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Anticipatory and consummatory neural correlates of monetary and music rewarding stimuli

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ABSTRACT

Most of the literature on the neural bases of human reward and punishment processing has used monetary gains and losses, but less is known about the neurophysiological mechanisms underlying the anticipation and consumption of other types of rewarding stimuli. In the present study, EEG was recorded from 19 participants who completed a modified version of the Monetary Incentive Delay (MID) task. During the task, cues providing information about potential future outcomes were presented to the participants. Then, they had to respond rapidly to a target stimulus to win money or listening to pleasant music, or to avoid losing money or listening to unpleasant music. Results revealed similar responses for monetary and music cues, with increased activity for cues indicating potential gains compared to losses. However, differences emerged in the outcome phase between money and music. Monetary outcomes showed an interaction between the type of the cue and the outcome in the Feedback Related Negativity and Fb-P3 ERPs and increased theta activity increased for negative feedbacks. In contrast, music outcomes showed significant interactions in the Fb-P3 and theta activities. These findings suggest similar neurophysiological mechanisms in processing cues for potential positive or negative outcomes in these two types of stimuli.

1. Introduction

Animals' goal-directed behaviour is guided by the search and consumption of rewarding stimuli and the avoidance of harmful ones. These decisions are based on the previous learning of cues and the consequences of the pursued actions, enabling adaptation to uncertain scenarios. Some influential accounts have proposed that reward can be dissociated in "wanting" (motivation to obtain the desired stimuli), "liking" (hedonic value of the rewarding stimuli) and "learning" (Pavlovian associations and cognitive representations; Berridge et al., 2009; Berridge and Robinson, 2003). These psychological mechanisms interplay in both the anticipation and outcome phases. In fact, anticipatory stages allude to all cognitive and motor operations required for the obtention of the desired reward ("wanting"), shaping expectations and future decisions ("learning"; Berridge and Kringelbach, 2015). In contrast, consummatory phases refer to outcome processing ("liking"), which reinforces behaviours based on prediction error ("learning"; Berridge and Kringelbach, 2015). Hence, reward processing is not a unitary mechanism, but a multifactorial construct with two distinct temporal stages, which involves concomitant psychological mechanisms (Berridge and Kringelbach, 2015; Glazer et al., 2018; Meyer et al., 2021). Even when they often appear mixed, each of these stages and psychological processes has been associated with distinct neural mechanisms and neurotransmitters (Berridge et al., 2009; Berridge and Kringelbach, 2015; Liu et al., 2011). Therefore, studying the reward phases is critical to understanding the different operations involved in the neural processing underlying this phenomenon.

In recent decades, several studies have delineated a common brain network involved in reward processing, which comprises the orbitofrontal cortex, striatum, insula and amygdala structures, among others (Liu et al., 2011; Sescousse et al., 2013). Nonetheless, evidence to date has shown some significant differences when contrasting anticipation

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and outcome reward phases (Liu et al., 2011; Oldham et al., 2018), type of delivered reward (Mas-Herrero et al., 2021; Sescousse et al., 2013) and valence of the outcome (favourable or unfavourable; Bartra et al., 2013; Fouragnan et al., 2018; Liu et al., 2011; Martins et al., 2021). In addition, EEG and MEG studies have described several Event-Related Potentials (ERPs) associated with reward processing (see Glazer et al., 2018, for review), most of them devoted to consummatory stages (Meyer et al., 2021), especially the Feedback-Related Negativity (FRN; Glazer et al., 2018). FRN is a frontocentral component that appears between 200 and 350 ms after feedback presentation and that has been reported as sensitive to valence of the outcome (favourable or unfavourable; Gehring and Willoughby, 2002; Hajcak et al., 2007; Miltner et al., 1997). Although initially it was proposed that this component was related to negative outcomes, different studies have found that it is modulated by the magnitude and the likelihood of appearance of the reward (Sambrook and Goslin, 2015), suggesting its involvement in reward prediction error computation. Nonetheless, an alternative explanation suggests that a positive reward, named reward positivity (RewP; Holroyd et al., 2008), is superimposed on the standard FRN and that, therefore, the reduction in the N2 observed in positive feedback would be the real reward effect (Holroyd et al., 2008; Proudfit, 2015). Following this component, a Fb-P3 at centro-parietal zones appears 300 to 600 ms after feedback presentation. This component has been found to be consistently sensitive to the probability and the magnitude of the outcome, although mixed evidence is found regarding valence and evaluation of performance (San Martin, 2012). These inconsistencies could possibly be explained by an overlap with FRN/RewP and the following Late Positivity Potential (LPP), making it difficult to isolate each component effect (Glazer et al., 2018). In contrast, anticipatory potentials related to cue processing (indicating possible future outcomes) have described mainly two ERPs: Cue-N2 and Cue-P3. Cue-N2 component appears at frontocentral zones 200 to 300 ms after cue presentation and has been associated with the valence of the cue, presenting more negativity on losing and neutral cues compared to winning ones (Novak and Foti, 2015). This reduced negative deflection for positive cues has been attributed to increased cognitive control and to expectation discrepancies (template mismatch; Glazer et al., 2018). Following this component, a centro-parietal Cue-P3 component is elicited 300 to 600 ms after cue presentation. In contrast to Cue-N2, Cue-P3 presents larger amplitude for both positive and negative compared to neutral conditions (Goldstein et al., 2006; Novak and Foti, 2015; Pfabigan et al., 2014), probably suggesting the allocation of attention to salient reward information (Novak & Foti, 2015). Finally, in those experimental paradigms that require a fast response after the cue, the Contingent Negativity Variation (CNV) ERP also shows motivational modulations associated with the valence of the potential outcome or the effort required to obtain it (Glazer et al., 2018).

In addition, despite the reduced number of studies addressing oscillatory components of reward processing compared to those analysing ERPs (Meyer et al., 2021), different frequency bands have been associated with reward processing. In particular, decreased alpha activity (Van Den Berg et al., 2014) and increases in beta activity (Bunzeck et al., 2011) have been described in reward anticipation. Besides, increased power in the beta-gamma frequency bands appears to be consistently associated with positive outcomes (Cohen et al., 2007; Cunillera et al., 2011; Marco-Pallarés et al., 2015; Mas-Herrero et al., 2015). This response appears 200 to 400 ms after the presentation of highly relevant or unexpected positive feedback (HajiHosseini et al., 2012) and might reflect the activation of frontostriatal areas involved in reward processing (Marco-Pallarés et al., 2015). Finally, theta oscillations have been related to outcome reward prediction error (Haji-Hosseini et al., 2012; Mas-Herrero and Marco-Pallarés, 2014), which, in turn, could prove sensitivity to valence (Marco-Pallares et al., 2008) and uncertainty (Cavanagh et al., 2012; Mas-Herrero and Marco-Pallarés, 2014).

Most of the above-mentioned results have been found by employing secondary (money) or abstract reinforcers (e.g., points). However, human beings, in contrast to most animals, are not only motivated by stimuli that have a clear role in accomplishing the Darwinian imperatives of survival (or which provide access to them), but also are eager to search for other complex stimuli such as social or aesthetic ones. Among the latter, music is present in every culture and is one of the most powerful sources of pleasure for most people, despite its apparent lack of utility in survival terms. Different studies have shown that pleasant music activates areas of the reward network (Blood and Zatorre, 2001; Martínez-Molina et al., 2016; Mas-Herrero et al., 2021). The experience of peak moments of music elicits release of dopamine in ventral striatum (Salimpoor et al., 2011). Interestingly, in a recent *meta*-analysis, Mas-Herrero et al. (2021) showed that listening to pleasant music not only activates areas of the reward network such as ventromedial prefrontal cortex, ventral striatum, and insula, but also engages areas associated with auditory perception and cognition, such as the superior temporal gyrus and inferior frontal gyrus. It is also important to note that music does not only present the hedonic properties, but also other components of reward processing. Therefore, it has been shown that music might elicit reward prediction errors in the Nucleus Accumbens, driving learning about consonant or dissonant musical outcomes (Gold et al., 2019). In addition, the anticipation (wanting) and experience of peak musical experiences are associated with dopamine release of distinct brain areas (dorsal and ventral striatum respectively, Salimpoor et al., 2011). Pharmacological manipulations also modulated differently the components of music reward processing, with dopaminergic manipulation affecting both liking and wanting (Ferreri et al., 2019) and opioids only affecting reward consumption (Mallik et al., 2017; Mas-Herrero et al., 2023). However, although the brain network underlying musical pleasure has been well delineated, the underlying mechanisms of musical pleasure remain under debate. Some recent theories based on the predictive coding framework propose that they might stem from the expectations that we generate while listening to music (Koelsch et al., 2019). These expectations create an uncertainty about the future course of the musical piece, which is resolved as music progresses, activating the reward network due to the intrinsic value of reducing uncertainty (Koelsch et al., 2019).

Therefore, prior neuroimaging studies have effectively mapped the brain network involved in music reward processing, as evidenced by Mas-Herrero et al., 2021. However, the findings from studies focusing on the electrophysiological components of music reward are not as consistent, leaving their characterization an open question. Different studies have consistently found an increase in the theta activity that is associated with music that has positive valence (Lin et al., 2010; Mikutta et al., 2014; Rogenmoser et al., 2016) and with consonant music (Sammler et al., 2007), which is normally rated as pleasant. This oscillatory activity seems to play a key role in the synchronization of different areas involved in music processing. Hence, an increase in theta connectivity between right temporal and frontal electrodes would be linked to an increase in music pleasure (Ara and Marco-Pallarés, 2021, 2020). However, it is unclear to what extent the processing of anticipation and outcome of musical reward engages neurophysiological mechanisms similar to those of other rewarding stimuli such as money.

In the present study, we propose a modification of the Monetary Incentive Delay (MID) using both money and music as rewards. This widely employed task emerges as an experimental tool to disentangle anticipation and consummatory stages, exploring behavioural and neurophysiological markers for reward processing (Knutson et al., 2000). In this task, a cue indicates different aspects of the potential outcome (e.g., whether it can be a monetary gain or loss, or its probability or magnitude). Then, after a variable time interval, a target appears and the participants have to respond to it as fast as possible. Then, depending on the response, the participant will receive or not the outcome. Adapting this task to other reinforcers rather than money, using a time-sensitive technique such as EEG, could help elucidate the neurophysiological processes underlying reward processing. In our paradigm, cues signal whether participants can win or lose money or listen to pleasant and unpleasant musical excerpts. Considering prior research (Glazer et al. 2008), we hypothesized that Cue-N2 and theta oscillatory activity would increase in the cue-negative conditions compared to cue-gain conditions, while the Cue-P3 components and the beta-gamma oscillatory activities would show the opposite behaviour, with increases for cues indicating potential gain. We also hypothesized that money and music would exhibit similar components in the anticipation of potential positive and negative outcomes. In addition, we conducted exploratory analysis on the cue conditions regarding the early N1 and P2 ERPs, as well as the late CNV component. In the feedback condition, we hypothesized that the FRN and theta oscillatory activities would increase in response to negative and unexpected outcomes. In contrast, previous studies did not provide clear hypothesis on the modulation of the P3 components. Finally, due to the distinct nature of stimuli, we did not directly compare music and monetary outcomes.

2. Materials and methods

2.1. Subjects

Twenty-four healthy subjects participated in the study (mean age 25.5 ± 4.4, 13 women). None of them had a history of neurological or psychiatric disorders and presented normal vision and hearing. All participants were informed that they would receive a fixed amount of money and a variable part depending on their performance. Four participants were excluded due to an excess of eye movements and other artefacts and one participant was excluded from the analysis because she was an outlier in the percentage of correct responses in the unpleasant music condition (<3.5 SD). The final sample was, therefore, composed of nineteen participants (mean age 26.2 ± 4.5, 9 women). Informed consent was obtained from all participants. The experiment was approved by the Biomedical ethics local committee.

2.2. Experimental paradigm

The experimental paradigm was a modification of the Monetary Incentive Delay task (Knutson et al., 2000) adapted for EEG to include two incentive stimuli: money and music. This task allows the disentanglement of anticipatory from consumption reward stages by providing a clear structure: cue-target-feedback (Knutson et al., 2000; for a review of possible applications see Lutz and Widmer, 2014). Participants were instructed to press a target (a filled square) as quickly as possible to win points or listen to pleasant music in the Cue Gain (CG) conditions, and to not lose or listen to unpleasant music in Cue Loss (CL) conditions. In this sense, the anticipatory reward stage includes a cue evaluation substage, which refers to the process of information depicted by the cue, and motor preparation towards the target, whereas the outcome reward phase would be the delivery of explicit feedback. The task consisted of 240 trials: 60 per cue and reward type condition (Cue Gain Money, Cue Loss Money, Cue Gain Music, Cue Loss Music).

At the beginning of the trial, an incentive cue with an associated performance contingency was presented. Cues had been previously explained to participants who were shown whether they were playing to win points or listen to pleasant music (Cue Gain, circle with a line in the middle), or to not lose points or listen to unpleasant music (Cue Loss, square with a line in the middle). The colour of the cue (green or white) indicated whether they were playing for music or for money. This colour was also maintained for targets and feedback in each trial. In half of participants, white cues, targets and outcomes corresponded to money and green ones to music. The colours were reversed in the other half of participants.

The cue was presented for 250 ms and then, after a random interval between 1500 and 2500 ms, a filled square appeared (target) and participants had to press a keyboard button as quickly as possible. Then, after half a second, the feedback appeared. In the monetary condition, if the participant had pressed quickly enough, they earned 5 euro cents (displayed as + 50 points on the screen) in Cue Gain condition and 0 euro cents (0 on the screen, indicating no loss) in Cue Loss condition. In contrast, if they were too slow, they earned 0 euro cents (0 on the screen, indicating no monetary reward) in Cue Gain condition and lost 5 euro cents (displayed as −50 on the screen) in Cue Loss condition. Feedback was presented for 1650 ms and then, after one second, the next trial started. In the music condition, if participants pressed quickly, they listened to pleasant music in Gain condition or brown noise (neutral sound) in the Loss condition. If participants failed, they listened to brown noise in the Cue Gain condition or unpleasant music in the Cue Loss condition. After music excerpts, participants had to provide a pleasure rating on a 1 to 7 Likert scale (1. I found it unbearable, 2. I disliked it a lot, 3. I disliked it a little, 4. It left me indifferent, 5. I quite liked it, 6. I liked it a lot, 7. I loved it). One second after the rating, next trial started.

The time limit to respond to the target was set using an adaptive algorithm. At the beginning of the experiment, a practice task of 15 trials was presented to participants. The last ten reaction times (higher than 100 ms and lower than 400 ms) were recorded and the time limit for the first trials was set at the mean of these reaction times plus half the standard deviation of the distribution. For each trial, the last ten reaction times were used to compute the time limit using the same procedure. To avoid imbalances in the number of trials of money and music (e.g., participants responding more quickly to monetary than music cues to win more money), the time limit was computed independently for music and monetary conditions.

Pleasant music was selected from previous studies (see, e.g., Martínez-Molina et al., 2016; Mas-Herrero et al., 2014) from classical pieces from the baroque, classical and romantic periods or similar pieces from these periods. In contrast, unpleasant music was selected from pieces that are rated low by most people, that is, pieces from some twentieth-century composers (including Penderecki, Berg, Webern, Messiaen, Ferneyhough and Varèse) and original Carmina Burana medieval songs (see Supplementary material for the full list of pieces). The duration of all the music excerpts as well as the brown noise was 15 s and the volume of the excerpts was normalized to be the same in all musical pieces.

2.3. EEG recordings

EEG was recorded from 32 electrodes located at standard positions on the scalp (Fp1/2, AFz (Gnd), Fz, F3/4, F7/8, FCz, FC1/2, FC5/6, Cz, C3/4, T7/8, CP1/2, CP5/6, Pz, P3/4, P7/8, L/R Mastoids, O1/2) at 250 Hz using a BrainAmp amplifier with tin electrodes mounted on an Easycap (Brain Products©). Vertical eye movements were monitored with an electrode at the infraorbital ridge of the right eye. An online 0.01 Hz high-pass filter and a notch filter at 50 Hz were applied to the recording. Data was referenced online to the outer canthus of the right eye and re-referenced off-line to the mean of the two mastoids. All electrode impedances were kept below 5kΩ during the recording.

2.4. Analysis

2.4.1. Behavioural results

Repeated-measures ANOVA was computed for two within factors: type of incentive reward stimuli (money or music) and contingency of the cue (potential gain or loss) to identify differences in participants' reaction times. In addition, a paired-sample t-student test was performed on liking rates to ascertain that pleasant music was rated higher than unpleasant music on Likert scales.

2.4.2. Event-Related Potentials

EEG was filtered between 0.1 Hz and 45 HZ offline using EEGLab (Delorme and Makeig, 2004) under MATLAB (MathWorks, 2019). Epochs for anticipation reward stage were extracted from –2000 ms before the cue presentation to 2000 ms after it. Consumption reward stage epochs were extracted in the same time interval but time-locked to feedback presentation. 240 trials were analysed, leading to 60 trials per reward and cue contingency condition in both analyses (Money Cue Gain, Money Cue Loss, Music Cue Gain and Music Cue Loss). In the outcome, there were eight possible conditions depending on the final outcome (positive or negative).

Artefact rejection was performed using Independent Component Analysis (ICA) (Bell and Sejnowski, 1995; A Delorme et al., 2012; Lee et al.,1999). After component removal, trials exceeding 100 µV mean amplitude were also rejected from further analysis.

For each epoch, Event-Related Potentials were extracted from −200 ms (baseline) to 1750 ms after cue presentation and from −200 ms to 1000 ms after feedback presentation. Differences in cue processing were assessed by performing a Repeated-measures ANOVA in nine electrodes (F3/z/4, C3/z/4, P3/z/4) with four factors: type of incentive reward (money or music), contingency of the cue (potential gain or loss), laterality (left, middle, right) and anterior-posterior (frontal, central and parietal) using the mean of the ERPs in the N1, P2, N2 and P3 time ranges. Given that the outcome stimuli were very different (music or visual stimuli), separate repeated-measures ANOVA were performed on money and music feedback in FRN/RewP and P3 time ranges. Within factors of both ANOVAs included: contingency of the cue (potential gain or loss), valence of the feedback (positive/gain or negative/loss), anterior-posterior (frontal, central and parietal) and laterality (left, middle, right).

2.4.3. Time-frequency analysis

Time-frequency analyses were performed convoluting cue and feedback single trials (−2000 ms to 2000 ms) using a complex Morlet wavelet (Herrmann et al., 2004; Tallon-Baudry et al., 1997) with studied frequencies ranging from 1 to 40 Hz with a linear increase of 1 Hz. In order to have a complete description of the oscillatory mechanisms underlying anticipation and consumption of the two types of stimuli, we computed both the total power and the induced power (that is, the oscillatory activity after removing phase-locked components). Total mean power increase or decrease with respect to baseline was extracted after cue and feedback presentation. Induced activity was computed by substracting the ERP to each single trial when applying the complex Morlet wavelet. Separate repeated-measures ANOVAs were conducted for both conditions with the same within factors as in ERP analysis in the theta (4–8 Hz, 100–400 ms in the cue condition, 100–600 ms in the outcome) and gamma (25–35 Hz, 200–600 ms in the cue condition) time–frequency ranges.

3. Results

3.1. Behavioural results

Mean ratings of pleasure presented significantly higher liking scores for pleasant music (5.4 ± 0.4) than for unpleasant music (3.2 ± 0.7, $t(18) = 12.9$, $p < 0.001$, d = 2.97, Fig. 1B). These results demonstrate that music excerpts classified as pleasant were consistently rated higher than unpleasant music stimuli.

Participants responded faster to targets preceded by a cue depicting that they were playing for money compared to playing for music. Mean reaction times were 246 ± 45 ms for the Monetary Cue Gain, 250 ± 44 ms for the Monetary Cue Loss, 268 ± 48 ms for the Music Cue Gain and 269 ± 48 ms for the Music Cue Loss (Fig. 1C). Repeated measures ANOVA (rm-ANOVA) revealed a significant higher reaction time in the music conditions compared to the money ones, $F(1,18) = 31.7$, $p < 0.001$, $\eta_p^2 = 0.64$, but not for the gain vs loss contingency, $F(1,18) = 0.6$, n.s., nor for the interaction between the two factors, $F(1,18) = 0.49$, n.s. Hence, participants respond significantly quicker to money, suggesting an incentive influence of the reward type on reaction times. Similarly, the percentage of correct responses was 74 ± 9 % for Monetary Cue Gain, 72 ± 7 % for Monetary Cue Loss, 69 ± 8 % for Music Cue Gain and 68 ± 5 % for Music Cue Loss. Again, there was a significant effect in money vs music, $F(1,18) = 14.6$, $p < 0.005$, $\eta_p^2 = 0.45$, but no significant effect in gain vs loss, $F(1,18) = 1.3$, n.s., nor interaction effect, $F(1,18) = 0.05$, n.s.

3.2. Cue ERP and time–frequency results (anticipatory reward stage)

Fig. 2 shows the ERPs associated with cue processing depending on cue contingency (potential gain vs loss) and potentially rewarding stimuli (music or money). Repeated-measures ANOVA in the N1 ERP component (80 to 120 ms) showed significant effect of contingency, $F(1,18) = 13.0$, $p < .005$, $\eta_p^2 = 0.42$, and interactions of this factor with

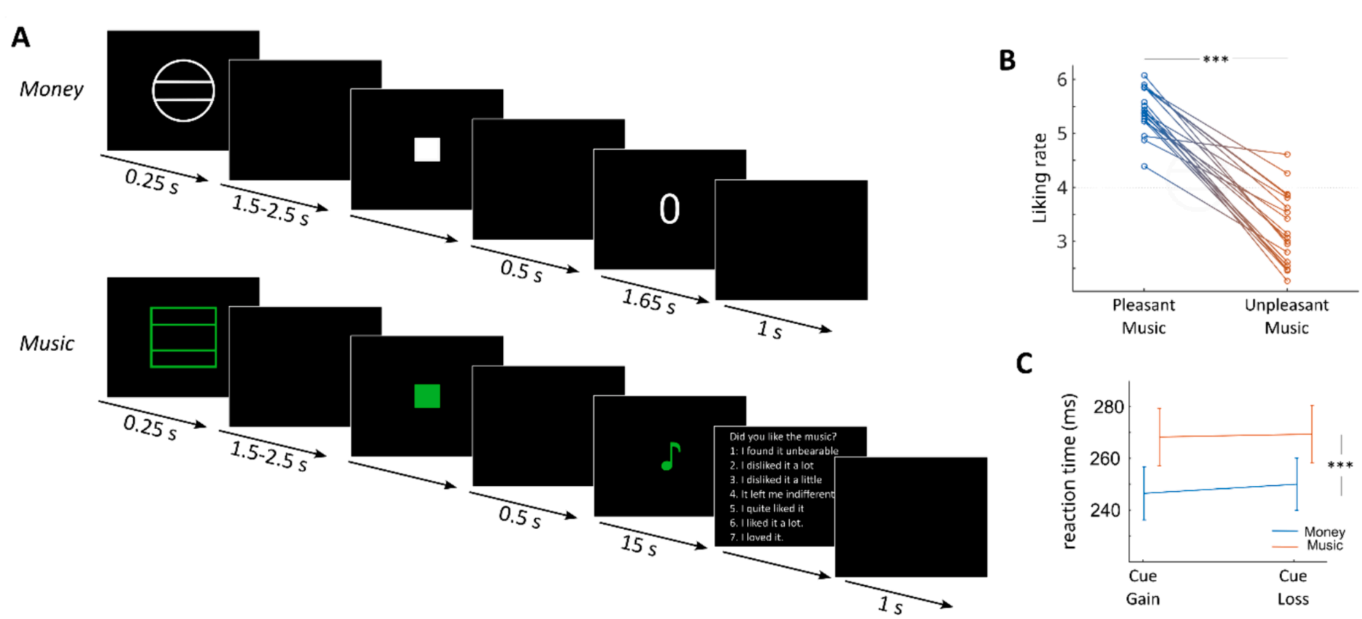

Fig. 1. **A.** Experimental paradigm used in the present study. **B.** Individual liking rates for pleasant and unpleasant music. **C.** Reaction times for the Cue Gain and Cue Loss conditions for music (red) and money (blue) conditions. Error bars indicate SEM. ***p < 0.001. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

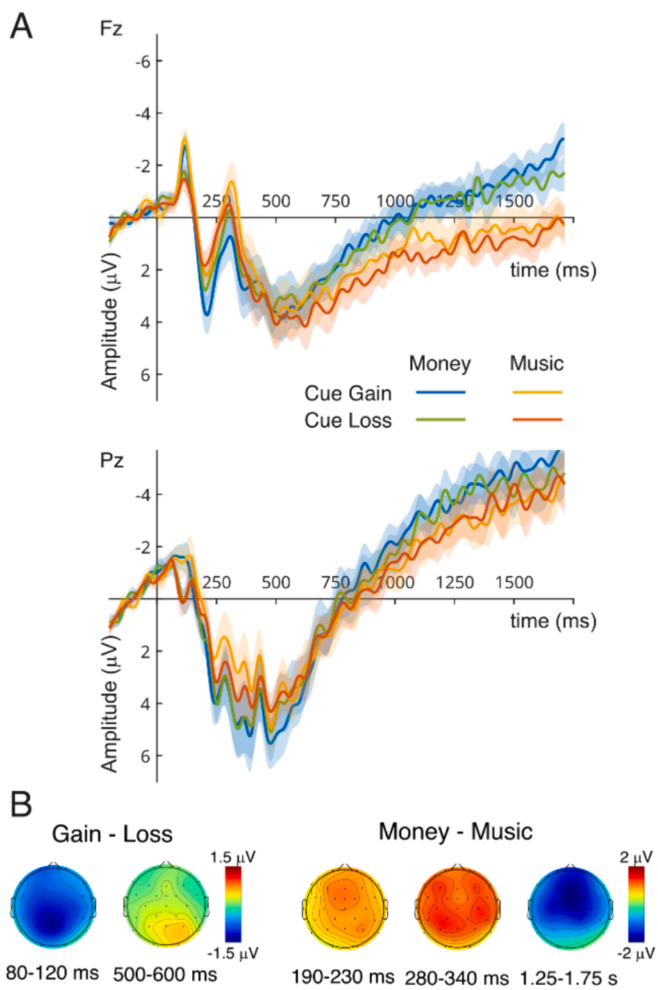

Fig. 2. A. Representation of Cue ERPs (anticipatory stage, shaded areas showing SEM) at Fz and Pz electrodes considering two conditions informed by cues: contingency (potential gain or loss) and incentive reward (money or music). ERPs were lowpass filtered at 20 Hz for visualization purposes. **B.** Scalp topography differences by contingency and incentive reward.

lateralization, $F(1,18) = 4.9$, $p < 0.05$, $\eta_p^2 = 0.21$, and with lateralization and anterior-posterior factors, $F(4,72) = 3.9$, $p < 0.01$, $\eta_p^2 = 0.18$. This effect was explained by an increase in Cue Gain compared to Cue Loss at centro-parietal electrodes. No significant effect of type of incentive stimuli, nor interaction with cue contingency was found at N1 time range. In contrast, rm-ANOVA in the P2 ERP component (190 to 230 ms) presented only a significant effect of incentive reward factor (money or music) in its amplitude, $F(1,18) = 7.9$, $p < 0.05$, $\eta_p^2 = 0.31$, with higher amplitude for money compared to music condition. In a similar way, rm-ANOVA in the Cue-N2 ERP component (260–340 ms) presented significant differences in incentive reward factor, $F(1,18) = 7.2$, $p < 0.05$, $\eta_p^2 = 0.29$, with greater amplitude in music than in money. In addition, a significant interaction of contingency, anterior-posterior and laterality factors was also found in this component, $F(4,72) = 2.6$, $p < 0.05$, $\eta_p^2 = 0.13$. In Cue-P3 time range (500–600 ms), only an interaction between contingency and anterior-posterior factor was found to be significant, $F(2,36) = 4.7$, $p < 0.05$, $\eta_p^2 = 0.21$, with enhanced amplitude for gains than for loses in posterior electrodes. Finally, in the CNV time range (1250–1750 ms after cue onset), only a significant effect between money and music was found ($F(1,18) = 25.2$, $p < 0.001$, $\eta_p^2 = 0.58$).

Time-frequency responses to cues presented influence of contingency in theta (4–8 Hz, 100–400 ms), and gamma oscillations (25–35 Hz, 200–600 ms, Figs. 3 and 4). Repeated-measures ANOVA in theta band showed a significant interaction of contingency and anterior-posterior factor, $F(2,36) = 5.6$, $p < 0.01$, $\eta_p^2 = 0.24$, with gain presenting higher power than loss conditions. In contrast, in the induced theta power we only found a marginal significant contingency x anterior-posterior x laterality effect, $F(2,36) = 2.5$, $p = 0.05$, $\eta_p^2 = 0.12$. In addition, gamma band total power (25–35 Hz, 200–600 ms) was also higher for cue gain compared to cue loss (significant contingency, $F(1,18) = 8.6$, $p < 0.01$, $\eta_p^2 = 0.32$). A significant laterality x type of rewarding stimuli was also found in this time–frequency range, $F(2,36) = 4.1$, $p < 0.05$, $\eta_p^2 = 0.19$. Finally, in the induced activity, gamma band results were similar to the total ones, with significant contingency (gain greater than loss, $F(1,18) = 8.8$, $p < 0.01$, $\eta_p^2 = 0.33$), and significant laterality x type of rewarding stimuli ($F(2,36) = 4.4$, $p < 0.05$, $\eta_p^2 = 0.20$).

3.3. Feedback ERP and time–frequency results (consummatory reward stage)

Analysis of feedback ERP (Fig. 5) and time–frequency (Figs. 6 and 7) were performed separately for money and music given the different nature of the two stimuli. Monetary outcome showed an increased FRN (Feedback-Related Negativity), peaking at approximately 300 ms, and a clear Fb-P3 for certain conditions (Fig. 5). Repeated-measures ANOVA in the FRN time range (280–320 ms) revealed a significant interaction between valence (gain/positive feedback or loss/negative feedback) and cue contingency (potential gain or loss), $F(1,18) = 119.1$, $p < 0.001$, $\eta_p^2 = 0.87$, indicating that FRN component was higher both for negative valence in the Cue Gain condition and for positive valence in Cue Loss condition. In addition, results also revealed a significant interaction between the valence and anterior-posterior factors, $F(2,36) = 5.4$, $p < 0.05$, $\eta_p^2 = 0.23$. Similarly, the analysis of the Fb-P3 peak (320–400 ms) revealed a significant interaction of valence with cue contingency $F(1,18) = 30.99$, $p < 0.001$, $\eta_p^2 = 0.63$, a significant valence x cue x laterality interaction, $F(2,36) = 4.24$, $p < 0.05$, $\eta_p^2 = 0.19$, and a significant interaction of the four factors, $F(4,72) = 3.95$, $p < 0.01$, $\eta_p^2 = 0.18$. In addition, significant interaction of valence with anterior-posterior factor, $F(1,18) = 8.7$, $p < 0.01$, $\eta_p^2 = 0.33$, and a triple interaction of these factors with lateralization, $F(4,72) = 3.54$, $p < 0.05$, $\eta_p^2 = 0.17$, were also found for Fb-P3 time range. Analysis of the 400–600 ms Fb-P3 time range also revealed a significant effect of valence, $F(1,18) = 10.8$, $p < 0.005$, $\eta_p^2 = 0.38$, and cue contingency, $F(1,18) = 4.7$, $p < 0.05$, $\eta_p^2 = 0.21$. Results also showed interactions of valence and cue contingency, $F(1,18) = 45.7$, $p < 0.001$, $\eta_p^2 = 0.72$, valence and anterior-posterior, $F(2,36) = 4.3$, $p < 0.05$, $\eta_p^2 = 0.19$, valence and laterality, $F(2,36) = 15.9$, $p < 0.001$, $\eta_p^2 = 0.47$, cue and laterality, $F(2,36) = 4.8$, $p < 0.05$, $\eta_p^2 = 0.21$, a triple interaction of valence, anterior-posterior and laterality, $F(4,72) = 4.9$, $p < 0.01$, $\eta_p^2 = 0.21$, a triple interaction of valence, cue and laterality, $F(2,36) = 9.8$, $p < 0.001$, $\eta_p^2 = 0.35$, and a quadruple interaction of valence, contingency, anterior-posterior and laterality factors, $F(4,72) = 4.8$, $p < 0.01$, $\eta_p^2 = 0.21$.

In contrast to the monetary feedback ERP processing, music feedback did not present significant condition effects, nor interaction between conditions and between conditions and electrodes in the FRN time range (280–320 ms; $F < 1.7$, $p > 0.1$). Nonetheless, in the peak of Fb-P3 ERP component (360–440 ms), rm-ANOVA revealed a significant valence main effect, $F(1,18) = 7.6$, $p < 0.05$, $\eta_p^2 = 0.29$, an interaction between valence and cue contingency, $F(1,18) = 23.0$, $p < 0.001$, $\eta_p^2 = 0.56$, an interaction between these two conditions and anterior-posterior, $F(2,36) = 4.98$, $p < 0.05$, $\eta_p^2 = 0.22$, and a significant laterality x valence x cue interaction, $F(2,36) = 8.2$, $p < 0.005$, $\eta_p^2 = 0.31$.

Time-frequency analysis of money feedback power (Figs. 5 and 6) showed an increase in the theta band (4–8 Hz, 100–600 ms) for negative feedback for cue contingency, as revealed by the valence of feedback significant main effect, $F(1,18) = 9.3$, $p < 0.01$, $\eta_p^2 = 0.34$. A similar valence effect was found for induced theta activity, $F(1,18) = 7.2$, $p < 0.05$, $\eta_p^2 = 0.29$, as well as a significant lateralization x valence x cue contingency, $F(2,36) = 4.6$, $p < 0.05$, $\eta_p^2 = 0.2$ In the music outcome, rm-ANOVA showed a significant interaction of cue contingency and

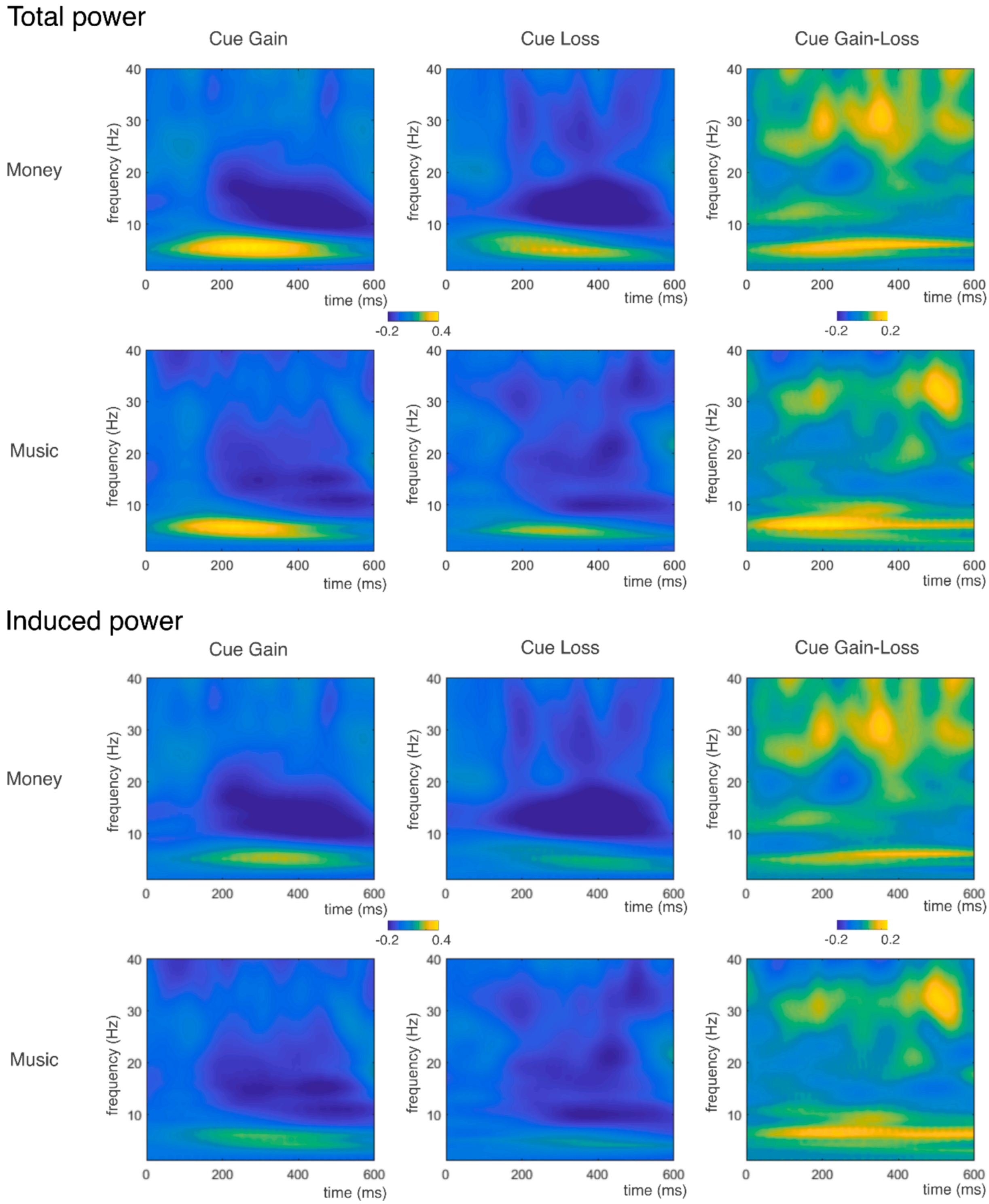

Fig. 3. Time-frequency analysis of cues of power changes for contingency (potential gain or loss) and incentive reward type (money or music) for total power (top) and induced power (bottom) at the Fz electrode. Graphical representations of the first row present power for potentially winning money (Money Cue Gain), power for potentially losing money (Money Cue Loss) and the difference between both conditions. The second row presents power for potentially hearing pleasant music (Music Cue Gain), power for potentially hearing unpleasant music (Music Cue Loss) and the difference between both conditions.

valence, $F(1,18) = 7.9$, $p < 0.05$, $\eta_p^2 = 0.31$, as reflected by higher increase in theta power for negative feedback in the Cue Gain and positive feedback in the Cue Loss, as well as a significant triple interaction of valence, contingency of the cue and anterior-posterior factors, $F(2,36) = 4.7$, $p < 0.05$, $\eta_p^2 = 0.21$. In contrast, none of these effects was significant in the induced activity of music feedback, nor any effect involving cue contingency or valence or their interaction with other factor.

4. Discussion

The goal of the present study was to determine whether the anticipation and consumption of pleasant and unpleasant music engage similar neurophysiological mechanisms to the winning or losing of

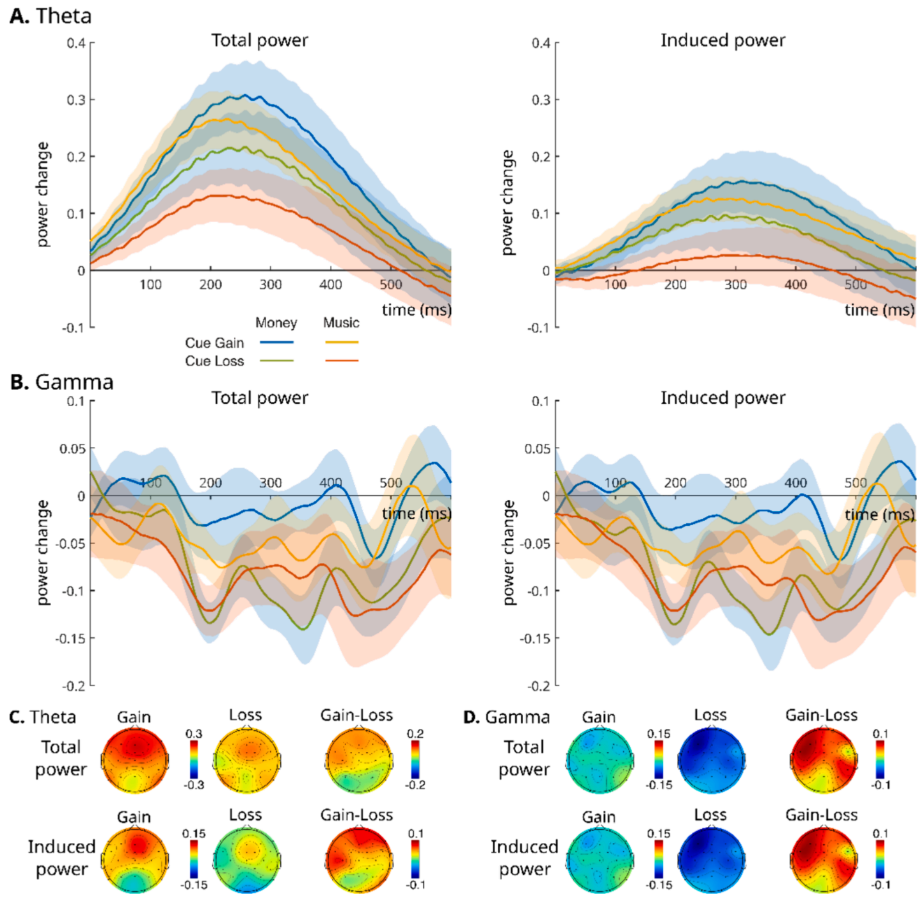

Fig. 4. Time evolution of the theta (A, 4–8 Hz) and gamma (B, 25–35 Hz) oscillatory activity for the different cue conditions for total and induced power at the Fz electrode (shaded areas showing SEM*)*. Bottom: topographical representations of gain and loss conditions for total and induced power for theta (C, 100–400 ms) and gamma (D, 200–600 ms) activities.

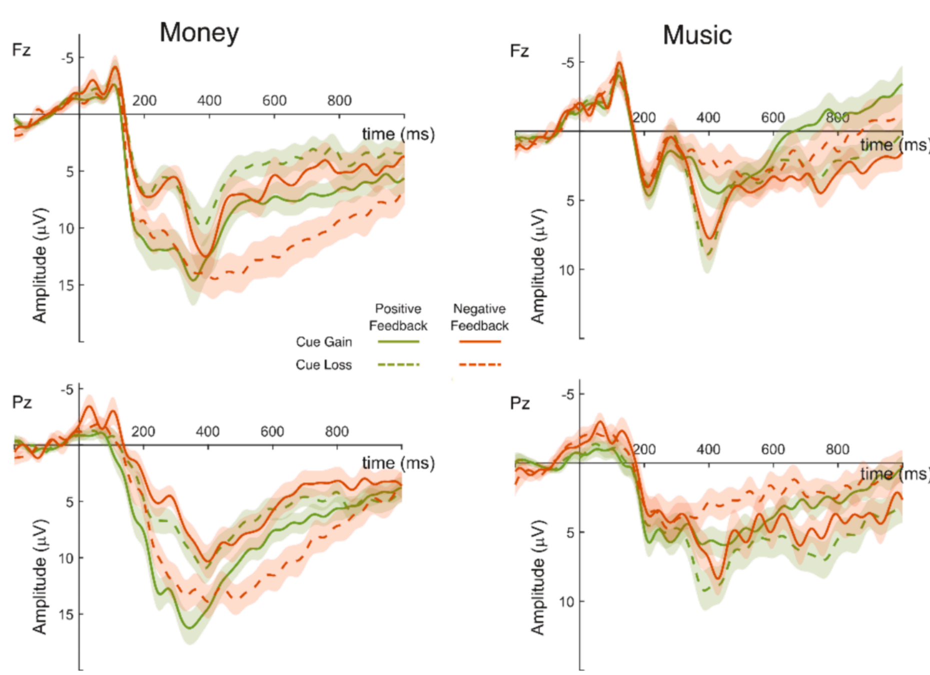

Fig. 5. Representation of Feedback ERPs (consummatory stage, shaded areas showing SEM) at Fz and Pz electrodes considering two conditions: valence of the feedback (gain/positive or loss/negative) and contingency of the cue (potential gain or loss). The first column presents ERP results of money positive (Gain) or negative (Loss) feedback in Cue Gain and Loss conditions. The second column shows the same but for music incentive reward. ERPs were lowpass filtered at 20 Hz for visualization purposes.

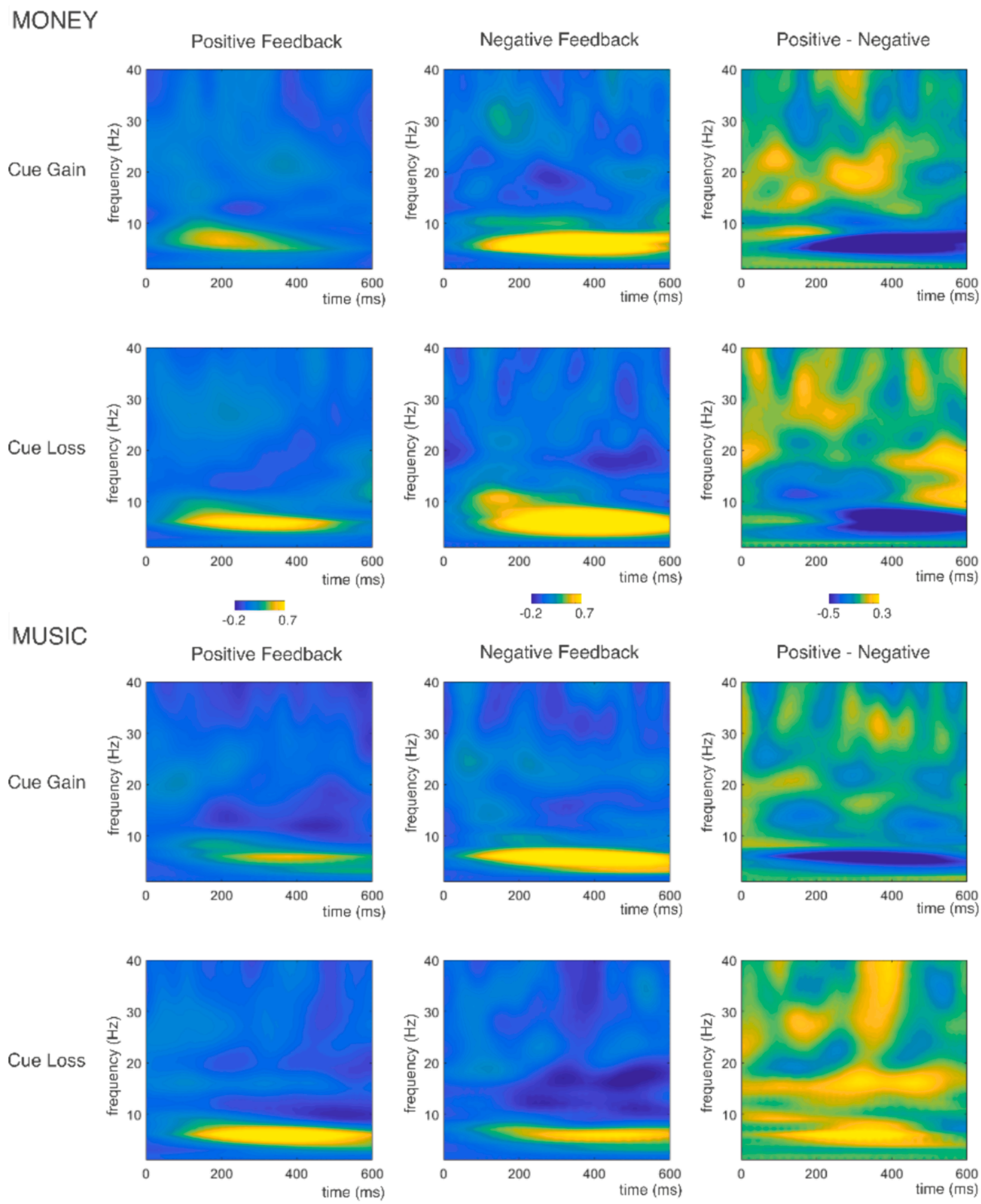

Fig. 6. Time-frequency analysis of power changes for the feedback (zero onset) for cue contingency (Cue Gain or Cue Loss) and valence of the feedback (positive or negative) in money and music at the Fz electrode. For each reward, the first column presents power changes for positive feedback, winning points or hearing pleasant music in Cue Gain (up) or not losing points or hearing brown noise in Cue Loss (bottom). The second column shows power changes for negative feedback, not winning points or hearing brown noise in Cue Gain (up) or losing points or hearing unpleasant music in Cue Loss (bottom). The third column presents difference between positive feedback and negative feedback in Cue Gain (up) and Cue Loss (bottom).

money, employing a modification of MID task (Knutson et al., 2000). Results show that similar ERPs and oscillatory components were found in cues indicating potentially positive or negative outcomes for the two types of stimuli, with significant enhancement of the P2 and N2 components for money and music respectively. In addition, consummatory reward processing was affected by the different nature of the monetary and musical stimuli.

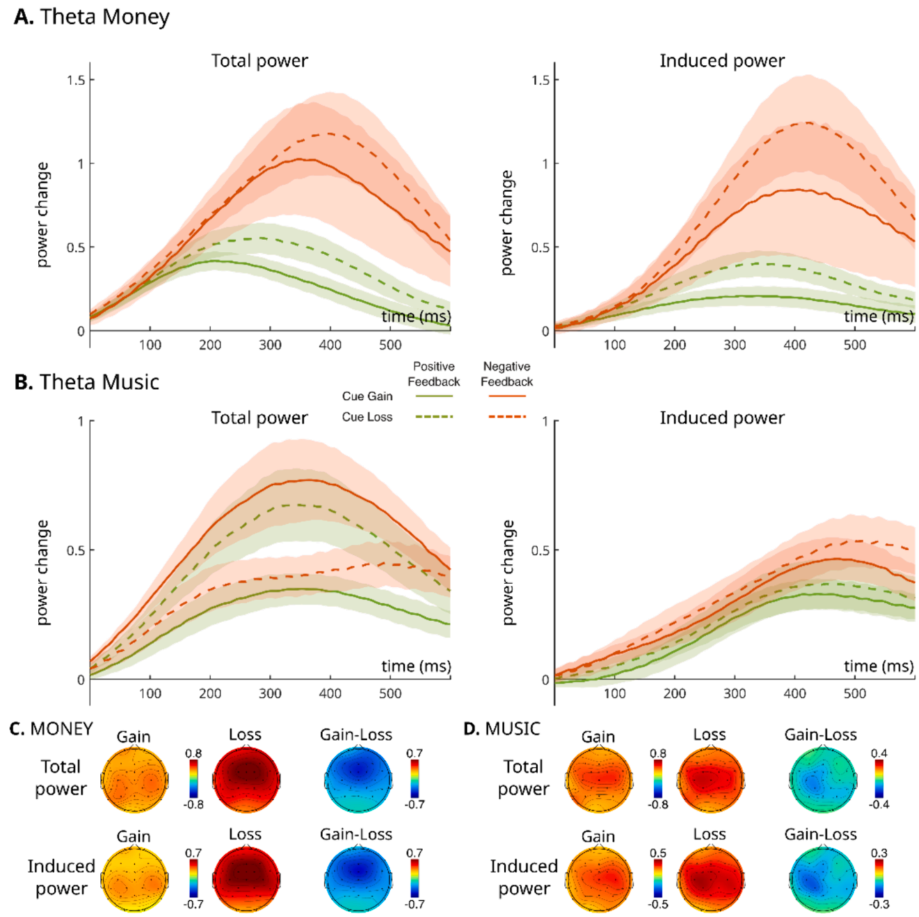

Fig. 7. Time evolution of the theta activity (4–8 Hz) for money (A) and music (B) outcome oscillatory activity for the different conditions for total and induced power at the Fz electrode (shaded areas showing SEM). Bottom: topographical representations (100–600 ms) of gain and loss conditions for total and induced power for money (C) and music (D).

Anticipation of positive and negative monetary and musical outcomes

In the anticipatory phase, we observed that cue evaluation is a heterogeneous process, with ERPs sensitive to either type of information or possible outcome. We first found that both, N1 and P3 ERPs were modulated by the contingency (possibility to gain or loss), with increased amplitude for Cue Gains compared to Cue losses. Previous results have found increased posterior N1 components to both potential gain of money (Doñamayor et al., 2012; Flores et al., 2015) and happy faces (Flores et al., 2015) compared to neutral conditions. This earlier enhancement of response towards rewards cues is congruent with animal models literature and might show the initial stages of motivation (Bunzeck et al., 2011), as proven by dopaminergic reward responses modulation (Apitz and Bunzeck, 2014), as well as enhanced selective attention (Van Den Berg et al., 2014). With regards to the Cue-P3 enhancement with Cue Gains compared to Losses, previous studies have suggested that this component reflects the allocation of attention to cues categorizing the valence of reward and the associated motivation to achieve it (Glazer et al., 2018) correlating with personality measures of reward responsiveness (Pegg et al., 2021). The present result corroborates previous findings on potential monetary (Angus et al., 2017; Broyd et al., 2012; Goldstein et al., 2006; Pfabigan et al., 2014; Pornpattananangkul and Nusslock, 2015; Zheng et al., 2017) and social gains (Ait Oumeziane et al., 2017; Flores et al., 2015) eliciting enhanced cue-P3, as they might be more motivating than neutral or potentially punishing conditions. However, it is important to note that other results have not found modulation of cue-P3 with valence, presenting equal responses to potential win and loss cues, and being only significantly reduced in neutral conditions (Novak and Foti, 2015). In addition, the effect size of the cue-P3 interaction between contingency and anterior-posterior factor in present study is relatively small. Therefore, this effect should be further explored in future studies. Importantly, the fact that P3 did not show significant differences between money and music conditions supports the idea that similar attentive mechanisms are engaged in processing the latter.

In contrast, our findings state a significant effect of the type of information (money or music) in the P2 and N2 ERPs. An enhanced P2 component towards cues depicting potential gain has been attributed to attentional salience (Olofsson et al., 2008; Schmitt et al., 2015) and emotional evaluation (Doñamayor et al., 2012; Flores et al., 2015) of cues. Nonetheless, enhancement in the P2 component towards money, regardless of contingency, is congruent with behavioural results showing faster reaction times to targets in the monetary conditions compared to music ones, probably indicating a higher incentive value of the former. Hence, P2 amplitude differences between money and music could indicate an increase in early attentional mechanisms, facilitating posterior motor anticipation responses towards targets as well as increased emotional evaluation when participants play for money. Indeed, previous studies have shown shorter reaction times when comparing monetary with social reinforcers (Ait Oumeziane et al., 2017; Barman et al., 2015; Rademacher et al., 2014; Spreckelmeyer et al., 2009), with no significant differences of subjective motivational ratings between rewards (Wang et al., 2017). This is also supported by the enhanced CNV for monetary compared to music cues. CNV has been previously found after cues indicating the future incoming of monetary gains and losses (Broyd et al., 2012; Glazer et al., 2018) and is related to attentional orientation towards target stimulus and motor preparation (Gómez et al., 2003). Therefore, the differences found in this component between outcome types could reflect an increase of these mechanisms in monetary conditions, resulting in faster reaction times. Also consistent with prior results, participants presented no significant differences between potential win and loss in their reaction times (Angus et al., 2017; Broyd et al., 2012; Novak and Foti, 2015), nor with interaction with reward type. This indicates that, although money could be more engaging than music, within each reward condition, potentially winning money or hearing pleasant music and potentially avoiding losing money or listening to unpleasant music showed no significant differences within each stimulus type. In contrast to P2, Cue-N2 showed both effects of reward type (with increased negativity for music compared to money) and type of cue (being more negative for cue gains for cue losses), although this latter result should be treated cautiously due to its relative small effect size. Previous studies have shown increased Cue-N2 ERP for loss and neutral cues compared to gain ones (Glazer et al., 2018). A proposed explanation for this phenomenon would be biased expectations towards positive outcomes, which would result in the violation of expectations when another cue is delivered, which would be reflected in an increased Cue-N2. Despite the fact that, in our experiment, the four cues appeared with the same probability, as stated above participants seemed to be more engaged in the monetary than in the music conditions. Therefore, increased Cue-N2 for music compared to money would reflect a bias towards monetary cues. However, the interpretation of the increased Cue-N2 for gains compared to losses is less clear, as it goes against some previous results (see e.g. Novak and Foti, 2015; Pornpattananangkul and Nusslock, 2015). Given that, in the present study, cues are more complex than in other studies as they contain two types of information (type of stimuli and type of contingency), this could affect the expectancies and biases generated by participants, but further studies are needed to better understand this result.

The second main finding of the cue processing was the enhanced oscillatory activity in theta and gamma bands found in cues indicating the potential of winning. Oscillatory components associated with reward processing have been mainly reported in the outcome (Meyer et al., 2021), and much less is known about their role in the anticipation. Consistent with the present paper, beta-gamma activity has been linked to rewarding outcomes (Marco-Pallarés et al., 2015; Marco-Pallares et al., 2008; Mas-Herrero et al., 2015) and the anticipation of rewarding stimuli (Bunzeck et al., 2011), especially if they are relevant or unexpected. In contrast, theta activity has been consistently found as a marker of cognitive control (Cavanagh & Frank, 2014) and prediction error computation (Cavanagh et al., 2011; Mas-Herrero and Marco-Pallarés, 2014). Therefore, the present oscillatory results suggest that cues indicating a potential gain generate a higher increase in the cognitive control mechanisms (indexed by theta activity) as well as frontostriatal reward network processing (as reflected by beta-gamma, Marco-Pallarés et al., 2015) compared to cues signalling a potential loss, probably due to the higher motivational impact of gains in current experimental setting.

4.1. ERPs and oscillatory activity associated with outcome processing

ERPs following feedback presented significantly distinct processing depending on valence (positive/winning or negative/losing) and incentive condition (potential winning or losing). The first interesting result is the interaction between valence and cue contingency in the FRN of the monetary conditions, showing an increased response for losses in the Cue Gain condition and for no-losses in the Cue Loss condition. Given that in the two conditions the positive feedbacks were more frequent than negative ones, an interpretation of this component based on the probability of the outcome (signalling, e.g., reward prediction error, Holroyd and Coles, 2002) would not fit with current results. Indeed, there were no significant differences between the probability of no gain (in the Cue Gain) and loss (in the Cue Loss), so the degree of the expectancy of these two worse-than-expected outcomes should be similar, eliciting, according to these theories, similar FRN (see Sambrook and Goslin, 2015, for a review supporting this interpretation). In contrast, the responses appeared to be responding to the framing in each condition: in Cue Gain conditions higher prediction errors would occur in the no gain conditions, while in the Cue Loss conditions would be higher in the no-loss conditions. Therefore, the prediction error would be associated not with the probability or valence of the outcome but with the discrepancy with the framed context (either gain or loss; Watts et al., 2017). Interestingly, the theta activity for monetary outcomes did not follow these modulations, but an increased activity in negative feedback (no gain or loss in the corresponding conditions; (Marco-Pallares et al., 2008). Therefore, these two responses would present a dissociable behaviour, with the FRN selectively responding to the factor emphasized by the Cue (Gu et al., 2021) and theta activity associated with reward prediction error. Importantly, the total power activity and the induced oscillatory activity showed a similar behaviour, especially in the negative feedback conditions, suggesting that theta activity cannot be explained by the evoked components and, in addition, the time evolution is very slow, peaking at around 400 ms, very different from the FRN/reward positivity waveform. On the other hand, the P3 ERP showed a complex interaction between factors, with higher amplitude in the losses for the Cue Loss conditions and in gains for the Cue Gain conditions, suggesting higher attentional impact of these conditions, either on receiving monetary outcomes (Marco-Pallares et al., 2008) or on the motivation to avoid punishment by engaging appropriate behavioural adjustments (San Martin, 2012) in potential loss conditions (Donaldson et al., 2016; Pornpattananangkul and Nusslock, 2015).

Importantly for the present study, the electrophysiological responses to the musical outcome were affected by the characteristics of the musical stimuli. Under the monetary condition, the outcome was a visual stimulus that could be processed very quickly. However, music or brown noise started at the beginning of the outcome and probably participants needed more time to recognize whether they had won or lost. In addition, the value of the music unfolded over a time period of 15 s. Hence, the real liking or disliking for the musical excerpt was recognized while listening to the music and not immediately after the stimuli started. This might explain the lack of significant differences in the FRN time range among conditions. Interestingly, even though it was not sensitive to them, the response was in a similar time range to the FRN for the monetary condition. This would go in the direction of the accounts arguing that the FRN is essentially an N200 response appearing in all conditions, which would be reduced in response to a gain (Reward Positivity, RewP; Holroyd et al., 2008). Therefore, the frontocentral negativity around 250 ms in the music outcome would reflect an N200 response that is not modified by the different conditions. In contrast, both the peak of the P3 and the theta response showed similar behaviour, with increased activity for loss in the cue gain and the gain in the cue loss conditions. Two possible accounts could explain these results. First, similar to the monetary condition, the same stimulus (0 in the monetary conditions, brown noise in the music conditions) signalled a negative feedback in the Cue Gain condition and a positive feedback in the Cue Loss one. Therefore, this stimulus was presented more often than the other auditory stimuli and was probably easier to identify (as well as being less complex than real musical excerpts). The higher P3 and theta activity would, hence, be related to the quick identification of this signal and not to a response associated with reward or punishment. On the other hand, a complementary explanation would be the fact that, in a musical context, the delivery of a non-musical sound could be processed as an unexpected stimulus or a surprise, generating a prediction error that would be indexed by P3 and theta activity (Mas-Herrero and Marco-Pallarés, 2014). This activity would be, therefore, similar to the theta activity reported in the monetary outcome and elicited by the prediction error on the basis of context created by the cue (Watts et al., 2017) and not related to valence. Future studies using different auditory stimuli rather than a single one could help in determining the functional role of these components.

This study is not without limitations. The first one is the small sample size. Although 24 participants were initially recorded, in line with previous studies on EEG reward processing for a meta-analysis of 55 experiment in EEG feedback with a median number of participants of 18), finally only 19 participants were included in the final sample. This relatively small number of participants could especially affect those effects with smaller effect size, so future studies with more participants should be done to replicate current findings. A second potential limitation of current study is that the two types of stimuli might not be equally engaging or motivating. In fact, our results show that participants responded faster to monetary than music targets, supporting the idea that they were more willing to winning or not losing money than to listening to music. In addition, other factors such as individual differences in sensitivity to music reward, (Mas-Herrero et al., 2013, 2014) or variability in the pleasantness of the different melodies used as positive and negative feedback might also be involved in the different evaluation of money and music. Furthermore, the inclusion of brown noise in our study is grounded in the use of noise as a non-musical, neutral stimulus in prior research (see, for example, Moghimi et al., 2012, for the utilization of brown noise, and Cardona et al., 2020, for the use of white noise). In current study participants did not rate the hedonic properties of this stimulus, but the absence of significant differences in reaction times between the positive and negative music conditions suggests a preference for pleasant music over brown noise and, conversely, for brown noise over unpleasant music. This observation supports the notion that participants perceived brown noise as neutral. However, future studies could delve deeper into this issue by employing choice tasks to directly assess participants' preferences between musical and noise stimuli.

In conclusion, our study described the neurophysiological responses during the anticipation and outcome of positive or negative monetary and musical outcomes. We found that the anticipation of these two types of stimuli elicited similar neurophysiological components in response to cues indicating potential positive or negative outcomes. In contrast, feedback processing showed different neurophysiological responses, although it is unclear to what extend this could be related to the intrinsic differences in the nature of the stimuli (visual vs auditory) or to different mechanisms involved in the evaluation of monetary and musical outcomes. Future research should explore the functional implications of these feedback differences across different types of rewards, as well as how they interact with the ability to obtain positive feedback or avoid negative events.

CRediT authorship contribution statement

Italo Alí Diez: Writing – review & editing, Investigation, Data curation, Conceptualization. **Gemma Fàbrega-Camps:** Writing – review & editing, Data curation, Conceptualization. **Jeison Parra-Tíjaro:** Writing – review & editing, Data curation. **Josep Marco-Pallarés:** Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandc.2024.106186.

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