely perceive when someone is singing out-of-tune', and 'I'm usually unable to recognize a very familiar melody without the help of the lyrics'; we used the mean of the two items).

Second, participants completed a multiple-choice test about the information provided the day before. This test included five music-related questions, five neuroscience questions, and two attentional checks. The presentation order of the questions as well as the order of the four response options was the same for all participants due to software limitations.

The third part of the task was a music memory test, involving both recognition and recollection (Yonelinas, 2002; see also Cardona et al., 2020; Ferreri, Mas-Herrero, et al., 2021; Ferreri &

Rodriguez-Fornells, 2022). Participants listened to fifteen 10-second excerpts from *Fratres* (old stimuli) and fifteen 10-second excerpts from four other classical pieces (new stimuli). The new stimuli were selected from *Cantus*, *Festina*, *Ludus*, and *Silentium*, chosen for their stylistic resemblance to *Fratres*. The order of the excerpts was randomized for each participant. After each excerpt, participants indicated whether they had heard it the day before (old/new recognition). If they recognized the excerpt, they then chose one of three options for the recollection task: Remember (R), Know (K), or Guess (G). "Remember" (R) indicated they could recollect specific details about the episode, "Know" (K) meant they were confident they had heard it but had no specific memory, and "Guess" (G) signified they were unsure whether the excerpt had been heard previously.

Upon completing both information and music memory tests, the participant's performance in each of the tests was shown and further results from the data collected the day before were presented. Two different figures, together with their captions, were shown: 1) the mean rating of both curiosity and pleasure in the two plays of *Fratres*; and 2) the temporal evolution of curiosity and pleasure during Play 1. Finally, participants had the opportunity (optionally) leave a comment assessing their overall experience. The whole experimental phase of day 2 lasted around 30 minutes. The completion of this second phase was awarded by two free tickets for future concerts of the Symphonic Orchestra of Milano.

Gorilla Experiment Builder (<http://www.gorilla.sc>) was used to create and host our experiment (Anwyl-Irvine et al., 2020).

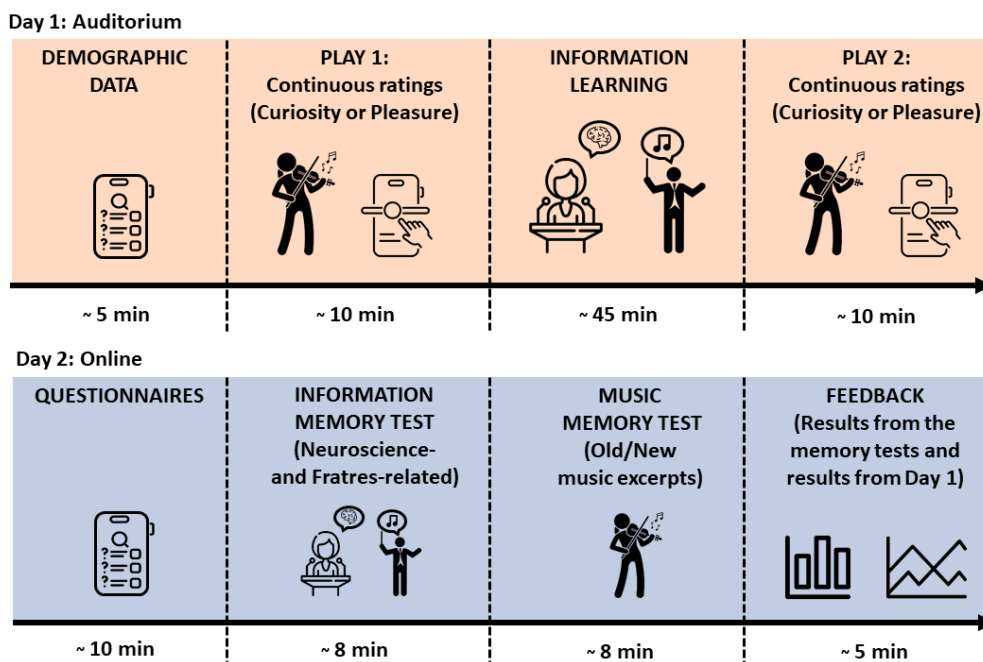


Figure 2. Experimental design.**Data Analysis**

As detailed in the previous section, each participant, depending on their assigned group, continuously rated either curiosity or pleasure during two performances: one during the first play, and another during the second play; the same rating was used for each individual across the two performances. To identify the time windows where curiosity was significantly higher or lower than pleasure during a particular play, or where curiosity (or pleasure) during the first play was significantly higher (or lower) than during the second play, we employed a cluster-based permutation test (Maris & Oostenveld, 2007). All these tests for time series data were performed using 1,000 permutations, and a two-sided test with an $\alpha < 0.05$, using the *permutest* package.

Subsequently, we evaluated whether there was a causality between curiosity and pleasure ratings in both, Play 1 and Play 2. Consistently with earlier research (Dean & Bailes, 2016; Omigie & Ricci, 2022), the first and last ten ratings were discarded to ensure that participants had settled into the task, and the continuous ratings were averaged across participants. To test the causality of curiosity over pleasure, we employed the Granger causality test on this grand-average time-series. This test is based on the principle that if a time series X (here, curiosity) Granger-causes (G-causes) a time series Y (here, pleasure), then past values of X should contain information that helps to predict Y (unrestricted model) beyond the information contained in past values of Y alone (restricted model; Granger, 1969). The test assumes that the time series data are stationary (i.e., with consistent mean and variance) and, if not, a detrending procedure is required. Stationarity was assessed by means of the Augmented Dickey-Fuller test. All curiosity and pleasure time-series were non-stationary in the present study (Dickey-Fullers > -3.19 ; $ps > 0.0894$) and were detrended using a differentiation process of order one, i.e., subtracting the previous observation from the current one ($Curiosity_t = Curiosity_t - Curiosity_{t-1}$). The resulting detrended time-series (Dickey-Fullers < -5.78 ; $ps < 0.01$) were used for the Granger causality test. We tested lag values ranging from -6 to 6 s, with positive values evaluating whether curiosity G-causes pleasure, and negative values evaluating whether pleasure G-causes curiosity. Lag selection was based on the Akaike Information Criterion (AIC) and the Likelihood Ratio Test (LRT), and the lags which best predicted the data were selected (Enders, 2004). We then assessed whether the inclusion of lagged values of X significantly improved the prediction of Y by comparing the restricted (i.e., the model which only considers past values of Y alone) and unrestricted models (i.e., the model which also considers past values of X) using the LRT. If the p-value of the LRT was below the chosen significance level ($\alpha < 0.05$), we rejected the null hypothesis, indicating that X G-causes Y.

Then, we investigated how individual differences in music reward affected curiosity and pleasure ratings. First, we focused on Play 1 and assessed the correlation between eBMRQ scores and the mean curiosity or mean pleasure ratings reported by each participant during the whole piece. The correlation was also performed with the mean ratings of each movement. Subsequently, and in order to see how musical hedonia affected ratings in the continuum, we selected the 50 most and the 50 least hedonic participants (according to their eBMRQ score) from each group (i.e., Curiosity and Pleasure groups), and performed both a linear regression model considering the eBMRQ classification (lowly vs highly hedonic) as a fixed factor and a cluster permutation analyses within each group (Maris & Oostenveld, 2007). In addition, a difference waveform (i.e., highly hedonic – lowly hedonic ratings) was calculated for both curiosity and pleasure to visualize how musical hedonia differently affected the two constructs. Finally, cluster permutation analyses were used in order to compare how the change in curiosity and pleasure from Play 1 to Play 2 varied depending on musical hedonia (i.e., highly and lowly hedonics).

Regarding the memory analyses, we first assessed memory performance for the information provided during the event. Linear models were used to determine how demographic data [i.e., age, liking for classical music (classicalLiking), familiarity with Frates (fratesFamiliarity), curiosity for music-related information (curiosityForMusic), and curiosity for neuroscience-related information (curiosityForNeuroscience)]; and questionnaires scores [i.e., the extended Barcelona Music Reward Questionnaire (eBMRQ), the Diverse subscale from the Perceptual Curiosity Scale (diversivePCS), the Diverse subscale from the Epistemic Curiosity Scale (diversiveECS), and the Absorption subscale from the Curiosity and Exploration Inventory (flowCEI)] modulated Frates- or neuroscience-related information. Specifically, the full models were specified as follows: a) Frates-related information $\sim$ age + classicalLiking + fratesFamiliarity + curiosityForMusic + eBMRQ + diversivePCS + diversiveECS + flowCEI, and b) Neuroscience-related information $\sim$ age + curiosityForNeuroscience + eBMRQ + diversivePCS + diversiveECS + flowCEI. The backward elimination method was used to select the final model. Subsequently, we analysed data from the two groups (i.e., Curiosity or Pleasure) separately. For each group, we assessed, by using a linear model, whether the mean of the ratings provided during Play 1 (either curiosity or pleasure depending on the group) could predict memory performance for Frates- and neuroscience-related information.

Then, memory for music was assessed. To that aim, dprime scores were calculated to quantify participants' ability to discriminate between old and new excerpts. Then, a linear model was used to determine the effect of demographic data and questionnaires scores on dprime. Thus, the full model was: $Dprime \sim age + classicalLiking + eBMRQ + diversivePCS + diversiveECS + flowCEI$. The

final model was selected by using the backward elimination method. Next, for each group (i.e., Curiosity and Pleasure groups), we assessed whether the mean ratings provided during Play 1 predicted dprime scores. Finally, and keeping the two groups apart, we tested, for each of the fifteen 10-second old items, whether the curiosity/pleasure reported for those seconds during Play 1 predicted memory performance. To that aim, we used logistic regression mixed models to predict both recognition and recollection responses. In the case of recognition, the response variable was defined as whether the old stimuli were correctly recognized or not. Random intercepts for excerpt and subject were included. Thus, the full model was: Recognized (Yes/No) $\sim$ Curiosity/Pleasure (mean of the 10s) + (1|Item) + (1|Participant). In the case of recollection, correctly recognized items (hits) were reorganized into two categories ('Remembered', including 'R' responses, and 'Not remembered', including 'K', 'G') and the fixed and random effects structure was the same as for recognition.

The analysis procedure, as well as the visualization of the results, were done using custom-made routines in R.

6.3 Results

Our first aim was to assess the evolution of curiosity and pleasure over time. The chosen piece, *Fratres* by Arvo Pärt, consisted of a ten-minute *tintinnabuli* composition structured in nine movements, which were clearly identifiable in the power spectrum of the piece recorded during the concert (see **Figure 3B**). Interestingly, we qualitatively observed that, in both plays, the continuous ratings provided by the participants were associated to the different movements.

During Play 1, i.e., when the piece was highly unfamiliar for the audience (mean familiarity provided before listening to the excerpt = 1.64 ± 1.39 and 1.79 ± 1.55 for the curiosity and pleasure group, respectively, in a 1-7 Likert scale), curiosity ratings were higher than pleasure ratings. Specifically, cluster permutation analyses showed that these differences were statistically significant during the initial period, from the onset of the performance to 243 s (cluster-level t -mass = 20,173.15; p cluster mass = 0.0010; see **Figure 3A**). On the other hand, during Play 2, and after providing profuse information about *Fratres* and neuroscience of music, the observed pattern of curiosity and pleasure changed: curiosity was still significantly higher than pleasure at the beginning of the performance ($0 \leq t \leq 97$ s, cluster-level t mass = 2,068; p cluster mass = 0.0010), but, from second 161 onwards, the pattern changed and pleasure was found to be significantly higher than curiosity in several time periods (cluster-levels t mass > 414; p s cluster t mass < 0.0130; see **Figure 3C**).

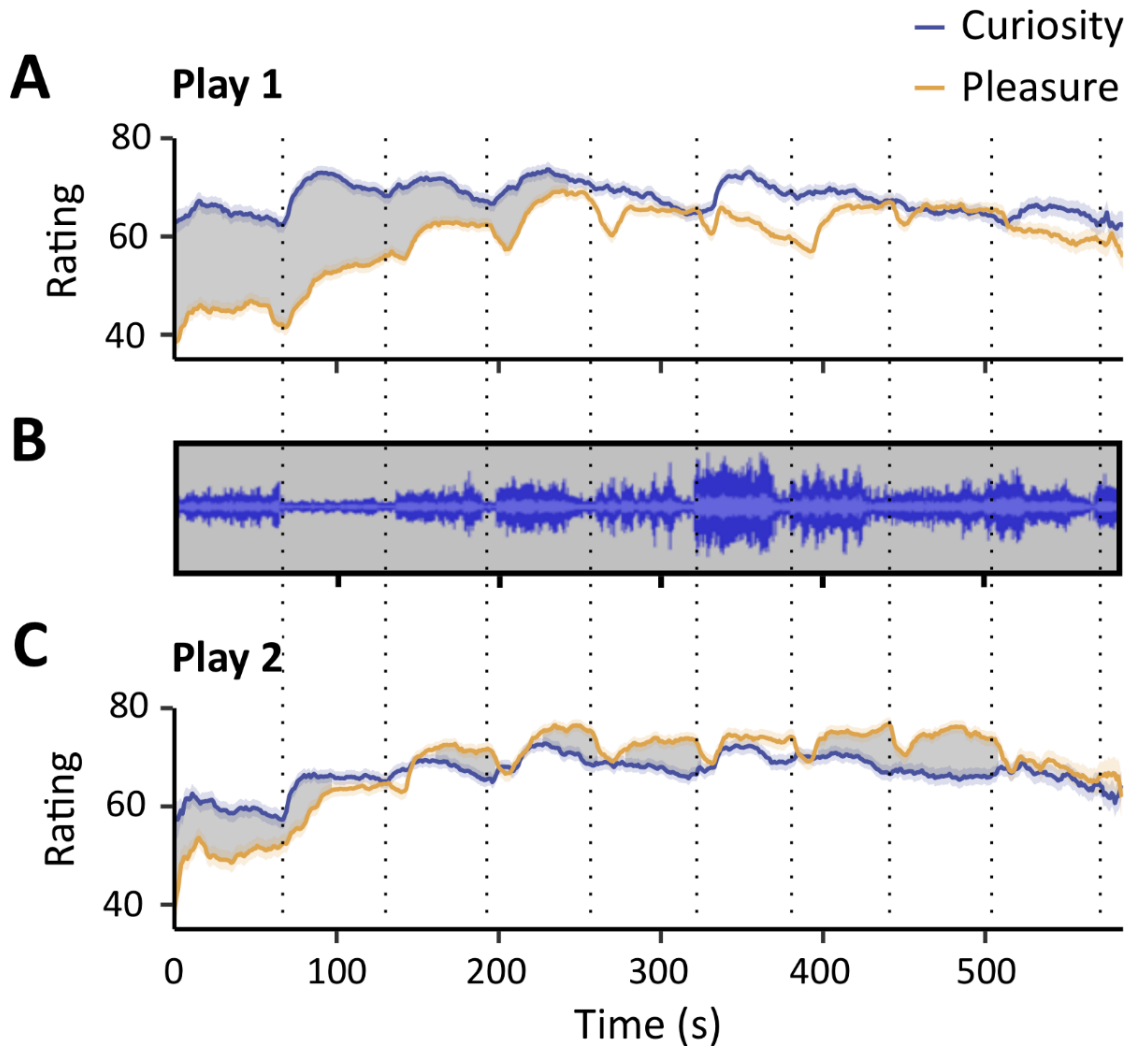


Figure 3. A and C) Temporal dynamics of curiosity (purple) and pleasure (orange) ratings during the first (A) and second plays (C), respectively. In (B), we depicted the song spectrum obtained from the recording of the concert. Grey shadows in the temporal dynamics indicate the time intervals where significant differences between curiosity and pleasure ratings were observed. Notably, both curiosity and pleasure dynamics seem to be driven by the movements (indicated by dashed vertical lines).

Next, we assessed whether curiosity or pleasure significantly changed from Play 1 to Play 2 (see **Figure 4**). Permutation cluster analyses showed that curiosity was significantly higher in Play 1 than in Play 2 during the first 174 s (cluster-levels t mass = 3,314, p cluster t mass = 0.0010), whereas pleasure was significantly higher in Play 2 as compared to Play 1 during the whole excerpt (cluster-levels t mass = 49,933; p cluster t mass = 0.0010).

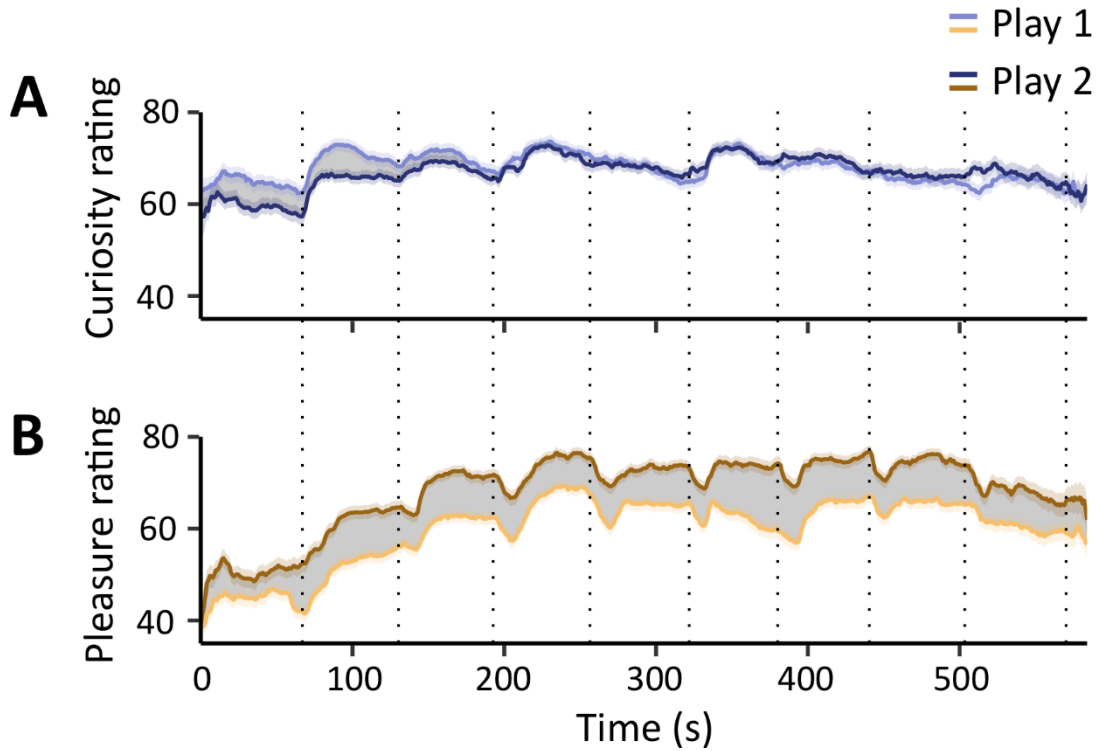


Figure 4. Temporal dynamics of curiosity (**A**) and pleasure (**B**) during Play 1 (dark colors) and Play 2 (light colors). Grey shadows indicate significant differences.

To further explore whether and how curiosity and pleasure interact during the performance, and whether curiosity is an anticipatory state of pleasure or the other way around, we performed a Granger causality analysis. The Granger causality test on Play 1 indicated that curiosity G-causes pleasure for a lag of 2 s ($AIC = 273.73$; $\chi^2(2) = 14.35$; $p = 0.0008$; see details in **Table 1** and **Figure 5A**). Thus, when the piece is highly unfamiliar, curiosity occurs two seconds prior the pleasure.

To ensure the robustness of our results, confirming that curiosity G-causes pleasure, but not vice-versa, we also considered negative lags. These lags referred to the possibility that pleasure G-causes curiosity. The Granger causality test indicated that the model with the selected lag (lag = -3 s; $AIC = 250.02$) did not improve the restricted model ($\chi^2(3) = 1.70$; $p = 0.6376$), confirming that pleasure does not G-cause curiosity in Play 1.

This temporal relationship changed completely for the continuous ratings during Play 2 (see **Table 2** and **Figure 5B**), after participants received detailed information about the piece. In this case, the Granger causality test indicated that the curiosity does not G-cause pleasure (lag = 2; $AIC = 347.47$; $\chi^2(2) = 0.93$; $p = 0.6295$), but pleasure does G-cause curiosity with a lag of 2 s (lag = -2; $AIC = 294.50$; $\chi^2(2) = 7.02$; $p = 0.0299$).

Study 4

Curiosity G-causes pleasure												
Lag	Unrestricted model fit				LRT against selected lag		Restricted model fit				LRT against restricted model	
	AIC	BIC	LL	df	df	χ^2	AIC	BIC	LL	df	df	χ^2
1	294.89	312.19	-143.45	4	2	25.16*						
2	273.73	299.68	-130.87	6			284.08	301.37	-138.04	4	2	14.35*
3	277.28	311.87	-130.64	8	2	0.45	286.01	307.63	-138.00	5	3	14.73*
4	281.15	324.39	-130.57	10	4	0.59	287.84	313.78	-137.92	6	4	14.69*
5	284.27	336.17	-130.14	12	6	1.46	288.95	319.22	-137.47	7	5	14.67*
6	287.72	348.26	-129.86	14	8	2.01	290.92	325.52	-137.46	8	6	15.20*

Pleasure G-causes curiosity												
Lag	Unrestricted model fit				LRT against selected lag		Restricted model fit				LRT against restricted model	
	AIC	BIC	LL	df	df	χ^2	AIC	BIC	LL	df	df	χ^2
-1	273.16	290.45	-132.58	4	4	31.13*						
-2	252.18	278.12	-120.09	6	2	6.15*						
-3	250.02	284.62	-117.01	8			245.72	267.34	-117.86	5	3	1.70
-4	251.13	294.37	-115.56	10	2	2.90	244.89	270.84	-116.45	6	4	1.77
-5	252.37	304.27	-114.19	12	4	5.65	244.25	274.52	-115.12	7	5	1.87
-6	256.21	316.75	-114.11	14	6	5.81	246.18	280.78	-115.09	8	6	1.97

Table 1. Granger causality tests for Play 1. The first column (lag) outlines the lag value for the models. The second column (unrestricted model fit) provides information on the model fit, including the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Log Likelihood (LL), and degrees of freedom (df). The third column (LRT against selected lag) presents the Likelihood Ratio Test (LRT) results for the current model against the model with the selected lag (i.e., the unrestricted model with lowest AIC value, and indicated in bold), including degrees of freedom (df), Chi-square values (χ^2), and whether both models were significantly different (indicated by the presence of an asterisk). Fourth column details information on the restricted model fit, including AIC, BIC, LL, and df. Last column (LRT against restricted model) presents the results of the LRT between the unrestricted and the restricted models. Last column was calculated for those lags that were not significantly different from the selected one.

Study 4

Curiosity G-causes pleasure												
Lag	Unrestricted model fit				LRT against selected lag		Restricted model fit				LRT against restricted model	
	AIC	BIC	LL	df	df	χ^2	AIC	BIC	LL	df	df	χ^2
1	360.87	378.17	-176.44	4	2	17.4*						
2	347.47	373.42	-167.74	6			344.40	361.70	-168.20	4	2	0.93
3	350.70	385.30	-167.35	8	2	0.77	346.20	367.83	-168.10	5	3	1.50
4	353.28	396.53	-166.64	10	4	2.19	346.99	372.94	-167.50	6	4	1.71
5	353.22	405.11	-164.61	12	6	6.25	347.12	377.40	-166.56	7	5	3.91
6	356.65	417.19	-164.33	14	8	6.82	348.88	383.48	-166.44	8	6	4.23

Pleasure G-causes curiosity												
Lag	Unrestricted model fit				LRT against selected lag		Restricted model fit				LRT against restricted model	
	AIC	BIC	LL	df	df	χ^2	AIC	BIC	LL	df	df	χ^2
-1	310.03	327.33	-151.02	4	2	19.53*						
-2	294.50	320.45	-141.25	6			297.52	314.82	-144.76	4	2	7.02*
-3	297.55	332.14	-140.77	8	2	0.96	299.13	320.75	-144.57	5	3	7.59
-4	300.87	344.11	-140.43	10	4	1.63	300.96	326.91	-144.48	6	4	8.09
-5	303.85	355.74	-139.93	12	6	2.65	302.00	332.27	-144.00	7	5	8.14
-6	304.76	365.30	-138.38	14	8	5.74	303.86	338.46	-143.93	8	6	11.10

Table 2. Granger causality tests for Play 2. The first column (lag) outlines the lag value for the models. The second column (unrestricted model fit) provides information on the model fit, including the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Log Likelihood (LL), and degrees of freedom (df). The third column (LRT against selected lag) presents the Likelihood Ratio Test (LRT) results for the current model against the model with the selected lag (i.e., the unrestricted model with lowest AIC value), including degrees of freedom (df), Chi-square values (χ^2), and whether both models were significantly different (indicated by the presence of an asterisk). Fourth column details information on the restricted model fit, including AIC, BIC, LL, and df. Last column (LRT against restricted model) presents the results of the LRT between the unrestricted and the restricted models. Last column was calculated for those lags that were not significantly different from the selected one.

Study 4

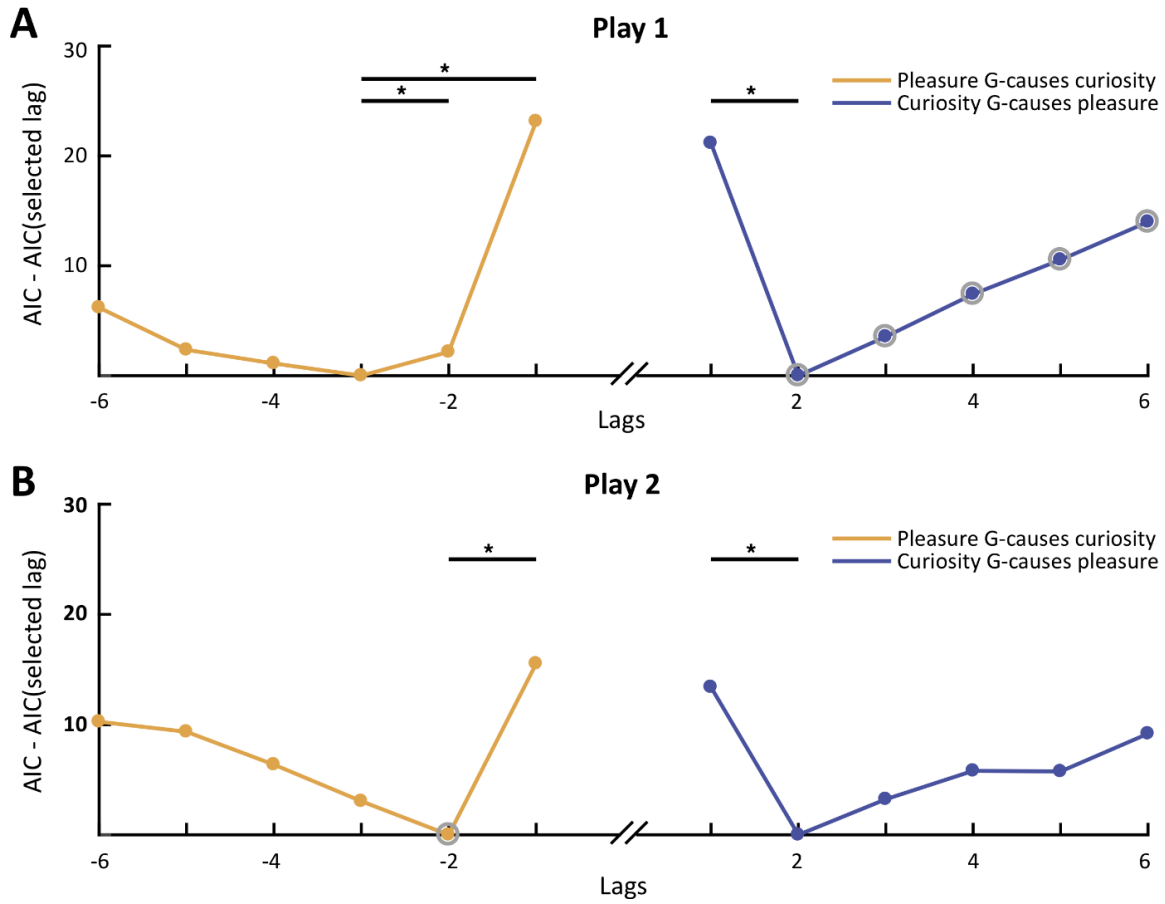


Figure 5. Results of the Granger causality test for Play 1 (A) and Play 2 (B). In both panels, positive lags indicate the evaluation whether curiosity Granger causes (G-causes) pleasure – i.e., whether an unrestricted model incorporating past values of both curiosity and pleasure better predicts future values of pleasure than a restricted model using only past values of pleasure –, while negative ones indicate the opposite, i.e., pleasure G-causes curiosity. Lag selection was first performed based on the Akaike Information Criterion (AIC); the lag with the lowest AIC was selected for each play and each direction of G-causality, giving, for pleasure G-cause curiosity and curiosity G-cause pleasure, respectively, -3 and +2 in Play 1, and -2 and +2 in Play 2. Asterisks indicate the lags that were significantly different according to a Likelihood Ratio Test (LRT). Then, the unrestricted model was compared against the restricted one using a LRT. Significant differences between unrestricted and restricted models are indicated by grey circles. In panel A, the results indicate that, for Play 1, curiosity G-causes pleasure with a lag of 2 s because (1) is the model with the lowest AIC value, and (2) this unrestricted model significantly improves the restricted one. In panel B, the results indicate that for Play 2 pleasure G-causes curiosity with a lag of 2 s.

Subsequently, we investigated how individual differences in sensitivity to music reward (i.e., the musical hedonia) affected curiosity and pleasure ratings. First, we assessed the correlation between eBMRQ scores and the mean curiosity or mean pleasure ratings reported by each participant during Play 1. Results showed that musical hedonia (i.e., eBMRQ scores) significantly correlated with mean ratings of both curiosity ($r = 0.16$, $p = 0.03$, **Figure 6A**) and pleasure ($r = 0.20$, $p < 0.01$, **Figure 6B**): the higher the musical hedonia, the higher the ratings. Then, we assessed the correlation between eBMRQ scores and the mean ratings of the nine movements and observed that the strongest correlations took place during the first half of the performance (see **Figure 6C**).

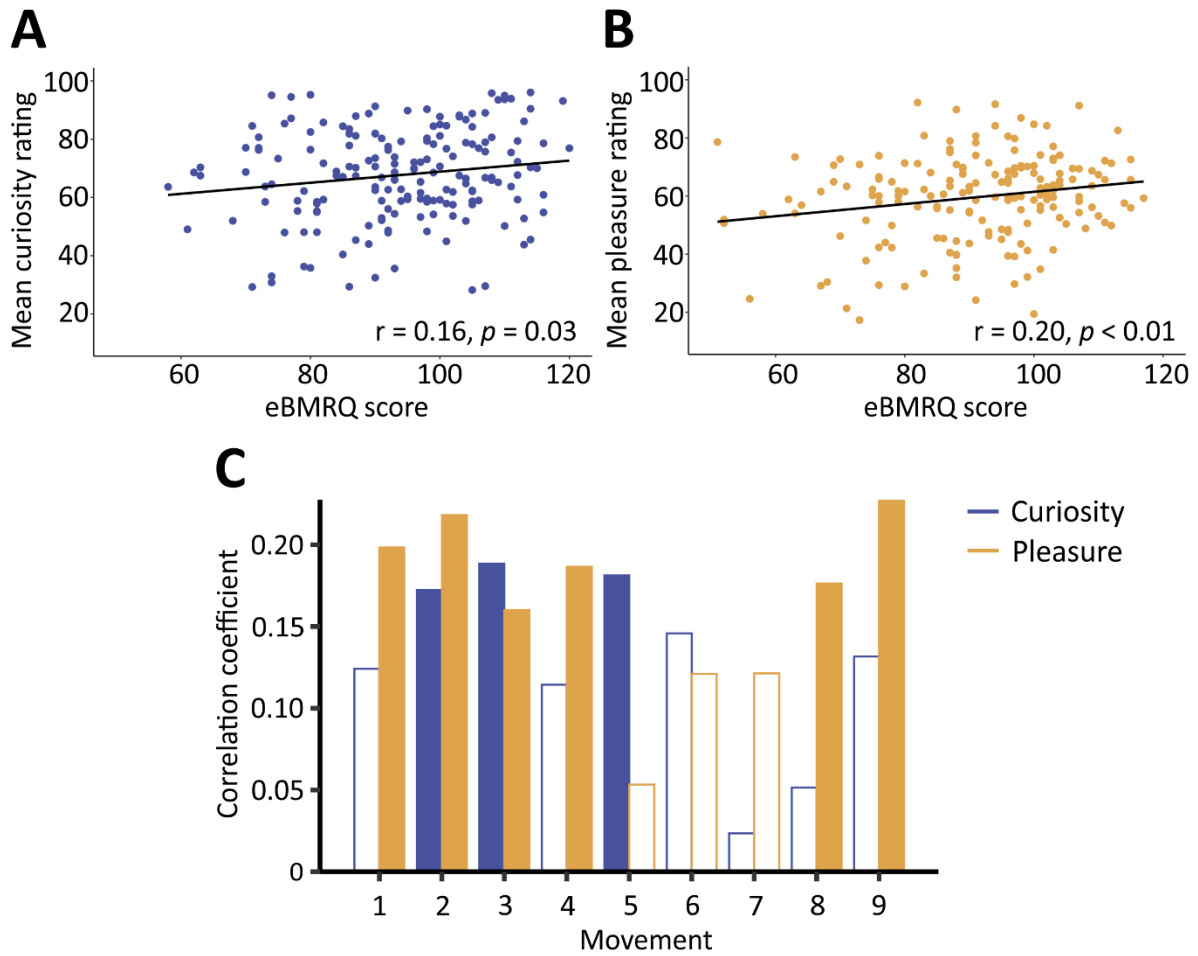


Figure 6. Correlation between musical hedonia (measured through the eBMRQ) and the mean curiosity (**A**) or pleasure (**B**) reported during Play 1. **C.** Correlation between musical hedonia and mean ratings for each movement. Filled bars indicate that the correlation is significant.

The findings highlighted an influence of musical hedonia on curiosity and pleasure ratings. Thus, we subsequently investigated whether the temporal dynamics of both measures varied depending on musical hedonia. For this purpose, we selected and compared the 50 most and the 50 least hedonic participants (according to their eBMRQ score) from each group (i.e., Curiosity and Pleasure groups). Results confirmed significant differences in both curiosity (mean curiosity of highly hedonics = 71.82 ± 22.41 , mean curiosity of lowly hedonics = 64.33 ± 23.57 , $\chi^2(1) = 4.18$, $p = 0.0410$), and pleasure (mean pleasure of highly hedonics = 62.75 ± 19.36 , mean pleasure of lowly hedonics = 55.64 ± 22.92 , $\chi^2(1) = 6.78$, $p = 0.0092$), with highly hedonic participants consistently reporting higher curiosity and pleasure ratings than lowly hedonics. These significant differences came from different time windows (see **Figures 7A** and **7B**), where highly hedonic participants felt a higher curiosity (eight different windows: 36-45 s; 53-72 s; 101-188 s; 214-302 s; 305-315 s; 325-367 s; 443-451 s; and 510-577 s; cluster-levels t mass ≥ 50 ; ps cluster t mass ≤ 0.0240) and/or higher pleasure (ten different windows: 17-30 s; 52-71 s; 87-161 s; 184-195 s; 198-211 s;

213-260 s; 335-354 s; 358-380 s; 399-447 s; and 450-554 s; cluster-levels t mass ≥ 78 ; ps cluster t mass ≤ 0.0060). These findings were also reflected in a difference waveform (i.e., highly hedonic – lowly hedonics ratings) computed for both curiosity and pleasure to easily visualize how musical hedonia differently affected the two constructs (**Figure 7C**).

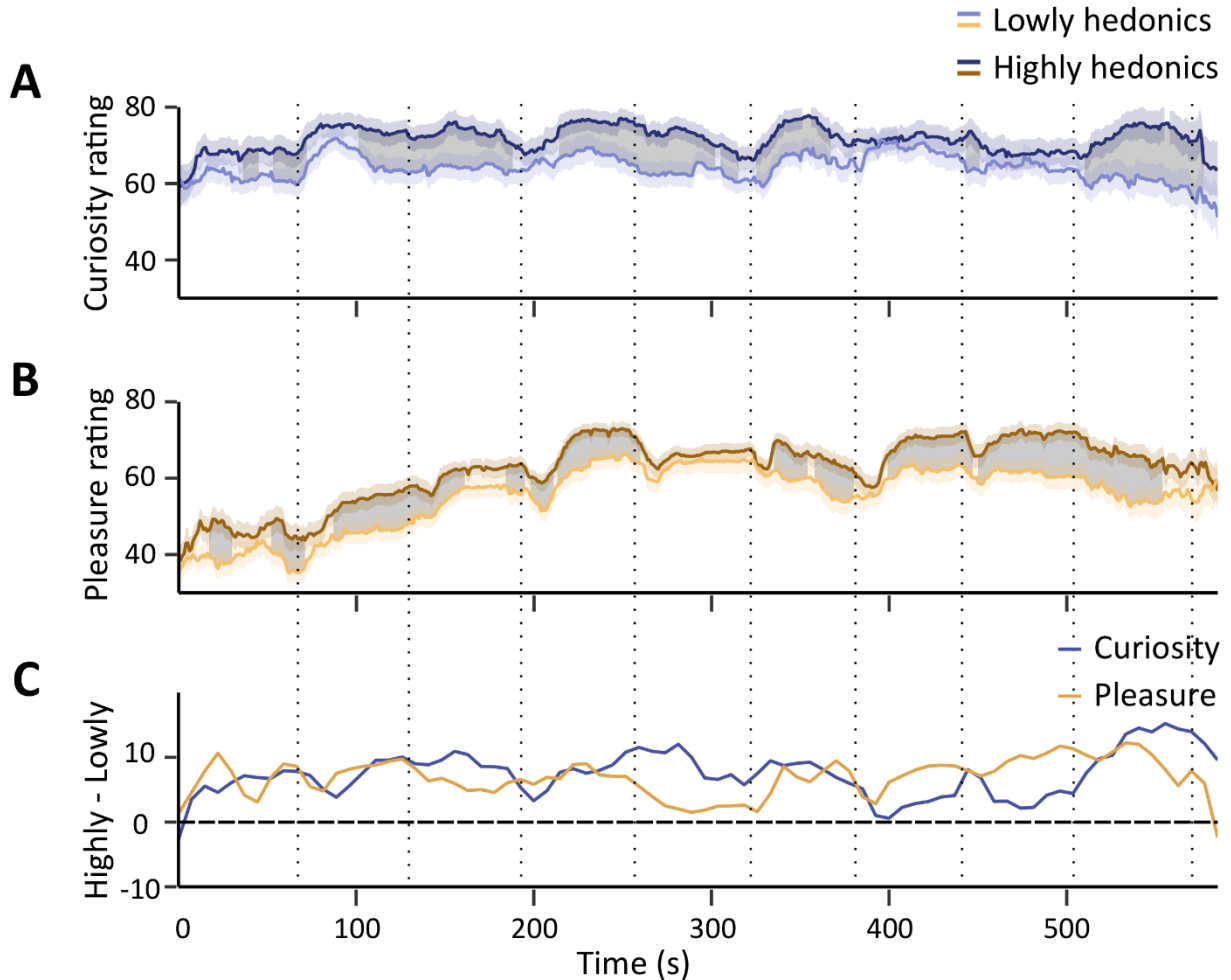


Figure 7. Temporal dynamics of both curiosity (**A**) and pleasure (**B**) reported by the 50 most hedonic (i.e., highly hedonics) and the 50 least hedonics (i.e., lowly hedonics) of each group during Play 1. Significant differences are indicated by grey shadows. **C.** Difference waveform showing how the differences between highly and lowly hedonics evolve over time for both curiosity (purple) and curiosity (orange).

Finally, we evaluated whether there exists a change in the continuous ratings of curiosity and/or pleasure from Play 1 to Play 2 depending on musical hedonia (i.e., highly and lowly hedonics). Results showed that highly hedonic participants have significant differences in curiosity (three different windows: 9-117 s; 119-131 s; and 490-498 s; cluster-levels t mass ≥ 54 ; ps cluster t mass ≤ 0.0470 ; see **Figure 8A**) and pleasure across different performances (one window from 61 to 514 s; cluster-level t mass = 18,023; p cluster t mass = 0.0010; see **Figure 8C**). Notably, the first two significant time windows in curiosity ratings, show that curiosity ratings in Play 2 decreased, while pleasure ones increased. Similarly, lowly hedonic participants also showed an increment on

pleasure rating during the Play 2 (three different windows: 49-259 s; 334-509 s; and 511-554 s; cluster-levels t mass ≥ 825 ; ps cluster t mass ≤ 0.0460 ; see **Figure 8D**), but they did not show a decrement on curiosity ratings (four different windows: 219-231 s; 246-254 s; 260-302 s; and 307-346 s; cluster-levels t mass ≥ 55 ; ps cluster t mass ≤ 0.0170 ; see **Figure 8B**).

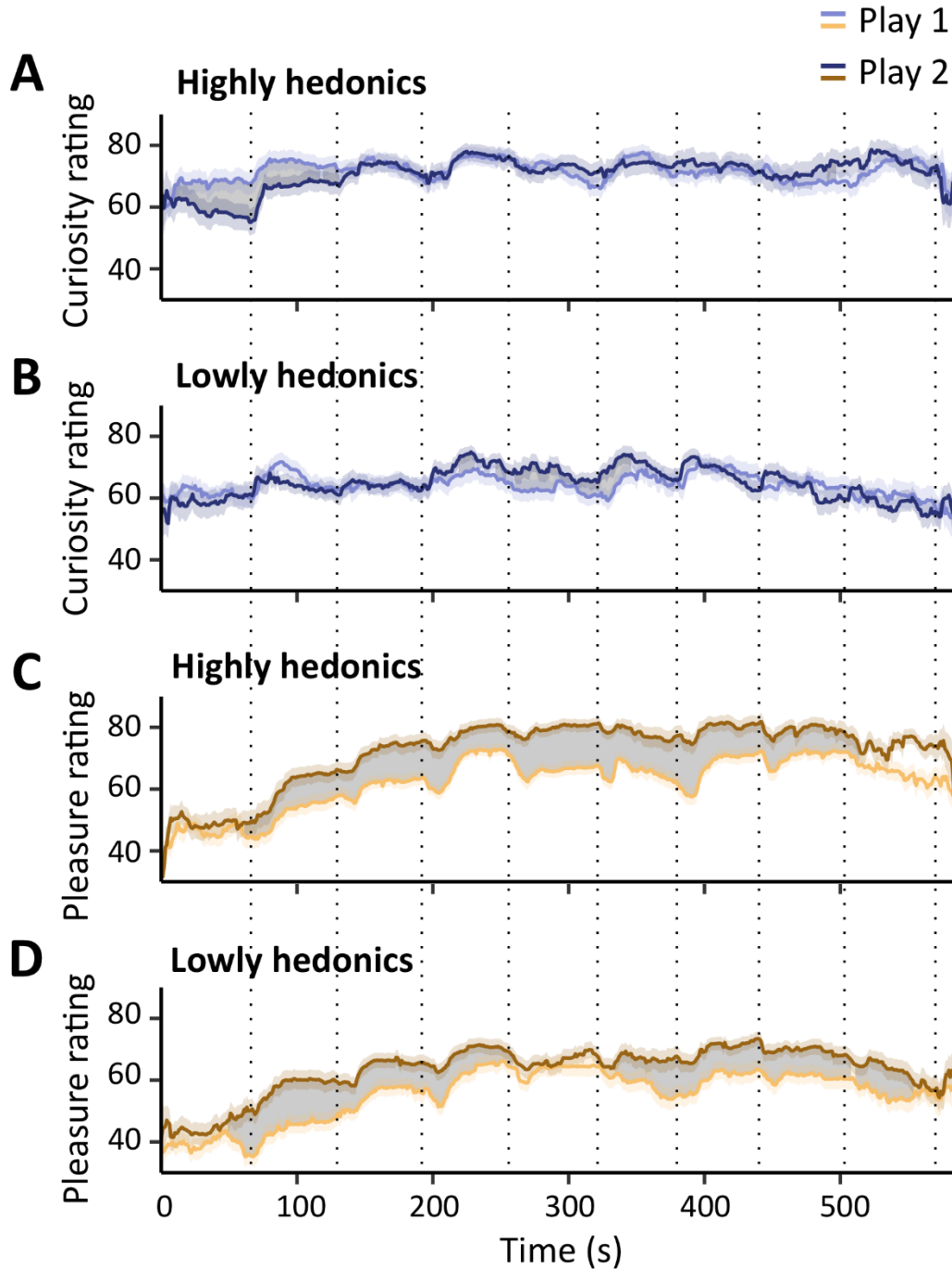


Figure 8. Temporal dynamics for Play 1 (light colors) and Play 2 (dark colors), considering individual differences according to the eBMRQ. The 50 participants with highest eBMRQ scores were classified as “highly hedonics”, while the 50 with lowest eBMRQ scores were labelled as “lowly hedonics”. Significant differences between Play 1 and Play 2 in both curiosity (**A** and **B**) and pleasure (**C** and **D**) are indicated by grey shadows.

Finally, we analysed memory performance. First, we assessed memory performance for both, *Fratres*- (correct responses = 89.4 ± 14.5) and neuroscience- (correct responses = 76.2 ± 19.2) related information provided during the event ($N = 322$). In order to assess the effect of the different predictors on memory performance, linear regression and the backward elimination method were used until reaching the minimum, final model. In the case of *Fratres*-related information, we started from the following full model: *Fratres*-related information (number of correct answers out of 5) $\sim$ age + classicalLiking + fratresFamiliarity + curiosityForMusic + eBMRQ + diversivePCS + diversiveECS + flowCEI. The final model ($\chi^2(1) = 5.84$, $p = 0.016$; see **Table 3** for measures of fit of the different models as well as likelihood ratio tests results used for model selection) only included classical music liking, which showed a significant main effect ($\chi^2(1) = 5.84$, $p = 0.016$) on memory for *Fratres*-related information: the more the liking, the better the memory performance. Regarding neuroscience-related information, we started from the full model: neuroscience-related information $\sim$ age + curiosityForNeuroscience + eBMRQ + diversivePCS + diversiveECS + flowCEI. The backward elimination process (see **Table 4**) led to a final model including: age + diversiveECS + flowCEI ($\chi^2(3) = 5.03$, $p = 0.002$). Thus, memory performance for neuroscience-related information was significantly influenced by age ($\chi^2(1) = 4.89$, $p = 0.028$), so that older participants showed poorer performance; curiosity ($\chi^2(1) = 7.68$, $p = 0.006$), with higher scores in the diversive subscale of the ECS being associated with better the memory performance; and flow ($\chi^2(1) = 6.32$, $p = 0.012$), so that the higher the tendency to get carried away, the worse the memory performance. Memory for information was not significantly influenced by the mean curiosity or mean pleasure reported during the first play.

When assessing the participants' memory for music ($N = 322$), we ran linear models to determine the effect of demographic data and questionnaires scores on dprime, a measure of the participants' ability to discriminate between old and new excerpts. The full model was, therefore: Dprime $\sim$ age + classicalLiking + eBMRQ + diversivePCS + diversiveECS + flowCEI. Model selection led to a final model ($\chi^2(2) = 19.01$, $p < 0.001$; see **Table 5** for measures of fit of the different models as well as likelihood ratio tests results used for model selection) including a significant main effect of age ($\chi^2(1) = 41.24$, $p < 0.001$) and eBMRQ ($\chi^2(1) = 6.57$, $p = 0.011$), as well as a tendency of diversiveECS ($\chi^2(1) = 3.73$, $p = 0.054$), so that the younger, more musical hedonic and more curious the participants, the higher the discrimination and, therefore, the better the memory performance (see **Figure 9**).

Subsequently, we analysed data from the two groups separately ($N = 161$ for each group) and tested whether the mean ratings provided during Play 1 predicted dprime scores. Whereas curiosity ratings did not show a significant effect ($F(1) = 0.425$, $p = 0.515$), pleasure ratings

significantly influenced dprime scores ($F(1) = 4.56$, $p = 0.034$): that the higher the subjective pleasure during Play 1, the better the discrimination between old and new excerpts the day after.

Finally, we tested, for each old item, whether the curiosity/pleasure reported for those seconds during Play 1 predicted recognition and/or recollection responses. Logistic regression mixed models revealed no significant effects of either curiosity or pleasure on recognition or recollection performance.

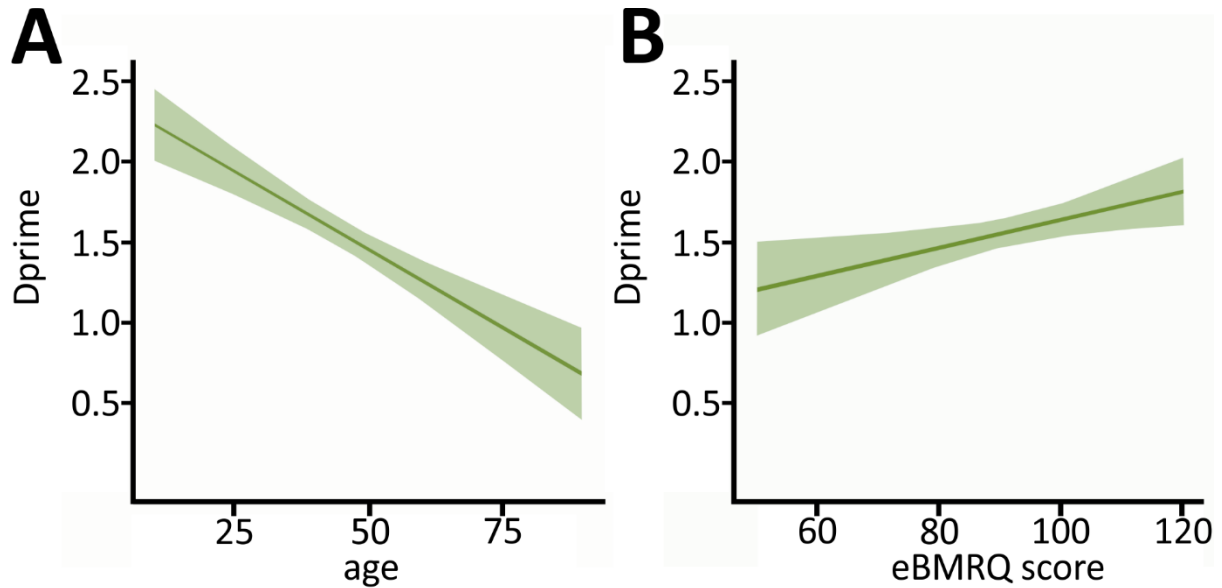


Figure 9. Significant effects of age and musical hedonia on the ability to discriminate between old and new excerpts.

Study 4

Fixed effects	df	Measures of fit				Likelihood ratio tests		
		AIC _{ci}	Δ_i AIC _c	w _i AIC _c	LL _i	χ^2	df	p
age + classicalLiking + fratresFamiliarity + curiosityForMusic + eBMRQ + diversivePCS + interestECS + flowCEI	8	716.4	11.51	0.00	-347.9			
classicalLiking + fratresFamiliarity + curiosityForMusic + eBMRQ + diversivePCS + interestECS + flowCEI	7	714.3	9.39	0.00	-347.7	0.01	1	0.943
classicalLiking + curiosityForMusic + eBMRQ + diversivePCS + interestECS + flowCEI	6	712.2	7.29	0.01	-347.9	0.02	1	0.892
classicalLiking + curiosityForMusic + diversivePCS + interestECS + flowCEI	5	710.2	5.28	0.03	-347.9	0.09	1	0.762
classicalLiking + diversivePCS + interestECS + flowCEI	4	708.2	3.31	0.08	-348.0	0.12	1	0.731
classicalLiking + interestECS + flowCEI	3	706.6	1.64	0.18	-348.2	0.40	1	0.530
classicalLiking + interestECS	2	706.0	1.06	0.24	-348.9	1.47	1	0.226
classicalLiking	1	704.9	0.00	0.40	-349.4	0.98	1	0.323
Null	0	708.7	3.78	0.06	-352.3	5.84	1	0.016

Table 3. *Tested structures for modelling participants' memory performance for Fratres-related information.* In the formulas, 'df' = degrees of freedom. AIC_{ci} = corrected Akaike Information Criterion. Δ_i (AIC_c) = difference between AIC_c for model i and best model's AIC_c. w_i(AIC_c) = Akaike weight measuring the level of support in favour of model i being the most parsimonious among the candidate model set. LL_i = natural logarithm of the maximum likelihood for model i. Likelihood ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

Study 4

Fixed effects	df	Measures of fit				Likelihood ratio tests		
		AIC _{ci}	Δ_i AIC _c	w _i AIC _c	LL _i	χ^2	df	p
age + curiosityForNeuroscience + eBMRQ + diversivePCS + interestECS + flowCEI	8	886.1	4.77	0.04	-434.8			
age + curiosityForNeuroscience + diversivePCS + interestECS + flowCEI	7	884.0	2.69	0.11	-434.8	0.02	1	0.886
age + curiosityForNeuroscience + interestECS + flowCEI	6	882.1	0.80	0.30	-434.9	0.19	1	0.664
age + interestECS + flowCEI	5	881.3	0.00	0.44	-435.6	1.26	1	0.262
interestECS + flowCEI	4	884.2	2.85	0.11	-438.0	4.89	1	0.028

Table 4. *Tested structures for modelling participants' memory performance for neuroscience-related information.* In the formulas, 'df' = degrees of freedom. AIC_{ci} = corrected Akaike Information Criterion. Δ_i (AIC_c) = difference between AIC_c for model i and best model's AIC_c. w_i(AIC_c) = Akaike weight measuring the level of support in favour of model i being the most parsimonious among the candidate model set. LL_i = natural logarithm of the maximum likelihood for model i. Likelihood ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

Study 4

Fixed effects	df	Measures of fit				Likelihood ratio tests		
		AIC _{ci}	Δ_i AIC _c	w _i AIC _c	LL _i	χ^2	df	<i>p</i>
age + classicalLiking + eBMRQ + diversivePCS + interestECS + flowCEI	8	776.3	3.57	0.06	-376.5			
age + classicalLiking + eBMRQ + interestECS + flowCEI	7	767.7	1.77	0.14	-376.7	0.29	1	0.588
age + eBMRQ + interestECS + flowCEI	6	766.1	0.20	0.31	-376.9	0.51	1	0.475
age + eBMRQ + interestECS	5	765.9	0.00	0.34	-377.9	1.85	1	0.175
age + eBMRQ	4	767.6	1.69	0.15	-379.7	3.73	1	0.054
age	3	776.3	10.42	0.00	-385.1	10.86	1	0.001

Table 5. *Tested structures for modelling participants' memory performance for neuroscience-related information.* In the formulas, 'df' = degrees of freedom. AIC_{ci} = corrected Akaike Information Criterion. Δ_i (AIC_c) = difference between AIC_c for model i and best model's AIC_c. w_i(AIC_c) = Akaike weight measuring the level of support in favour of model i being the most parsimonious among the candidate model set. LL_i = natural logarithm of the maximum likelihood for model i. Likelihood ratio tests compare the goodness of fit of that particular model to the previous one. Backward elimination was performed until no further variables or interactions could be removed without a statistically insignificant loss of fit.

6.4 Discussion

The present study investigated the temporal dynamics and interdependence of curiosity and pleasure implementing an innovative experimental design in a large, public music-science event. Participants in the audience were asked to continuously report their levels of curiosity or pleasure while listening to an unfamiliar minimalist piece, *Fratres* by Arvo Pärt, over two distinct sessions separated by an information learning phase. Results revealed that curiosity and pleasure not only changed over time, but also influenced each other, with both being affected by the information-learning phase and individual sensitivity to music reward. Additionally, our findings corroborate the relationship between music reward and memory.

Studies investigating curiosity have traditionally employed discrete and brief pieces of information, such as trivia questions (Gruber et al., 2014; Kang et al., 2009), blurry photos with ambiguous content (Jepma et al., 2012), or lottery trials (Kobayashi et al., 2019; Van Lieshout et al., 2018). These experimental designs lead to a rapid satiation and extinction of curiosity, failing to account for its temporal component. This limitation has been addressed by the evolving line drawing task (Hsiung et al., 2023), where participants watch videos of a single-line drawing unfold over time and provide curiosity ratings one to three times per video. While this setup dynamically explores curiosity, it still does not fully capture its temporal nature. Furthermore, traditional laboratory paradigms often fail to capture the complexity of real-world environments—such as diverse stimuli, social interactions, dynamic contexts—where human curiosity usually unfolds. In this context, music emerges as a compelling tool for studying curiosity over time. To the best of our knowledge, only one study has used music to characterize curiosity dynamics so far (Omigie & Ricci, 2022), showing that the perceptual experience of change precedes and Granger-causes the feelings of curiosity. Our study was the first to investigate the temporal dynamics and potential interplay of both curiosity and pleasure in a naturalistic, highly ecological setting.

By continuously monitoring curiosity and pleasure during music listening, we demonstrated that curiosity precedes pleasure, with curiosity ratings being significantly higher than pleasure ratings during the initial minutes of the first play. This finding suggests that curiosity acts as an anticipatory signal before the onset of pleasurable feelings (Gruber et al., 2014; Kang et al., 2009), and is supported by evidence that curiosity Granger-caused pleasure with a lag of 2 seconds during Play 1. Consistent with these findings, Gruber et al. (2014) observed increased activity in midbrain dopaminergic regions when participants anticipated answers to trivia questions they

were highly curious about. This waiting period can be seen as both a positive anticipatory state and a savoring phase, where individuals anticipate the value of the forthcoming reward (Loewenstein, 1987) and experience a positive reward event (Iigaya et al., 2021). This also aligns with reward-learning theories that suggest curiosity leads to knowledge acquisition, which is inherently rewarding (Gottlieb et al., 2013; Murayama, 2022; Oudeyer & Kaplan, 2007; Ripollés et al., 2014, 2016). The activation of midbrain reward regions is thought to trigger dopamine release in the ventral striatum, enhancing feelings of pleasure and promoting further exploration (Gruber & Ranganath, 2019; Ripollés et al., 2018). In our study, this explorative behavior likely manifested as sustained attention to the unfolding music, resulting in information updating and increased pleasure, thereby reinforcing further information-seeking by enhancing the expected reward value of new information. Importantly, this pattern occurred only during the first play, when listeners were unfamiliar with the stimulus.

During the second play, and unlike curiosity, pleasure dramatically increased compared to the first play. According to the literature, after gaining new information and experiencing reward-related emotions, individuals often reassess and re-evaluate the value of certain goods. This can affect incentive salience and increase the desire for further exploration in this domain (Hélie et al., 2017). In this study, the increased pleasure –mostly driven by the information gain and an increased familiarity with the stimulus– might have increased the value of the music piece (i.e., the experience utility) revealed by the unfolding music, thus boosting exploration and curiosity and preventing its decay. Accordingly, results showed that during Play 2 pleasure precedes curiosity, with pleasure Granger-causing curiosity with a lag of 2 seconds.

The observed effect supports the idea that curiosity, information gain, and pleasure share cognitive and reward-related neural structures (Bromberg-Martin & Hikosaka, 2009; Gruber & Ranganath, 2019). The impact of receiving information may have enabled listeners to experience savoring effects in anticipation of listening to the musical excerpt again, similarly to what occurs when people anticipate positive, delayed rewards. Nevertheless, since the study only measured continuous ratings during the music and did not assess pleasure or curiosity before the second exposure, we cannot fully confirm this interpretation. Additionally, the increased pleasure is likely to be partly due to the repetition of the excerpt, which increases familiarity, rather than solely due to the information gained between the two exposures. Given the complexity and novelty of the excerpt, along with the unique experimental setting, we aimed to maximize the impact of the second exposure by providing substantial information gain. This approach was chosen instead of merely repeating the excerpt, which would have only increased familiarity with the still-complex musical structure without enhancing learning processes. Although further research is needed to

disentangle these two factors, our study revealed a complex, bidirectional relationship between curiosity and pleasure. While curiosity signals during the first listening session are decoded into enhanced pleasure, after acquiring new information (similarly to what happens in educational settings) the increased pleasure further stimulate curiosity signals. This indicates a feedback loop between curiosity and pleasure, which might become crucial for designing effective curiosity-based motivational interventions, vital in education (Engel, 2011).

Crucially and contrary to dominant ideas in the field of curiosity (Lowenstein et al., 1994), curiosity was not satiated in the present study. Curiosity ratings remained steady during Play 1, Play 2, and even from Play 1 to Play 2 (except for a slight drop in the first few minutes), despite participants receiving a detailed explanation about the musical piece. Lowenstein (1994) described curiosity as an *aversive state* driven by a perceived gap in knowledge. Consuming information is rewarding, but curiosity typically decreases once enough information is obtained. In a similar vein, Kang et al. (2009) found that curiosity is lowest when participants feel confident in their knowledge (see also Marvin & Shohamy, 2016). In contrast, our findings suggest that curiosity for music is highly resistant to a decline of enjoyment (also known as hedonic adaptation) and satiation, unlike other reinforcers (see Kahneman & Snell, 1992; O'Brien, 2021). One possible explanation is that, after the conductor's detailed explanations, participants refined their internal model of the musical piece. This allowed them to better anticipate how the music would unfold and identify potential sources of pleasure during listening. However, due to the inherent complexity of music, there remained a significant degree of uncertainty and room for learning. As a result, predictions may only have been partially accurate, creating prediction errors that sustain curiosity and encourage active learning (Gold et al., 2019; Zatorre, 2024). This pattern of non-satiated curiosity aligns with the *learning progress* hypothesis, which suggests that during learning, the brain provides intrinsic rewards that reinforce curiosity and information-seeking (Gottlieb & Oudeyer, 2018; Oudeyer et al., 2007; Schmidhuber, 1991; see also Ripollés et al., 2014; 2016). In the current study, the complexity of the music might have generated continuous internal rewards that maintain curiosity: this positive feedback loop between reward and curiosity may explain the lack of satiation observed.

Several indicators show that our paradigm was effective and the measures were reliable. First, our results align with previous research linking musical structure to emotional intensity (Grewe et al., 2007; Juslin & Sloboda, 2001; Sloboda, 1991, 1992; Sloboda & Lehmann, 2001). Subjective ratings matched the structure of the musical piece, with continuous ratings dividing into nine segments corresponding to the nine movements of *Fratres*. Each movement was marked by recurring percussion motifs and a recurring theme in different octaves. This structure not only

facilitates transitions between movements, but also establishes associative links throughout the composition, influencing perceptual expectations (Sloboda, 1991, 1992) and striking an ideal balance between familiarity and surprise (Cheung et al., 2019). The observed dynamics suggest that lay listeners easily detect these manipulations and indicated that our measures were sensitive enough to capture these changes.

Further supporting our experimental design and crucially for research on musical pleasure and curiosity, we found that individual differences in musical reward sensitivity, measured by the eBMRQ (Cardona et al., 2020; an extended version of the BMRQ, Mas-Herrero et al., 2013), affected subjective ratings. The reliability of this measure of musical hedonia is well established, with higher scores being associated with higher brain activity in the right NAcc during music listening (Martinez-Molina et al., 2016; 2019) and better memory performance for music (Ferreri & Rodriguez-Fornells, 2017; Ferreri, Mas-Herrero, et al., 2021). Recent studies also show that genetic factors contribute significantly to variance in music reward sensitivity measured by the BMRQ (Bignardi et al., 2024). In our study, higher eBMRQ scores were associated with greater curiosity and pleasure, especially during the initial movements of the piece (see Figure 6). The increased pleasure reported by high hedonics, particularly during the second listening, may reflect valence-dependent effects in curiosity, where people gain more anticipatory utility from positive emotional events (Charpentier et al., 2018; Golman et al., 2017; Kuzmanovic et al., 2016; Lefebvre et al., 2017; Marvin & Shohamy, 2016). For high hedonic individuals, decoding music into pleasurable experiences might be easier, enhancing their ability to experience and savor positive emotions (Martínez-Molina et al., 2016; Mas-Herrero et al., 2013). Additionally, we observed that curiosity ratings significantly decreased during the first few minutes of the second play compared to the first, particularly among highly hedonic participants, who started the second play with less curiosity. These findings, while complex to interpret, underscore the intricate relationship between curiosity and pleasure, suggesting that accounting for individual differences in reward sensitivity could provide a unique perspective on human reward processes.

The memory task completed the following day revealed several key findings. Participants who had a stronger preference for classical music, who were more likely to be engaged in flow states, and had higher scores in diversive epistemic curiosity were better in retrieving the *Fratres*- or neuroscience-related information. Furthermore, the general pleasure experienced during the first play predicted better memory for the music the day after. Consistently, higher scores in musical hedonia are also associated with better memory performance (Cardona et al., 2020; Ferreri & Rodriguez-Fornells, 2017). Taken together, these findings highlight and confirm that the reward experienced during the encoding of an event can promote the consolidation of the information,

likely through the activation of the dopaminergic reward system (Ferreri, Mas-Herrero, et al., 2021; Lisman et al., 2011). However, we found no effect of curiosity or pleasure experienced during specific excerpts on memory for those excerpts. This lack of effect is likely due to the task's difficulty and the similarity between the excerpts, all of which were from the same, long piece - contrasting with typical laboratory conditions. This emphasizes the need for innovative paradigms to better explore the relationship between pleasure, curiosity, and memory in real-world settings (Cardona et al., under review).

A major strength of this study is its natural setting, which facilitates a more realistic exploration of behavior than traditional laboratory settings typically allow. Music concerts offer an ideal context for researching music's emotional impact in its authentic complexity (Cameron et al., 2022; Chabin et al., 2022; Czepiel et al., 2023; Tervaniemi, 2023). This approach also allows for the recruitment of a larger, more diverse participant sample, enhancing the study's breadth and promoting citizen science. However, while ecological contexts like concerts offer many advantages, they also come with certain limitations. Firstly, preserving the artistic integrity of the event is essential, which in this study meant limiting observations to 10-minute sessions. Secondly, tasks must be kept simple due to the numerous distractions and the impracticality of providing individualized assistance, which might also explain the considerable number of drop-outs. Consequently, participants were asked to rate only one construct, requiring us to compare curiosity and pleasure ratings across different groups. Despite these limitations, we believe the two groups were sufficiently large and comparable to yield results similar to those obtained from within-subject measures. Furthermore and crucially, this approach also allowed prevented any potential contamination from rating multiple constructs within the same task. Another critical point concerns the use of continuous rating techniques. These methods require listeners to engage in self-monitoring, which may not always align with a natural listening experience. However, some evidence suggests that continuous rating tasks can enhance the quality of the listening experience (Madsen & Coggiola, 2001; McAdams et al., 2004), and fundamentally contributed to monitor the temporal dynamics of affective ratings in this study. Additionally, it is noteworthy that we did not consider the physical properties of the musical piece in relation to the ratings. Research indicates that ratings of curiosity and pleasure are often linked to prediction errors arising from musical structure (Cheung et al., 2019; Gold et al., 2019; Omigie & Ricci, 2023). In this study, however, we were specifically interested in examining the relationship between curiosity and pleasure at a more empirical level.

In conclusion, this study characterized for the first time the temporal evolution of curiosity and pleasure, as well as they interplay, in a high-ecological, naturalistic scenario. By highlighting their

Study 4

temporal dynamics, bidirectional dependence, as well as their relation with individual differences in musical hedonia and memory, these findings offer new insights into the study of human curiosity and pleasure through the lens of music cognition, and important avenues for interventions in educational settings.

General Discussion

7 General Discussion

Music constitutes an essential part of our lives, serving as a powerful mood and emotional regulator through its ability to evoke emotions, inspire movement, and foster social bonds. Over the last decades, extensive research has explored music-driven hedonic experiences, revealing that listening to favorite music activates midbrain dopaminergic regions involved in reward processing and motivation. Yet, many factors influencing musical experiences remain unexplored. Indeed, musical affective experiences form a complex domain, shaped by multiple variables that may differ based on individual profiles, particularly in the richness of musical encounters in real-life situations. For instance, music can sometimes induce peak emotional experiences where individuals lose awareness of time and space and forget about themselves, and are usually valued as highly pleasant. This total absorption in music – still underexplored in the scientific literature – may influence the experienced reward. Also, our affective experience with music may be influenced by whether and how we seek it in our lives: the active and effortful pursuit of discovering new music may also contribute to the reward experienced during music consumption, making musical curiosity another relevant – yet unexplored – factor. Therefore, the main aim of the present thesis was to deepen our understanding of music reward by examining additional, previously unexplored processes that shape musical experiences. To this end, we developed a multi-approach research framework focusing on two specific processes: absorption (Study 2) and curiosity (Studies 3 and 4), in both laboratory and real-life settings.

It is also noteworthy that reward processes are not an end in themselves, but rather contribute to and modulate human behavior. From a neurocognitive perspective, extensive research has demonstrated that rewarding stimuli, through dopaminergic transmission, can promote memory consolidation and enhance information recall. This effect has been observed with tangible rewards, such as money (Adcock et al., 2006; Wittmann et al., 2005; Wolosin et al., 2012), as well as more abstract rewards, like music or states of curiosity (Ferrerri, Mas-Herrero, et al., 2021; Gruber et al., 2014). Building on this evidence, another key aim of this thesis was to extend previous research by exploring whether and how the experience of music-related rewards might influence memory performance. Specifically, we examined whether music pleasure and curiosity can facilitate the recall of both musical and non-musical information (Studies 1, 3, and 4).

In the following sections, I will summarize the main studies of this thesis, resuming aims, methods and findings, and discuss how they may contribute to research on music reward.

7.1 New insights on music reward: absorption and curiosity

7.1.1 The forgotten role of absorption in music reward

Absorption, a condition characterized by a reduced self-consciousness and heightened feelings of connectedness, has been often described in the context of music. Accordingly, Sufi music, tarantella, or even whistling have been used as catalysts for achieving altered states of consciousness (Katz & De Rios, 1971; Kirkegaard, 2012). Similarly, religious practices often use music as a means of accessing holy, transcendent, or spiritual experiences (Hills & Argyle, 1998; Miller & Strongman, 2002; Penman & Becker, 2009), usually described as intensely pleasurable. Thus, achieving these altered states of consciousness and total absorption in music may contribute to the reward individuals derive from the musical experience. However, the relationship between absorption and reward resulted unexplored in the literature.

A decade ago, the *Barcelona Music Reward Questionnaire* (BMRQ, Mas-Herrero et al., 2013) was developed to measure individuals' sensitivity to music-related reward. It included facets such as *Emotion Evocation*, *Mood Regulation*, *Musical Seeking*, *Social Reward*, and *Sensory-Motor* aspects. This questionnaire represents one of the most important and employed psychometric tools in music cognition. It allows researchers to quantitatively assess how music elicits pleasure and reward across diverse populations, thus helping to deepen our understanding of the psychological and neurological mechanisms underlying musical enjoyment. Indeed, BMRQ scores have been shown to correlate with activity in the right NAcc during music listening (Gold, Mas-Herrero, et al., 2019), music use during the COVID-19 pandemic (Ferreri, Singer, et al., 2021), and memory performance for music material (Ferreri, Mas-Herrero, et al., 2021; Ferreri & Rodriguez-Fornells, 2017). However, we observed that none of the BMRQ facets captured the peak emotional states and intense responses associated with the concept of absorption, such as perceptual narrowing, fusion with the object of attention, or altered sense of time and space. To address this limitation, in Study 2 we aimed to incorporate new items related to absorption in music into the BMRQ.

Through a review of the literature, we identified the *Absorption in Music Scale* (AIMS; Sandstrom & Russo, 2011), which measures an individual's capacity for deep engagement and immersion in music. This scale assesses how intensely a person can focus on and become emotionally absorbed in musical experiences, reflecting their overall absorption and responsiveness to music. A productive exchange with Prof. Russo (Toronto Metropolitan University, author of the AIMS) enabled us to adopt a psychometric approach to investigate the relationship between the two scales and to explore how the AIMS could enhance our understanding of music reward as assessed by the BMRQ.

In the first phase of the study, three hundred and seventy participants completed both the BMRQ (Mas-Herrero et al., 2013) and the AIMS (Sandstrom & Russo, 2011). Results showed a strong positive relationship between the two measured concepts, indicating that higher music reward sensitivity is associated with a greater proneness to experience music-related absorption states. However, there was still some unshared variance, suggesting that, indeed, the BMRQ did not fully account for absorption. Consequently, we performed a unidimensional exploratory factor analysis of the 34 AIMS items and selected four items to add to the BMRQ, creating the extended BMRQ (eBMRQ). In the second phase, 550 participants completed the eBMRQ for validation purposes. Exploratory and confirmatory factor analyses confirmed the reliable psychometric properties of the eBMRQ, suggesting that including an absorption facet improves the characterization of individual differences in sensitivity to music reward.

The findings from Study 2 are relevant for several reasons, encompassing both theoretical and methodological perspectives. First, they broaden our understanding of music reward by suggesting that the experience of absorption or transcendence during music listening may be a crucial factor. The intense state of involvement typical of absorption states, sometimes leading to transcendent experiences, could play a key role in how we process and derive pleasure from music. Future experimental studies may benefit from considering absorption and transcendental states as pivotal mechanisms in investigating the cognitive and neural processes underlying music reward.

Second, the findings contribute to the development of a new psychometric measure that captures individual profiles related to music engagement. By refining the BMRQ, we contributed to a better characterization of individual differences in the ability to derive reward from music. This measure could be therefore essential for advancing our understanding of how people relate to music in different ways. The eBMRQ offers researchers a valuable tool to assess, for instance, whether the impact of music on certain cognitive processes varies based on individuals' musical hedonia. Previous research has shown that such individual differences in musical hedonia are critical for understanding how music-driven reward influences cognitive processes (e.g., Ferreri & Rodriguez-Fornells, 2017) and promotes the therapeutic effects of music in clinical interventions (e.g., Grau-Sánchez, 2018). In this thesis, the importance of individual profiles is further highlighted in Studies 3 and 4, where variations in music reward were shown to significantly impact memory and other cognitive functions. These insights emphasize the potential of personalized approaches in both research and clinical settings, where understanding a person's unique relationship with music may lead to more effective interventions and outcomes.

7.1.2 Curiosity: a new perspective on music reward?

In a second phase of our multi-approach research, we used an experimental approach to investigate the influence of curiosity on music reward. Specifically, in Study 3 we examined the role of curiosity in driving music-related exploratory behaviors. Curiosity, or at least a non-instrumental form of music-related information seeking, was already considered in the BMRQ through the *Musical Seeking* facet, which included items such as “*I inform myself about the music I like*” or “*I’m always looking for new music*”. However, we suspected that people tend to overestimate their willingness to engage in demanding exploration of new songs, genres, or artists. In many cases, what individuals consider exploration is limited to passive behaviors, such as relying on YouTube’s algorithm to recommend new songs, which rarely deviate from the user’s preferred styles.

Therefore, using an experimental approach, we aimed to obtain an objective measure of curiosity and information seeking, computing the value individuals assign to discovering new music. In other words, we sought to determine the extent to which participants were willing to sacrifice money (i.e., their willingness to pay, WTP) for exploring new music. To that aim, and constituting one of the hardest methodological challenges and strongest points of the present thesis, we developed a new experimental paradigm. Our main source of inspiration was the task developed by Blanchard et al. (2015, see also Deaner et al., 2005) to measure the value monkeys assigned to information. In this case, monkeys had to choose between informative and uninformative options each one associated to a different amount of water. In our case, in order to test exploration behavior in the context of music, we presented participants with two options, either listening to their favorite songs or new, unreleased electronic music (to which they had been pre-exposed for 10-seconds just before the decision). In experimental design terms, the choice to use unreleased electronic music was straightforward for two reasons: it ensured novelty, a key element to promote exploration, and it lacked lyrics, which was crucial for the surprise memory test administered the following day. However, selecting the alternative option posed a greater challenge. We needed to ensure that the songs were familiar to the participants to prevent exploratory behavior. Several studies with similar constraints used songs in top-ten charts (Ferreri et al., 2019, 2021). However, there was a risk that participants did not like mainstream music and, consequently, chose the exploration option not as a result of their curiosity, but as a way to avoid listening to the songs presented in the alternative option. Therefore, we decided to use participants’ favorite songs, thus turning the task into a kind of exploration-exploitation paradigm. By using favorite songs, we added an extra challenge to the task since, in trials in which exploring entailed a monetary sacrifice (i.e., when the monetary reward associated to the

exploration option was lower than the one associated to the favorite option), curiosity had to compensate not only for the monetary cost but also for the guaranteed musical reward provided by the favorite song.

Another key consideration when developing the task was determining the minimum number of trials needed to accurately generate a psychometric function for each participant without making the task excessively long. We first had to identify both the number of differential values and the specific values required to construct the psychometric function. We needed values that would undoubtedly lead participants to choose the most rewarding options, as well as intermediate values where participants might consider sacrificing money to pursue their curiosity. To that end, we selected seven differential values (i.e., -5, -2, -1, 0, 1, 2, and 5 euros). Next, we needed to decide the number of trials per differential value. The more trials, the more accurate the psychometric function but the longer the task. We ultimately determined that five trials per differential value would provide the right balance between accuracy and task duration.

Therefore, in Experiment 1 from Study 3, sixty-three participants performed this exploration-exploitation tradeoff paradigm in a laboratory setting. The first important outcome was the success of the task itself: we were able to reconstruct psychometric functions and, through the application of mixed models, we were also able to assess the influence of curiosity on willingness to pay (WTP). Furthermore, we managed to elicit sufficient curiosity for participants to be willing to sacrifice some money. Beyond the methodological success, the task yielded some interesting results. We demonstrated that subjective feelings of curiosity, as reported by participants using a 7-point Likert scale right after the 10-secs preview, significantly influenced their WTP for exploring new music. In other words, heightened music-induced curiosity states enhanced exploratory behavior. This was in line with Kang et al. (2009), who showed a strong correlation between subjective curiosity ratings and participants' willingness to spend limited tokens and time. In this vein, a key contribution of our research lies in our use of money – a tangible resource with real-life instrumental value – to quantify the objective value of curiosity. By testing whether the curiosity reported by participants translated into a willingness to sacrifice resources, we observed how curiosity is not merely a subjective feeling but can have measurable economic implications.

Furthermore, we observed that the effect of curiosity on WTP was stronger when exploration involved monetary losses rather than gains, suggesting that exploring new music offers an intrinsic reward that compensates for monetary sacrifices.

Finally, another relevant finding of this experiment was how individual differences in musical hedonia modulated the effect of curiosity on WTP. Specifically, we observed that high musical hedonics opted to exploit rather than explore when curiosity was low, potentially sacrificing a larger monetary reward. This effect might be explained by an increased capacity in this group to decode pleasure from music, so that the most musically rewarding option would hold greater subjective value than the most monetary rewarding one. More broadly speaking, this confirms the importance of reliable measures of individual profiles to accurately capture the diverse ways in which people value and engage with musical experiences, as well as to better understand how these preferences influence decision-making in contexts involving monetary and abstract rewards.

However, one limitation of this experiment is that it was conducted in a highly controlled laboratory setting. It has long been discussed that, in many cases, models developed under particular experimental manipulations fail to capture much variance outside the context of that manipulation (Nastase et al., 2020). Consequently, over the years, there has been a growing interest on using naturalistic and ecologically valid approaches in neuroscience (see Cameron et al., 2022; Chabin et al., 2022; Czepiel et al., 2023). These approaches are particularly valuable in the music research field as they allow for the study of music's emotional impact within its natural complexity (Tervaniemi, 2023).

7.2 From lab to real life

As pointed out by Tervaniemi (2023), research in the neuroscience of music started within the confines of controlled laboratory settings, predominantly focusing on auditory modalities. However, in recent years, there has been a notable shift towards adopting methodologies that align with naturalistic and ecologically valid approaches in neuroscience. This transition is exemplified by studies examining physiological responses (Czepiel et al., 2023), body movements (Cameron et al., 2022), and interpersonal neural synchronization within the audience (Chabin et al., 2022) during live music concerts. Studying music reward mechanisms in naturalistic settings might therefore offer a unique perspective to the complex, rich musical affective experience.

7.2.1 Music curiosity in an electronic music festival

Considering the limitations of laboratory settings and aiming to investigate music curiosity in real-life scenarios, in Experiment 2 from Study 3 we adopted a naturalistic approach to test whether the strong influence of curiosity on exploratory behaviors observed in the laboratory would hold

in a real-world music event. To this end, we collaborated with the Sónar electronic music festival in Barcelona and organized a live DJ set where one hundred and fifty participants engaged in an experiment while listening to new, unreleased electronic music. Given the complexity of the ecological setting, we were compelled to simplify the task. The main difference from the laboratory version was how we measured the willingness to pay. While in the lab experiment participants chose between two options, each one associated with a monetary reward, in the naturalistic setting we created a virtual currency called Sónar coins, which participants could use to purchase the tracks (i.e., add them to a personalized playlist) or access exclusive track- or artist-related information. Importantly, to avoid the confounding effects of sequentiality, we used a lottery strategy, similar to the one employed in the lab experiment. Another critical adjustment was the timing of subjective curiosity assessments. Asking participants about their curiosity after only ten seconds of listening, as we did in the lab, would not only have been unnatural in a real DJ set context but would also likely have led to distractions or delayed responses, making the responses non-comparable across subjects. Instead, we asked participants to rate their curiosity after approximately one minute, giving them enough time to listen to the music piece and ensuring that everyone had a similar amount of information about its evolution before providing their ratings. With these adjustments, we ended up with a task where participants used their smartphones to rate their subjective feelings of curiosity (on a 1-to-7 Likert scale) and indicate their WTP after listening to one minute of each track.

Similar to the laboratory findings, the results revealed that music-induced curiosity significantly enhanced exploratory behavior in a real-world context. This is particularly noteworthy given the inherent complexity of natural settings, which include numerous distractors and confounders. Additionally, there was a risk that after listening to a full minute of each track, curiosity might be satiated, thereby ruling out any potential effect on WTP, but this was not the case.

Remarkably, we were also able to predict participants' choices in the real-world environment based on the laboratory data. Specifically, a classifier trained on laboratory data predicted with a 76% accuracy participants' choices in the natural setting based on their subjective curiosity ratings, demonstrating the robustness of the observed effects across different environments. Overall, this suggests that, despite the inherent limitations posed by the noisy environment, reliable experimental observations can still be achieved in real-world settings. Consequently, this provides new support for the feasibility of conducting music research outside the confines of the laboratory.

Differently from the laboratory experiment, however, we did not observe that individual differences in electronic liking and musical hedonia modulated the curiosity-driven effect on

participants' choices. A possible explanation for this discrepancy lies in the differences between experimental paradigms. As mentioned earlier, in the naturalistic setting participants rated their curiosity and made the exploration/exploitation choice after the pre-exposure phase. Consequently, ratings and choice were likely influenced by participants' prior knowledge and general relationship with music (e.g., musical hedonia). In contrast, in the real-life setting, participants rated the music after listening to the whole excerpt played by the DJ, thus providing a retrospective judgement. In this case, the exposure to the specific excerpts and their evolution over time might have played a main role in influencing participants' a-posteriori choice, thus reducing the impact of subjective prior knowledge and predictions (Omigie & Ricci, 2022).

In summary, the findings in Study 3 emphasize the powerful role of curiosity in driving exploratory behavior. Importantly, we provided evidence supporting the comparability between controlled laboratory conditions and more complex, real-world settings. From a music market perspective, these findings could have practical implications, for example, in the design of music recommendation algorithms on platforms like Spotify or Youtube. By incorporating users' musical hedonia profile and their curiosity for exploring new music, platforms could offer more personalized recommendations that strike a balance between novelty and familiarity.

One potential criticism of the two experiments included in Study 3 is the uncertainty about what was actually being measured – was it truly curiosity, or would similar results have been observed if participants had rated pleasure instead? In our opinion, the task clearly measured curiosity. During the instructions, participants were explicitly told they would rate their curiosity on a 7-point Likert scale, where a rating of 1 indicated that they would not mind if the music stopped playing immediately, while a rating of 7 indicated that they were very curious about how the music would unfold over time. Furthermore, from a theoretical perspective, curiosity and pleasure are clearly distinguishable constructs. Pleasure is primarily an emotional construct, whereas curiosity is a mixed construct involving both emotional and cognitive aspects. Besides, while pleasure is usually associated to consummatory states (i.e., *liking* according to Berridge's framework; Berridge et al., 2009), curiosity is rather linked to anticipation states (i.e., *wanting*). However, this waiting period during curiosity states usually entails savoring, an inherently rewarding experience (Ilgaya et al., 2016; Loewenstein, 1987; Zhu et al., 2017). Therefore, we cannot completely rule out the possibility that participants may have used the anticipation of pleasure, or even the experienced pleasure, to compute their curiosity ratings. Despite humans use both concepts in different moments and situations, suggesting their potential validity of their use in scientific research, further research is needed to clarify the conceptual differences between them and address any reliability issues concerning what these measures capture.

7.2.2 The link between musical pleasure and curiosity: a symphonic experiment

As a follow-up experiment and in order to address any doubts about participants' ability to differentiate between the two constructs, we designed Study 4. In this study, two groups of participants continuously rated either curiosity or pleasure for the same stimulus at the same time.

The main aim of this study was to explore the temporal dynamics and potential interaction between music-induced pleasure and curiosity. Most studies investigating curiosity have traditionally employed discrete and brief pieces of information, such as trivia questions (Gruber et al., 2014; Kang et al., 2009), blurry photos with ambiguous content (Jepma et al., 2012), or lottery trials (Kobayashi et al., 2019; Van Lieshout et al., 2018). These designs lead to a rapid satiation and extinction of curiosity, failing to capture its temporal aspect. To address this, in Study 4 we capitalized on the temporal evolution of music to study curiosity in a more comprehensive way. Moreover, based on previous research suggesting that curiosity may act as an anticipatory state of reward (Kang et al., 2009; Marvin & Shohamy, 2016), we explored the temporal interplay between curiosity and pleasure. Additionally, since pleasure tends to increase with familiarity and curiosity tends to decrease once the knowledge gap is closed, we assessed how the dynamics changed after music-related information gain.

To that aim, we conducted an experiment in a unique music-and-science pedagogical event. Six hundred and sixty participants continuously rated their levels of pleasure or curiosity while listening to a 10-minute classical music piece performance. They did it twice, once at the beginning and again at the end of the event, after receiving extensive information about the piece. In addition, participants filled out a series of questionnaires, including the eBMRQ.

The study's findings revealed that during the first listening, curiosity emerged before pleasure, suggesting that curiosity may influence pleasure. This was supported by the Granger-causality analysis, which indicated that curiosity preceded pleasure by two seconds. However, during the second play, after information gain (i.e., a detailed explanation of the music piece and neuroscientific information about music and the brain), this dynamic reversed – pleasure preceded curiosity with a three-second lag. This shift suggests that initial curiosity leads to pleasure, which is then enhanced by additional information, fostering further curiosity.

When examining the impact of information, we found that curiosity levels remained stable after participants received detailed information about the music (i.e., large information gain), while pleasure levels significantly increased during the second listening. This resistance of musical curiosity to satiation was unexpected to us and contrasts with traditional views stating that

curiosity diminishes once sufficient information is obtained (Lowenstein, 1994). Several factors may explain this phenomenon. One is the inherent complexity of music, with its multiple layers and evolving structure, which makes it difficult for listeners to fully grasp all its nuances in a single exposure. As a result, during subsequent exposures, a significant degree of uncertainty remains, leading to only partially accurate predictions, thus generating prediction errors that sustain curiosity. Another factor could be the listeners' reassessment of their ability to understand the piece. According to Gruber and colleagues (2019), context- and information-based prediction errors trigger an appraisal process so that curiosity is only induced when individuals believe they are able to cope with the uncertainty. In this case, the information provided by the Orchestra director may have reassured listeners on their ability to cope with all the information contained in the music, thus enhancing curiosity. Additionally, learning may also contribute to this lack of satiation. The learning progress hypothesis suggests that, during learning, when the brain detects an improvement, it provides intrinsic rewards that reinforce curiosity and drive further information seeking (Gottlieb & Oudeyer, 2018; Oudeyer et al., 2007; Schmidhuber, 1991). In this case, listeners' ongoing learning about the music and testing of new prediction errors may have triggered continuous internal rewards, creating a positive feedback loop between reward and curiosity that prevented satiation. Thus, the combination of complexity, updated appraisal, and the reinforcing nature of learning may have contributed to these interesting findings.

Study 4 uncovered a nuanced relationship between curiosity, pleasure, and information processing in the context of music listening. Additionally, the findings highlighted the resilience of musical curiosity to satiation and underscored the importance of individual differences in musical hedonia in shaping the experiences of both curiosity and pleasure.

Summing up, the three-way approach used in this thesis – combining psychometric, experimental, and naturalistic methodologies – provided new insights on the complexity of musical reward, which can only be understood by considering the different constructs that shape the emotional musical experience, both in laboratory and naturalistic settings. Based on previous literature, it is clear that music is a stimulus capable of activating ancient brain circuits and mechanisms linked to survival. As suggested by Goupil and Aucouturier (2019), the critical research question now is not whether music is rewarding, but why. In recent years, a growing body of research has explored the link between dopaminergic responses to rewarding stimuli and cognitive aspects. This evidence indicates that reward mechanisms are not only important in their own right but serve as crucial triggers for storing and recalling information, making them essential for memory and learning processes. Accordingly, recent research in music cognition has proposed that music

reward might play a central role in music-driven memory performance. This thesis has built on this idea, providing new insights into the relationship between reward and memory.

7.3 The influence of musical pleasure and curiosity on memory

Extensive research has demonstrated that rewarding stimuli can promote memory consolidation and enhance information recall (Adcock et al., 2006; Gruber et al., 2014; Shohamy & Adcock, 2010; Wittmann et al., 2005; Wolosin et al., 2012). This effect has been attributed to the interaction between midbrain dopaminergic regions – including the substantia nigra/ventral tegmental area complex (SN/VTA) – and the hippocampus (Goto & Grace, 2005; Lisman et al., 2011; Lisman & Grace, 2005). According to the neo-Hebbian framework for episodic memory (Lisman et al., 2011), reward-driven dopamine release in the hippocampus would strengthen synaptic long-term potentiation, thus promoting long-term memory formation (Schultz, 2002) and consolidation (Chowdhury et al., 2012). This effect has been observed with tangible rewards, such as money (Adcock et al., 2006; Wittmann et al., 2005; Wolosin et al., 2012), as well as more abstract rewards, like music or states of curiosity (Ferreri, Mas-Herrero, et al., 2021; Gruber et al., 2014).

Interestingly, these improvements can be observed not only for the rewarding stimulus itself, but also for associated non-rewarding information (Gruber et al., 2014). This phenomenon, known as the penumbra effect, can be explained by the Behavioral Tagging hypothesis (Duncan et al., 2012; Lisman et al., 2011). According to this hypothesis, a short-lasting memory triggered by a weak event can be consolidated into a long-term memory if it occurs close in time to an independent strong event, that is, a novel or rewarding stimulus inducing dopamine release. At a cellular level, weak potentiation sets a tag at a specific synapse, creating a short-term memory trace that is sensitive to further potentiation. A strong event upregulates the availability of plasticity-related proteins (PRPs), which stabilize the local tags created by the weak event. If the PRPs are released while the local tag is still active, the tag will capture the PRPs, thereby strengthening memory via long-term potentiation.

Building on this evidence, we explored whether music-induced pleasure and curiosity can facilitate the recall of both musical and non-musical (i.e., non-rewarding), associated information.

7.3.1 Musical pleasure enhances memory for music

In 2017, Ferreri & Rodriguez-Fornells provided the first experimental evidence on the impact of musical pleasure on memory for music. In their study, participants listened to classical music

excerpts and rated, among others, the amount of pleasure experienced. Twenty-four hours later, participants' memory was tested using the recognition-recollection paradigm (Yonelinas, 2002). Results revealed that musical excerpts rated as more pleasurable were better remembered the next day (Ferrerri & Rodriguez-Fornells, 2017). Furthermore, participants with higher musical hedonia demonstrated improved recollection performance.

In a follow-up study, Ferrerri et al. (2021) explored the neurochemical brain mechanisms underlying this effect using a double-blind, within-subject pharmacological study involving levodopa (i.e., a dopamine precursor), risperidone (i.e., a dopamine antagonist), and placebo. They found that the effect of reward on memory was modulated by both dopaminergic signaling and individual differences in musical hedonia. Specifically, greater pleasure was consistently associated with improved recollection in participants with high sensitivity to musical reward, but this effect was lost when dopaminergic signaling was disrupted in participants with average or low musical hedonia.

To sum up, these two studies provided the first experimental evidence of a direct implication of music reward in memory formation by reliably showing: i) that musical pleasure can drive memory benefits, and ii) that this effect is modulated by synaptic dopaminergic availability as well as individual differences in musical hedonia.

In Study 4, we attempted to replicate these results outside the laboratory. Specifically, twenty-four hours after the music-and-science event, participants performed a recognition-recollection memory task. Results indicated that higher average pleasure ratings during the initial performance (i.e., Play 1) were associated with better recognition. Additionally, participants with higher musical hedonia exhibited enhanced recognition performance. These findings are crucial, as they further confirm that laboratory data can be replicated in real-life, ecological settings not only for affective-reward responses (as previously discussed for curiosity-driven exploratory behavior) but also for cognitive processes related to information storage and recall.

It is noteworthy, however, that while musical pleasure and musical hedonia significantly predicted memory performance, in this study they influenced recognition rather than recollection, which contrasts with previous findings (Ferrerri & Rodriguez-Fornells, 2017; Ferrerri, Mas-Herrero, et al., 2021). This discrepancy highlights the importance of the methodological setting and paradigm. Unlike typical laboratory studies, Study 4 assessed memory for a single 10-minute musical excerpt, rather than multiple shorter excerpts lasting around 30 seconds each. This change in design may have altered access to stored information, potentially hindering recollection performance. Therefore, these findings should be interpreted with caution.

While these studies provided compelling evidence on the positive impact of musical pleasure on memory for music itself, it remained unexplored whether musical pleasure could also affect memory for concurrently present, nonmusical material. Previous studies on music's influence on verbal memory had yielded contradictory results. Some studies suggested that music attracts participants' attention away from the information to be remembered (Ferreri et al., 2015; El Haj et al., 2014), while others indicated a beneficial effect (Ferreri et al., 2013; Goupil & Aucoeur, 2019; Moussard et al., 2012; Thaut et al., 2005; Wallace, 1994).

7.3.2 Does the positive effect of musical pleasure on memory extend to non-musical information?

To shed some light into this conundrum, in Study 1 we investigated whether musical reward, represented by both the pleasure induced by the music itself and participants' ability to extract reward from music (i.e., participants' musical hedonia), would improve memory for nonmusical, associated information. To that aim, participants encoded lists of words in three different auditory contexts: highly pleasant music, lowly pleasant music, and white noise. Twenty-four hours later, their memory for the encoded words was tested with a recognition-recollection paradigm. In addition, participants completed the BMRQ. Results revealed that both musical pleasure and musical hedonia positively influenced verbal episodic memory. In particular, more hedonic participants showed an enhanced recollection, especially when musical excerpts were highly pleasant.

Various mechanisms have been proposed to explain music's beneficial effect on verbal memory including the generation of a temporal scaffolding network that supports sequence learning, changes in listeners' arousal or mood, and induction of emotional states that activate the reward system (Ferreri & Verga, 2016). Study 1 provides the first evidence that this effect is driven (at least in part) by musical reward, particularly musical pleasure and individuals' musical hedonia. Crucially, our findings suggest that participants' musical hedonia may be critical in determining whether music will positively impact their memory or not, providing a potential explanation for the mixed results found in previous literature.

In Study 1 we additionally investigated whether the positive effect of musical pleasure persists even when music is not concurrently present during encoding. In other words, we assessed whether musical pleasure exerted a penumbra effect (Duncan et al., 2012; Lisman et al., 2011). To that end, we manipulated the duration of the auditory stimuli during encoding, with music played either before and during, or only before the encoding. Results showed no significant differences in memory performance between the two auditory background conditions, thus suggesting the

presence of a penumbra effect. However, because strong events have been seen to rescue weak memories both proactively (up until 2-3 hours afterwards) and retroactively (up to 1 hour before; see Dunsmoor et al., 2022, for a recent review on the penumbra effect), the experimental design did not allow us to determine which stimuli acted as strong events strengthening weak memory traces (i.e., words). Therefore, further experiments should be performed to investigate whether the penumbra effect was dependent on the pleasantness of the stimuli or not. Despite this limitation, the study indicates that for more hedonic participants, the positive effect of music extends to non-musical, unrelated material even when it is not concurrently present.

Therefore, Study 1 provided valuable insights into the role of music in enhancing memory for nonmusical information, suggesting that such effect relies on reward and highlighting the importance of accounting for participants' musical hedonia. The present findings suggest that music could be effectively used in memory-enhancing interventions for individuals with an increased ability to extract reward from music. This opens promising avenues for memory stimulation and rehabilitation protocols, such as those targeting healthy and pathological aging, where tailoring music interventions to individual profiles could lead to more reliable and positive outcomes.

As previously discussed, curiosity processes can significantly influence musical pleasure. Furthermore, several studies have reported that curiosity enhances memory, not only for the study object itself but for related information as well, via the activation of the dopaminergic reward system (Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016). Therefore, a natural next step would be to test whether not only musical pleasure, but also musical curiosity might impact memory formation.

Accordingly, in Studies 3 and 4 of the present thesis we explored the effect of musical curiosity on memory for both the music itself and related information.

7.3.3 Studying the effect of musical curiosity on memory

In Study 3, we assessed whether subjective curiosity ratings for new, unfamiliar electronic music excerpts could predict successful memory retrieval. Additionally, we explored the effect of musical hedonia and electronic music liking on memory performance. These effects were investigated in both laboratory and natural settings (Experiments 1 and 2, respectively). In both experiments, participants completed a recognition-recollection task twenty-four hours after performing the curiosity trade-off task or attending the event, respectively. In the laboratory setting, results showed that curiosity ratings significantly predicted whether the excerpt would

be successfully recognized and remembered. That is, the higher the curiosity, the higher the probability of not only recognizing but also having episodic memory traces. In the natural setting, results revealed that the effect of curiosity on memory was dependent on electronic music liking. Specifically, only electronic music fans better recognized those songs they were curious about.

These findings are in line with extensive research reporting memory enhancements for stimuli participants are particularly curious about. Notably, curiosity-driven memory improvements have been observed in both immediate (Galli et al., 2018; Gruber et al., 2014; Stare et al., 2018; Wade & Kidd, 2019) and delayed (from hours to weeks) memory tests (Fastrich et al., 2018; Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016; Stare et al., 2018).

Importantly, and differently from pleasure-related findings, Study 3 results showed that curiosity did not only improve recollection, an hippocampal-dependent process, but also recognition, rather linked to regions surrounding the hippocampus such as the perirhinal and entorhinal cortices. Studies in primates have identified selective responses to novelty in the anterior ventral medial temporal cortex, in the perirhinal cortex (Fahy et al., 1993; Ogasawara et al., 2022; Xiang & Brown, 1998), as well as in the hippocampus and the amygdala (Rutishauser et al., 2006; Wilson & Rolls, 1993). This suggests that curiosity, which is closely related to novelty, might activate medial temporal lobe structures above and beyond the hippocampus, thus enhancing both recognition and recollection performance.

In Study 4, we attempted to replicate these findings. In this case, mean curiosity ratings reported during the initial performance (i.e., Play 1) did not significantly influence memory performance. However, as also discussed for pleasure results, these null results should be interpreted with caution since, given the limitations imposed by the real-life approach, the experimental design was not optimal for assessing memory performance.

To explore the potential effect of musical curiosity on related nonmusical information, Study 4 evaluated whether the subjective curiosity experienced during Play 1 influenced participants' performance on a multiple-choice test performed 24 hours after the event. However, probably due to the outstanding performance of our participants on the memory test, no significant results were found. Although the effect of curiosity on memory is consistently replicated in music cognition studies conducted in laboratory settings, naturalistic environments require further consideration regarding the selection of stimuli and testing methods to properly capture these effects. Future research should focus on refining stimuli design and assessment techniques to better isolate and measure the influence of curiosity in ecologically valid contexts.

Taken together, our findings suggest that musical reward encompasses more than just pleasurable feelings; it also exerts a significant positive impact on cognition, particularly long-term memory. Moreover, this effect appears to be similar to the one driven by curiosity. These results raise important questions about the mechanisms underlying this beneficial effect of both music-induced pleasure and curiosity on memory. Some theories have been proposed in this regard. One possible explanation involves reward prediction errors (RPEs). Both theoretical and experimental evidence suggests that musical pleasure arises from the generation of expectations and predictions during music listening. In this view, music-induced pleasure feelings might be driven by the intrinsic value of successfully anticipating (or not) musical events. Accordingly, Gold and colleagues (2019) provided the first evidence that activation of the NAcc is triggered by musical RPEs signaling the difference between expected and perceived events during music listening. Similarly, curiosity has been proposed to be triggered by significant prediction errors (PEs; Gruber & Ranganath, 2019; Marvin & Shohamy, 2016). In turn, RPEs have been suggested to play a role in episodic memory formation through the activation of the ventral striatum (Calderon et al., 2020; Ergo et al., 2020; Jang et al., 2019).

Interestingly, Gold et al. (2019) also found a significant positive relationship between BMRQ scores and RPE signaling in the right NAcc, with less hedonic participants generally reflecting musical RPEs less reliably. This suggests that, consistent with our findings, higher musical hedonics may be better at encoding RPEs, potentially leading to enhanced episodic memory performance.

However, our paradigms do not allow us to directly confirm or rule out this theory. Future research should explore these mechanisms in more depth to better understand the role of RPEs in the link between musical pleasure, curiosity, and memory.

7.4 Future directions

Overall, the present thesis explored new, innovative ideas regarding the role of absorption and curiosity in shaping musical reward and memory processes. Throughout this discussion, I have underscored both the strengths and limitations of the conducted studies, emphasizing the need for further research and refined methodological approaches when methodological constraints or difficult-to-interpret results emerged. Looking ahead, I believe the most important next step involves integrating specific neural data with the behavioral observations presented in this thesis. This would provide a deeper understanding of the mechanisms underlying the findings and offer a more comprehensive view of the phenomena under investigation.

Due to the great effort involved in designing new paradigms to test these ideas, we were not able to further explore the underlying neural mechanisms supporting these processes. However, we believe the paradigms we developed could be readily adapted for their use with hemodynamic (e.g., fMRI) or electrophysiological techniques to examine the spatial and temporal dynamics of music-induced curiosity and reward processes. For instance, an fMRI task using the exploration-exploitation tradeoff paradigm developed in Study 3 could provide valuable insights into the roles of cortical music-related regions and reward centers in the elicitation of musical curiosity. In addition, it would be important to clarify which regions support both music reward and curiosity states, while distinguishing them from regions involved in information seeking and decision-making. In a further stage, it would be relevant to investigate the causal role of dopamine in eliciting music-related curiosity and reward. This could be done through psychopharmacological interventions (Ferreri et al., 2019) or PET studies (Salimpoor et al., 2011), which could shed light on dopamine dynamics in these emotional and cognitive states. From a temporal perspective, and specifically focusing on the outcomes in Study 4, electroencephalographic measures would be particularly useful to further explore the temporal evolution and interaction between curiosity and pleasure. For example, tracking event-related potentials (ERPs) such as the feedback-related-negativity (FRN), P3, the late-positive-potential (LPP), and beta oscillatory activity (Alicart et al., 2020; Rüterbories et al., 2024) might help capture the neural correlates of curiosity, while simultaneously monitoring theta frontotemporal oscillations (Ara & Marco-Pallarés, 2020) might shed light on how pleasure unfolds over time in response to music.

Given the evidence in Study 2 suggesting that the deep involvement achieved during absorption states could play a crucial role in how we process and derive pleasure from music, it would also be interesting to explore these immersive states during music listening by combining subjective self-report measures with neuroimaging techniques (such as fMRI) and physiological monitoring (e.g., heart rate variability and skin conductance). This approach would allow for a more precise experimental assessment of the connection between music-induced immersive experiences and the activation of reward processes, thus offering greater clarity on how absorption contributes to musical reward.

Another critical line for future research should focus on translating these findings into practical applications. This could involve leveraging the insights gained from the relationship between musical reward, curiosity, and memory to enhance cognitive and emotional outcomes in therapeutic settings. It is well established that engaging in rewarding and pleasurable experiences during therapy can enhance its success rate, making music a promising tool for clinical purposes. Indeed, music has been shown to be effective in various therapeutic contexts, including mental

health treatment and rehabilitation. For instance, a recent clinical trial conducted in our group (Segura et al., 2024) demonstrated the effectiveness of music-supported therapy for motor rehabilitation in chronic stroke patients. Accordingly, this line of research may reveal new ways to optimize interventions for conditions where reward processes are crucial, such as depression, anxiety, and neurodegenerative disorders. We believe including the concepts studied in this thesis – such as absorption, curiosity, exploration, information-seeking, and pleasure – will offer novel perspectives and approaches in clinical settings, raising new questions and enhancing music's potential to improve the outcomes of interventions across various clinical domains.

Conclusions

8 Conclusions

This PhD work aimed to deepen our understanding of music reward by exploring how it is influenced by absorption and curiosity, and by further investigating its impact on learning and memory. The findings in this thesis open new perspectives on music reward by suggesting that multiple processes influence how we experience and derive pleasure from music. First, we demonstrated that, in addition to emotional evocation, mood regulation and other previously described factors contributing to the multifaceted nature of music reward, absorption states constitute an important factor influencing individuals' relationship with music. Then, we investigated curiosity and provided compelling evidence on its significant influence on reward by showing how musical curiosity drives exploration even at the expense of tangible rewards. Finally, we proposed a new line of research investigating the complex interplay between music-induced pleasure and curiosity over time, offering preliminary evidence of an interdependence between the two that may evolve as the stimulus becomes more familiar.

Importantly, we extended our research beyond the controlled laboratory conditions to more complex, real-world environments, thereby increasing the ecological validity of our findings. This approach allowed us to observe how music-induced pleasure and curiosity operate in natural contexts, enriching our understanding of these phenomena.

Additionally, we expanded the research on the positive effect of musical reward on episodic memory by demonstrating that this effect not only applies to music itself but also transfers to non-musical, verbal material. In the same vein, we showed that reward-related processes, such as musical curiosity, also shape the encoding and retrieval of information.

Finally, this thesis also underscored the crucial role of individual differences in shaping how curiosity and pleasure affect musical experiences. Our findings revealed that individual differences in musical hedonia modulate the levels of curiosity and pleasure experienced, as well as their influence on memory. These results emphasize the need for reliable measures of individual profiles to fully capture the diverse ways people value and engage with musical experiences.

Overall, we hope that the findings in this thesis encourage researchers to further investigate the intricate dynamics of musical reward, particularly by examining the interaction between pleasure, curiosity, and memory. Exploring these interactions across different contexts and individual differences could offer deeper insights into the cognitive and emotional processes that underlie our relationship with music, thus opening new paths for educational and clinical interventions.

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Appendix



OPEN

The impact of musical pleasure and musical hedonia on verbal episodic memory

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Music listening is one of the most pleasurable activities in our life. As a rewarding stimulus, pleasant music could induce long-term memory improvements for the items encoded in close temporal proximity. In the present study, we behaviourally investigated (1) whether musical pleasure and musical hedonia enhance verbal episodic memory, and (2) whether such enhancement takes place even when the pleasant stimulus is not present during the encoding. Participants (N = 100) were asked to encode words presented in different auditory contexts (highly and lowly pleasant classical music, and control white noise), played before and during (N = 49), or only before (N = 51) the encoding. The Barcelona Music Reward Questionnaire was used to measure participants' sensitivity to musical reward. 24 h later, participants' verbal episodic memory was tested (old/new recognition and remember/know paradigm). Results revealed that participants with a high musical reward sensitivity present an increased recollection performance, especially for words encoded in a highly pleasant musical context. Furthermore, this effect persists even when the auditory stimulus is not concurrently present during the encoding of target items. Taken together, these findings suggest that musical pleasure might constitute a helpful encoding context able to drive memory improvements via reward mechanisms.

Music has a strong emotional power. Accordingly, the most common goal of musical experience is related to music's ability to modulate emotional state in the listeners¹. Several studies have shown that, besides recreation, distraction or mood regulation, music-evoked emotions can also drive memory enhancements in both healthy^{2–4} and clinical^{5,6} populations. Most part of these studies focused on two crucial dimensions of musical emotions, namely arousal and valence⁷. In the present study, we aimed at studying the link between music, memory and emotion by focusing on a particular aspect of music-induced affective responses⁸: *pleasure*. Together with motivational and learning aspects, pleasure constitutes a crucial emotional component of reward processing⁹. Pleasure is a complex construct, particularly for humans who, in addition to primary (e.g., food) and secondary reinforcers (i.e., a reward with a learned value associated to a primary reinforcer, such as money), can also trigger rewards from internal mental states (e.g., flow and curiosity^{10,11}), intrinsic motivational processes^{12,13}, and more abstract rewards such as music and aesthetic appreciation¹⁴. Music-induced pleasure is strongly related to increases in physiological arousal, such as skin conductance responses (SCR) or heart rate¹⁵, and to the activity of core reward-related regions within the mesolimbic dopaminergic system^{16–21}. Interestingly, humans show music-specific hedonia (i.e., individual differences in sensitivity to musical pleasure, efficiently measured through the Barcelona Music Reward Questionnaire, BMRQ²²). While listening to music, high-musical hedonic individuals, compared to low- or to music anhedonics, report more intense feelings of pleasure. Furthermore, these subjective ratings are associated to higher SCR as well as higher brain activity and increased functional connectivity in several core regions of the human reward and dopaminergic system^{23,24}. Even though music does not provide direct survival advantages, it recruits brain networks similar to the ones activated by primary rewards, such as food or sex. This raises crucial questions about the nature and the possible implications of music hedonic signals.

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The forgotten role of absorption in music reward

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Abstract

Interindividual differences in music-related reward have been characterized as involving five main facets: musical seeking, emotion evocation, mood regulation, social reward, and sensory-motor. An interesting concept related to how humans decode music as a rewarding experience is music transcendence or absorption (i.e., music-driven states of complete immersion, including momentary loss of self-consciousness or even time-space disorientation). Here, we investigated the relation between previously characterized facets of music reward and individual differences in music absorption. A first sample of participants ($N = 370$) completed both the Barcelona Music Reward Questionnaire (BMRQ) and the Absorption in Music Scale (AIMS). Results showed that both constructs were highly interrelated ($r = 0.78$, $p < 0.001$), indicating that higher music reward sensitivity is associated with a greater tendency to music-related absorption states. In addition, four items from the AIMS were identified as suitable to be added to an extended version of the BMRQ (eBMRQ). A second sample ($N = 550$) completed the eBMRQ for a validation study. Exploratory and confirmatory factor analyses on the whole sample ($N = 920$) showed the reliable psychometric properties of the eBMRQ and suggested that taking into account an absorption facet could contribute to a better characterization of individual differences in the sensitivity to experience music-related reward and pleasure.

KEYWORDS

absorption, music, reward, transcendence

INTRODUCTION

Music has an inherent capacity to evoke a rich and meaningful landscape of emotions and feelings in humans. As such, it is efficiently used across cultures and ages as a powerful mood regulator.^{1–9} In special or extraordinary circumstances, people might experience strong peak emotional experiences during music listening and some of them could be associated with transcendence or absorption states.¹⁰ Absorption

is usually described as “an effortless, non-volitional quality of deep involvement with the objects of consciousness,”¹¹ in which attention becomes deeply focused and narrowed, thus lessening awareness of internal states or external conditions.¹² In these states, a person might feel like being merged with something bigger (sometimes materialized as an attentional-capture process, harmony/diffusion with the environment or the universe, experiencing joy, peace, ecstasy, and more complex emotions) or that goes beyond what is considered

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