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Original article

Greater neural delay discounting on reward evaluation in anhedonia

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ABSTRACT

Background/objective: Recent years have witnessed a surge of interest in dissecting the anticipatory and the consummatory aspects of anhedonia in terms of temporal dynamics. However, few research has directly examined reward valuation as a function of time in anhedonia.

Method: Using a delay discounting task, this event-related potential study examined the neural representation of rewards available immediately or in six months in a high-anhedonia group ($N = 40$) and a low-anhedonia group ($N = 40$) recruited from a nonclinical sample.

Results: We found that anhedonia was associated with greater neural delay discounting during reward evaluation. This was evidenced by a blunted effect of reward magnitude on the reward positivity (RewP) in the high-anhedonia compared to the low-anhedonia group when the rewards would be delivered six months later. Representation similarity analysis revealed that the aberration in processing delayed rewards is further corroborated by enhanced neural coding of reward time during the RewP period in the high-anhedonia versus low-anhedonia group.

Conclusions: These findings provide empirical evidence to show that anhedonia is driven by a blunted neural representation of future rewards instead of immediate rewards, suggesting an inability to form mental representations of future positive experiences in anhedonia.

Introduction

Anhedonia, defined as a diminished interest in pursuing rewards and an inability to experience pleasure once obtained, has been proposed as a core feature for multiple psychiatric disorders as diverse as schizophrenia (Pelizza & Ferrari, 2009; Whitton et al., 2015), bipolar disorder (Whitton et al., 2015), and substance use disorder (Hatzigiakoumis et al., 2011). Therefore, understanding the neural mechanisms underlying anhedonia could provide valuable insights to facilitate the development of preventive and potentially universal or targeted interventions aimed at decreasing the onset of relevant symptoms in healthy populations. Recent studies on anhedonia have shifted the focus from its initial definition of an inability to experience pleasure (Avakian & Markou, 2012) to other aspects of reward deficits (Rizvi et al., 2016). One of the most important progresses is the distinction between two temporal components in anhedonia (Gard et al., 2006; Romer et al., 2015; Treadway & Zald, 2011): an anticipatory component and a consummatory component. Whereas anticipatory anhedonia is future-oriented and associated with deficits in motivation and goal-directed behaviors, consummatory anhedonia is immediate and linked to deficits in resolving desire and experiencing in-the-moment pleasure. Moreover, recent progress has shown that deficient reward processing is more relevant to anticipatory anhedonia than consummatory anhedonia (Nusslock & Alloy, 2017; Romer et al., 2015). Specifically, there are inconsistent findings on whether anhedonia is accompanied by reduced consummatory responses to pleasurable stimuli, but there is converging evidence that anhedonia is associated with deficits in anticipatory aspects of pleasure (Romer et al., 2015). Despite a strong scientific interest in dissecting the anticipatory and the consummatory aspects of anhedonia, there is a dearth of research directly examining reward valuation as a function of time in anhedonia.

This issue can be tested under the framework of delay discounting, which describes how the subjective value of a reward declines as the delay to receive it increases (Ainslie, 1975). In the delay discounting

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task, individuals choose between an immediate smaller reward and a delayed larger reward. If anhedonia is driven by a deficit in the online experience in response to rewards, anhedonic individuals would prefer delayed rewards over immediate rewards, evidenced as smaller delay discounting. Alternatively, if anhedonia-related deficit is future-oriented, individuals with high anhedonia would prefer immediate over delayed rewards, resulting in larger delay discounting. Several studies have examined delay discounting in anhedonia but found inconsistent results. Whereas some studies reported larger delay discounting in anhedonic individuals (Cai et al., 2019; Olson et al., 2018; Veldhoven et al., 2020), another study found that higher anhedonia scores in healthy undergraduate students were associated with smaller delay discounting (Lempert & Pizzagalli, 2010). Moreover, a recent study showed that anhedonia is associated with greater delay discounting in patients with posttraumatic stress disorder but not among healthy controls (Olson et al., 2024). Mixed results of delay discounting have also been reported in anhedonia-related diseases including depression (Dombrovski et al., 2011; Engelmann et al., 2013; Pulcu et al., 2013; Takahashi et al., 2008) and schizophrenia (Ahn et al., 2011; Horan et al., 2017; Wing et al., 2012).

The divergent findings of delay discounting in anhedonia and relevant psychiatric disorders are attributable to a methodological issue in previous behavioral delay discounting tasks. Specifically, immediate rewards are typically used as the reference to calculate the subjective value of delayed rewards (Kirby et al., 1999). This approach makes the underlying mechanism of abnormal delay discounting in anhedonia unclear, as it reflects the relative valuation between immediate and delayed rewards. For example, the larger delay discounting observed in previous tasks could be driven by hypersensitivity to immediate rewards, hyposensitivity to delayed rewards, or both. These possibilities could be tested directly by measuring neural responses to immediate and delayed rewards in anhedonia.

Here, we recorded electroencephalography (EEG) from a high-anhedonia group and a low-anhedonia group when they were evaluating either a small (¥1) or large (¥10) reward delivered either immediately or six months later. We focused on the reward positivity (RewP) of the event-related potential (ERP) component, a relatively positive deflection between 250 and 350 ms over frontocentral areas (Miltner et al., 1997). It is thought to reflect reward sensitivity during feedback evaluation (Proudfit, 2015). Previous research has established the RewP as a neural manifestation of delay discounting, with its amplitude being reduced for delayed versus immediate rewards (Cherniawsky & Holroyd, 2012; Schmidt et al., 2017; Zheng et al., 2023a, 2023b). We tested two competing hypotheses about the neural delay discounting effect in anhedonia. If anhedonia is associated with reduced anticipatory reward processing, the high-anhedonia group would exhibit greater neural delay discounting compared to the low-anhedonia group. Conversely, if anhedonia is linked to reduced consummatory reward processing, the high-anhedonia group would display less neural delay discounting compared to the low-anhedonia group.

Material and methods

Participants

We recruited a high-anhedonia group and a low-anhedonia group based on their scores on the Chinese version of the Revised Chapman Physical Anhedonia Scale (RCPAS), which was administered to 1521 undergraduates (1155 females and 366 males) in introductory psychology courses at the Dalian Medical University (Spring Semester, 2022). The RCPAS consists of 61 true-false statements to assess individual differences in the ability to experience pleasure from physical and sensory stimuli. A higher score indicates a higher level of physical anhedonia. Before filling out the questionnaires, responders were informed that they would be randomly selected to participate in several EEG experiments as well as a clinical interview. Based on previous research (Wang et al., 2020; Wen et al., 2024), we invited responders whose RCPAS scores were 0.8 standard deviations (*SD*) below or above the mean score of the sample pool. Specifically, the high-anhedonia group ($N = 40$) had an RCPAS score more than 0.8 standard deviations ($SD = 8.05$) above the mean ($M = 13.97$) score of the sample pool (i.e., RCPAS score > 20.41). We also recruited 40 healthy controls as the low-anhedonia group, who had an RCPAS score of 0.8 *SD* below the mean score of the sample (i.e., RCPAS score < 7.53). A sensitivity analysis was conducted using the *simr* v1.0.6 package (Green & MacLeod, 2016) to compare the regression weight (*b*) for each effect of interest with the smallest detectable effect size at a power of 80 % based on the current sample. The results showed that the most significant effects observed were larger than the smallest detectable effect, indicating that the sample size provided sufficient statistical power. We used the Structured Clinical Interview for *Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition* (DSM-V) to exclude participants with current or past Axis I disorders including major depressive disorder and other psychiatric illness. All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of brain injuries, neurological disorders, or substance abuse. Each participant provided written informed consent prior to the experiment, and this study was approved by a local Institutional Review Board.

Procedure

Participants performed a simple guessing task after an effort-reward tasks (to be reported elsewhere). In the guessing task, they could win either a small or a large reward, to be delivered immediately or six months later. On each trial (Fig. 1), participants were presented with four doors in the center of the screen. They could choose a door by pressing the corresponding key (“D”, “F”, “J” or “K”) with their left or right middle or ring fingers. Participants were informed that each door choice would result in one of four outcomes: receiving either ¥1 or ¥10 immediately or after six months. After a door was chosen, it was highlighted with a white border for 1000 ms. Following a jittered interval between 1200 and 1500 ms, the outcome was displayed for 1000 ms. Each trial ended with an intertrial interval ranging from 900 to 1200 ms.

This task included four blocks of 40 trials each, with a short break between blocks. Participants were encouraged to use any strategy to win monetary rewards. Unbeknownst to the participants, the outcomes were predetermined and delivered in a pseudorandom manner to ensure an even distribution of 40 trials for each type of outcome. Participants were informed that an outcome from each block would be randomly drawn and delivered at the corresponding time. Prior to the experiment, participants completed four trials to familiarize themselves with the task. After the experiment, participants completed the Temporal Experience of Pleasure Scale (TEPS; Gard et al., 2006) to measure their anticipatory and consummatory pleasures, the Behavioral Inhibition System/-Behavioral Activation System Scales (BIS/BAS; Carver & White, 1994) to measure their approach and avoidance motivational tendencies, and the Beck Depression Inventory-II (BDI; Beck et al., 1996) to measure their depressive symptoms.

Data recording and processing

EEG data were recorded using 28 Ag/ AgCl electrodes (Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, Oz, and O2) based on the international 10–20 system. EEG signals were referenced online to an electrode placed between Cz and CPz and rereferenced offline to the average of two electrodes on the left and right mastoids. Horizontal electrooculogram (EOG) was recorded using a pair of electrodes placed at the external canthi of each eye, and vertical EOG was recorded using another pair of electrodes placed above and below the left eye. Both EEG and EOG signals were amplified using a Neuroscan Grael 4 K amplifier with a low-pass filter at 100 Hz and digitized at a sampling rate of 512 Hz. Electrode

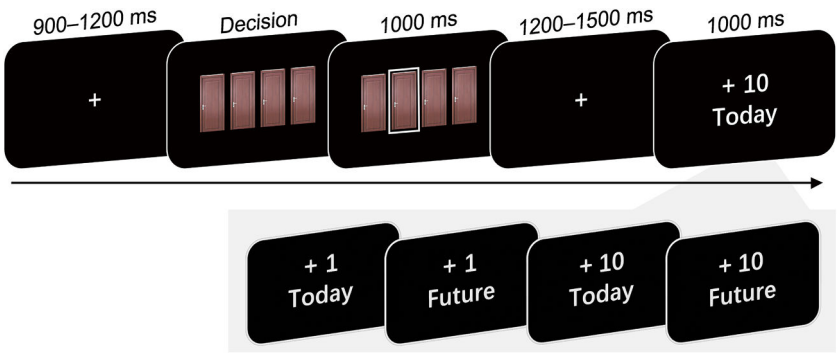

Fig. 1. Trial sequence of the simple guessing task. On each trial, participants chose one of four doors and received either a small (¥1) or a large (¥10) reward delivered immediately or six months later.

impedances were kept below 5 KΩ throughout the experiment.

The EEG data were preprocessed using the EEGLAB v2021.0 (Delorme & Makeig, 2004) and ERPLAB v8.10 (Lopez-Gamundi et al., 2021) toolboxes in MATLAB v2020b (MathWorks, USA). The data were filtered using a zero phase-shift Butterworth filter with a bandpass of 0.1–35 Hz (12 dB/octave roll-off). Electrodes with excessive noises were interpolated using the spherical interpolation algorithm, and EEG proportions with extreme voltage offsets or recorded during break periods were removed using two semi-automatic ERPLAB algorithms. The EEG data were then decomposed into independent components using the infomax independent component analysis (ICA) algorithm (Delorme & Makeig, 2004). Each IC was evaluated by the ICLabel algorithm (Pion-Tonachini et al., 2019) and, if it had a high probability of being classified as eye blink components (>85 % eye and <1 % brain), was rejected. The ICA-corrected data were then segmented into epochs from −200 to 1000 ms relative to feedback onset and baseline-corrected using the mean activity between −200 and 0 ms. Epochs were further examined for artifacts and automatically discarded if they met any of the following criteria: a voltage difference >50 μV between sample points, a voltage difference >200 μV within a trial, or a maximum voltage difference <0.5 μV within 100-ms intervals. Both groups had a similar number of artifact-free trials for each type of outcome (see Table S1 in the Supplemental Materials for details). Using an orthogonal selection approach (Luck & Gaspelin, 2016), trial-level RewP was measured as the mean activity between 250 and 350 ms over frontocentral electrodes (Fz and FCz). To confirm the specificity of the RewP findings, we also measured trial-level P3 as the mean activity between 300 and 450 ms over centroparietal electrodes (CPz and Pz).

Data analysis

Statistical analyses were performed in R. ERP data were fitted using mixed-effects single-trial regression models with varying intercepts and slopes (unstructured covariance matrix), as implemented with the *lme4* v.1.1.33 package (Bates et al., 2015). For each dataset, the model included group (low anhedonia, high anhedonia), time (immediate, delayed), magnitude (small, large), and their interactions as fixed effect predictors. All predictors were categorical and contrast coded (−0.5 for low anhedonia and +0.5 for high anhedonia; −0.5 for small and +0.5 for large; −0.5 for immediate and +0.5 for delayed). Random effects were determined based on the singular value decomposition to obtain the maximal converging models. Follow-up pairwise tests of significant interactions were performed on estimated marginal means using the *emmeans* v1.7.1.1 package (Lenth, 2022).

Furthermore, we conducted a representation similarity analysis (RSA) on the ERP time series to examine how neural representations encode reward time (immediate vs. delayed) and magnitude (small vs. large) over time. RSA is sensitive to effects based on the geometry of neural responses between different experimental conditions (Kriegeskorte et al., 2008), which cannot be captured through a univariate analysis of ERP activity over specific channels. Specifically, we calculated representational dissimilarity between time (immediate vs. delayed) and magnitude (small vs. large) based on the ERP topographies using the Mahalanobis distance, yielding a 4 × 4 neural representation dissimilarity matrix (RDM) for each participant at each time point. We also constructed a 4 × 4 model RDM for time and magnitude, respectively. We transformed the upper triangular portion of each matrix into a vector and z-scored both the model and neural RDMs. We performed a multiple regression analysis at each time point for each participant to fit the model and neural distance vectors. This resulted in a time course of regression coefficient estimates for the neural coding of time and magnitude, respectively. We conducted cluster-based permutation testing to correct for multiple comparisons over time points (Maris & Oostenveld, 2007).

Results

Demographic characteristics

The high-anhedonia versus low-anhedonia group showed lower levels of drive, fun seeking, and reward responsiveness as measured by the BAS. They also had lower levels of anticipatory and consummatory pleasures as measured by the TEPS, as well as a higher level of depressive symptom as measured by the BDI-II compared to the low-anhedonia group. No group differences were found for demographic information including gender, age, and education level (Table 1).

Table 1
Sample characteristics ($M \pm SD$).

	High anhedonia	Low anhedonia	*p* value	Cohen'*d*
Gender (M/F)	10/30	12/28	0.802	NA
Age (years)	19.50 ± 1.54	20.10 ± 2.06	0.144	0.33
Education (years)	13.30 ± 1.42	13.80 ± 1.88	0.184	0.30
PAS	29.68 ± 5.82	4.50 ± 1.71	<0.001	5.87
BDI-II	10.30 ± 9.11	4.15 ± 5.46	<0.001	0.82
BIS/BAS				
BIS	15.10 ± 2.60	15.15 ± 2.12	0.920	0.02
Drive	11.10 ± 2.79	12.59 ± 1.82	0.006	0.63
Fun seeking	14.08 ± 2.47	15.56 ± 1.73	0.003	0.70
Reward responsiveness	12.75 ± 1.78	13.77 ± 1.39	0.006	0.64
TEPS				
Anticipatory pleasure	33.25 ± 6.85	43.33 ± 4.80	<0.001	1.70
Consummatory pleasure	40.05 ± 7.21	51.13 ± 5.71	<0.001	1.70

Note. PAS, Physical Anhedonia Scale; BDI, Beck Depression Inventory; BIS/BAS, Behavioral Inhibition System/Behavioral Approach System; TEPS, Temporal Experience of Pleasure Scale. One participant from the low-anhedonia group did not complete the questionnaires.

Behavioral data

Decision-making time was similar between the high-anhedonia group (709 ± 535 ms) and the low-anhedonia group (616 ± 340 ms), $t(78) = 0.93$, $p = 0.355$, Cohen'$d = 0.21$. Both groups selected doors evenly without any preference ($ps > 0.05$), as revealed by a Group × Door ANOVA (see Table S2 in Supplementary Materials for detailed results). We also examined how door choice was influenced by the outcome on the previous trial. A Group × Time × Magnitude ANOVA revealed a significant main effect of magnitude, $F(1, 78) = 4.17$, $p = 0.045$, $\eta_p^2 = 0.05$, and a significant interaction between group and magnitude, $F(1, 78) = 5.52$, $p = 0.021$, $\eta_p^2 = 0.07$. Follow-up pairwise comparisons revealed that the high-anhedonia group changed their door choices more frequently after receiving large rewards compared to small rewards (87 % vs. 79 %, $p = 0.003$), but no significant difference was found for the low-anhedonia group (78 % vs. 79 %, $p = 0.828$). A similar ANOVA on decision-making times revealed significant main effects of time, $F(1, 78) = 27.09$, $p < 0.001$, $\eta_p^2 = 0.26$, and magnitude, $F(1, 78) = 46.68$, $p < 0.001$, $\eta_p^2 = 0.37$, as well as a significant interaction between time and magnitude, $F(1, 78) = 31.82$, $p < 0.001$, $\eta_p^2 = 0.29$. Follow-up pairwise comparisons revealed that decision-making time was slower after receiving small rewards compared to large rewards when they were immediate (613 ms vs. 786 ms, $p < 0.001$) but not when they were delayed (618 ms vs. 630 ms, $p = 0.466$). No other significant effects were found ($ps > 0.05$).

Electrophysiological data

ERP data

Table 2 shows coefficient estimates for each ERP model. As shown in Fig. 2A, the RewP showed a more positive response for large rewards compared to small rewards, $\beta = 1.76$, $p < 0.001$. The RewP also exhibited a discounting effect of time, with its amplitude being less positive for delayed rewards compared to immediate rewards, $\beta = -1.05$, $p < 0.001$. Moreover, the RewP tracked the interaction between time and magnitude, $\beta = -1.47$, $p < 0.001$, which was further modified by a significant three-way interaction among group, time, magnitude, $\beta = -1.47$, $p = 0.042$. To decompose the three-way interaction, a linear mixed-effects model was performed separately for the high- and low-anhedonia groups, with time, magnitude, and their interaction as predictions (see Table S3 in Supplementary Materials for detailed results). For the high-anhedonia group, we observed significant main effects of time, $\beta = -0.80$, $p = 0.007$, and magnitude, $\beta = 1.72$, $p < 0.001$, as well as a significant two-way interaction between time and magnitude, $\beta = -2.21$, $p < 0.001$. Follow-up pairwise comparisons showed that the RewP was less positive for small rewards compared to large rewards when they were immediate, $\beta = -2.83$, $z = -5.59$, $p < 0.001$, but not when they were delayed, $\beta = -0.62$, $z = -1.22$, $p = 0.223$. For the low-anhedonia group, there were significant main effects of time, $\beta = -1.29$, $p < 0.001$, and magnitude, $\beta = 1.79$, $p < 0.001$, but the two-way interaction between time and magnitude was not significant, $\beta = -0.75$, $p = 0.136$, suggesting that the magnitude effect was present regardless of when rewards were delivered during the RewP period.

As depicted in Fig. 2B, the P3 was more positive for large rewards compared to small rewards, $\beta = 1.05$, $p < 0.001$, and less positive for delayed rewards compared to immediate rewards, $\beta = -0.83$, $p < 0.001$. The P3 tracked the two-way interactions between time and magnitude $\beta = -2.18$, $p < 0.001$, between group and magnitude, $\beta = -1.24$, $p = 0.028$, as well as the three-way interaction among group, time, and magnitude, $\beta = -2.09$, $p = 0.007$. To decompose the three-way interaction, we performed a linear mixed-effects model separately for the high- and low-anhedonia groups (see Table S4 in Supplementary Materials for detailed results). For the high-anhedonia group, we observed a significant main effect of time, $\beta = -0.84$, $p = 0.001$, and a significant time-by magnitude interaction effect, $\beta = -3.23$, $p < 0.001$. Post hoc comparisons revealed that P3 amplitude was less positive for small rewards compared to large rewards when they were immediate, $\beta = -2.04$, $z = -4.56$, $p < 0.001$, but more positive for small rewards compared to large rewards when they were delayed, $\beta = 1.19$, $z = 2.64$, $p = 0.008$. For the low-anhedonia group, we observed significant main effects of time, $\beta = -0.82$, $p = 0.008$, and magnitude, $\beta = 1.66$, $p < 0.001$, as well as a significant time-by-magnitude interaction, $\beta = -1.14$, $p = 0.027$. Post hoc comparisons revealed that P3 amplitude was less positive for small rewards compared to large rewards when rewards were immediate, $\beta = -2.23$, $z = -4.31$, $p < 0.001$. This magnitude effect was less pronounced when rewards were delayed, $\beta = -1.10$, $z = -2.39$, $p = 0.017$.

To controlling for the potential confounding effects of depressive symptoms, we performed additional analyses for our ERP components by including the BDI score as a nuisance regressor (z-scored across participants as a subject-level variable) in the RewP and P3 models. Results revealed that the above ERP results remained the same (see Table S5 in Supplementary Materials for detailed results). These control analyses indicated that the relationship between anhedonia and ERP data was unaffected by depressive symptoms in the current sample.

Time-resolved neural encoding data

Next, we conducted the multivariate RSA to examine the time-resolved neural presentations of time and magnitude in anhedonia (Fig. 3). For the low-anhedonia group, the neural coding of magnitude emerged shortly after feedback onset and lasted for almost the entire epoch (98–728 ms, $p < 0.001$; 772–1000 ms, $p = 0.028$). We did not find any reliable neural coding for time. The neural coding for magnitude was significantly greater than for time (227–1000 ms, $p < 0.001$). For the high-anhedonia group, magnitude coding emerged shortly after feedback onset (90–767 ms, $p < 0.001$), followed by time coding (135–351 ms, $p = 0.013$). The neural coding for magnitude was significantly greater than for time only during a short interval (245–418 ms, $p = 0.030$).

Table 2
Model results of the linear mixed-effects regression for RewP and P3 amplitudes.

	RewP			P3		
Predictors	Estimates	95 % CI	*p*	Estimates	95 % CI	*p*
Intercept	6.46	5.38–7.55	**<0.001**	10.77	9.67–11.87	**<0.001**
Group	0.27	−1.90–2.45	0.806	0.51	−1.69–2.72	0.647
Time	−1.05	−1.42–−0.67	**<0.001**	−0.83	−1.22–−0.44	**<0.001**
Magnitude	1.76	1.22–2.30	**<0.001**	1.05	0.49–1.60	**<0.001**
Group:Time	0.49	−0.26–1.23	0.199	−0.02	−0.80–0.76	0.964
Group:Magnitude	−0.07	−1.15–1.00	0.894	−1.24	−2.34–−0.13	**0.028**
Time:Magnitude	−1.47	−2.18–−0.77	**<0.001**	−2.18	−2.95–−1.42	**<0.001**
Group:Time:Magnitude	−1.47	−2.88–−0.05	**0.042**	−2.09	−3.61–−0.56	**0.007**

Note. Statistics are derived from linear mixed-effects models with predictors as noted. The final model is described using Wilkinson notation as: Amplitude ~ Group × Time × Magnitude + (1 + Time + Magnitude | Participant) for RewP and Amplitude ~ Group × Time × Magnitude + (1 + Time × Magnitude | Participant) for P3. Statistically significantly *p* values (<0.05, two-sided) are shown in bold. RewP, reward positivity; CI = confidence interval.

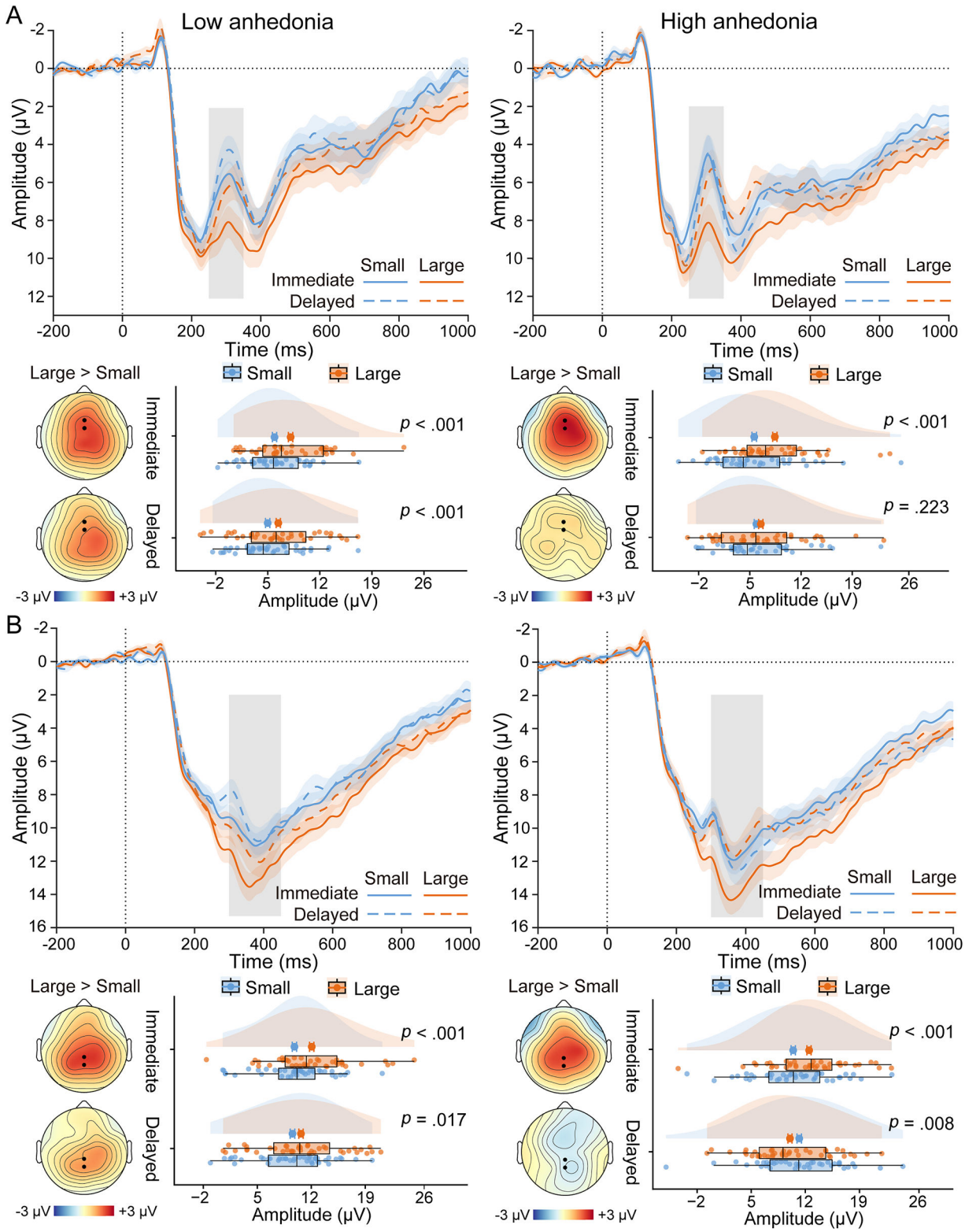

Fig. 2. (A–B) Anhedonia effects on the time domain data. (A) Grand-averaged ERP waveforms over frontocentral areas as a function of time and magnitude for the low- and high-anhedonia groups, respectively. Raincloud plots and topographic maps show the magnitude effect on the RewP as a function of time. (B) same as (A), except that ERP waveforms represent an average over centroparietal areas, and data points present amplitude data for the P3.

Discussion

Recent years have witnessed a surge of interest in distinguishing the anticipatory and the consummatory components of anhedonia in terms of temporal experience (Gard et al., 2006). However, few research has directly examined reward valuation as a function of time in anhedonia. In this study, we investigate this issue by characterizing neural responses to small and large rewards delivered immediately or six months later in anhedonia using a nonclinical sample. We found that anhedonia was associated with greater neural delay discounting during reward

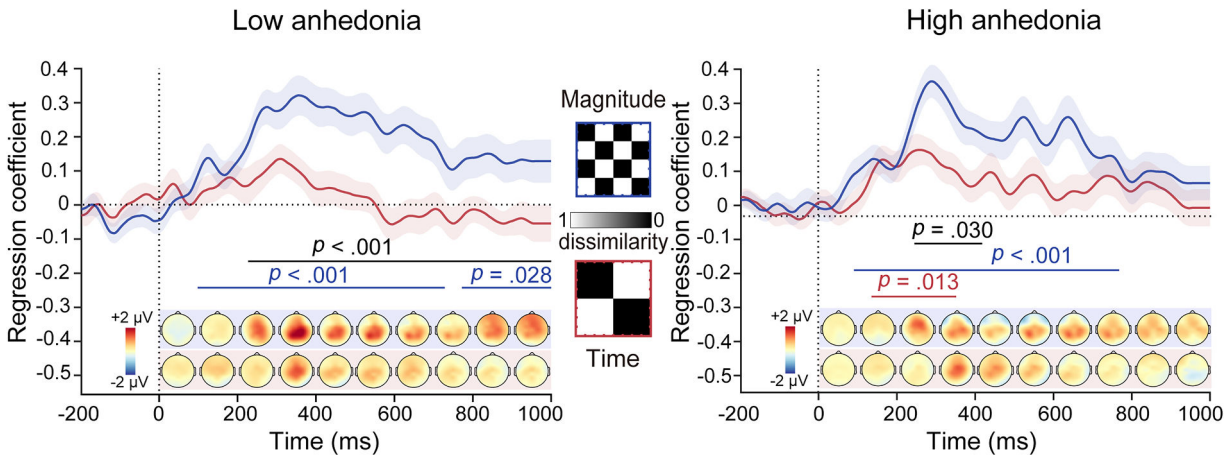

Fig. 3. (A) Time-resolved neural representations of time and magnitude in anhedonia. Model RDMs are depicted in the middle. Colored shaded error bars around lines indicate the standard error of the mean across individuals. Colored horizontal lines indicate significant differences from zero, and black horizontal lines present significant differences between time and magnitude. Topographic maps illustrate magnitude effects (large vs. small) and time effects (immediate vs. delayed) from 0 ms to 1000 ms in increments of 100 ms after feedback onset.

evaluation. This was evidenced by a blunted effect of reward magnitude on the RewP in the high-anhedonia group compared to the low-anhedonia group when the rewards would be delivered six months later. This aberration in processing delayed rewards was further corroborated by enhanced neural coding of reward time in the high-anhedonia relative to the low-anhedonia group. Our results provide the first neural evidence that delay discounting in anhedonia is attributable to the hyposensitivity to delayed rewards instead of the hypersensitivity to immediate rewards.

We observed the classic RewP effects such that its amplitudes were increased for larger versus low rewards (Goyer et al., 2008; Meadows et al., 2016) but decreased as the time to receive them increased (Cherniawsky & Holroyd, 2012; Schmidt et al., 2017; Zheng et al., 2023a, 2023b) . In line with the established finding that healthy adults exhibited comparable valence effects (i.e., gain versus loss) on the RewP across immediate and delayed outcomes (Huang et al., 2017), the low-anhedonia group exhibited similar effects of reward magnitude (i.e., large versus small rewards) regardless of whether the rewards were delivered immediately or six months later. In contrast, the high-anhedonia group showed a magnitude effect on the RewP for immediate rewards but not for delayed rewards, suggesting a neural delay discounting in anhedonia. Our finding of greater neural delay discounting is consistent with previous behavioral studies observing a greater delay discounting among anhedonic individuals (Cai et al., 2019; Olson et al., 2018; Veldhoven et al., 2020). Importantly, our findings extend these studies by measuring neural responses to immediate and delayed rewards separately in anhedonia. We provide direct evidence that delay discounting in anhedonia is attributable to the hyposensitivity to delayed rewards instead of the hypersensitivity to immediate rewards. This greater neural delay discounting was further supported by our multivariate RSA results. The RSA is a data-driven approach, characterizing the representational geometry of reward magnitude and reward time in terms of the multivariate similarity among ERP topographies (Kriegeskorte et al., 2008). While both groups showed reliable neural coding for reward magnitude, only the high-anhedonia group exhibited neural coding of reward time during the RewP period (135–351 ms). In contrast, the low-anhedonia group failed to display any neural coding of reward time across the whole window of feedback processing. These data-driven results are consistent with our univariate RewP findings, indicating that time is an important dimension for anhedonia.

A potential explanation for greater neural delay discounting in anhedonia is attributed to the inability to form mental representations of future positive experiences. One hypothesis is that anhedonic individuals have a bleak view of the future and cannot form mental representations of positive future experiences, resulting in a bias towards immediate rewards over delayed ones (Beck, 2005). Importantly, our electrocortical data provide direct evidence for this inability to build neural representations of future rewards in anhedonia. These findings contribute to a mechanistic understanding of anhedonia by measuring neural responses to immediate and delayed rewards in anhedonia, which is more advantageous than previous behavioral studies that measure the subjective value of delayed rewards using immediate rewards as the reference (Cai et al., 2019; Lempert & Pizzagalli, 2010; Olson et al., 2018; Veldhoven et al., 2020). Our finding of the blunted neural representation of future rewards in anhedonia suggests that future intervention and prevention should focus on future-oriented thinking in anhedonia. Developing a positive outlook towards the future may help prevent anhedonic individuals from falling into the trap of immediate gratification.

Our findings contribute to understanding mechanisms underlying anhedonia. Echoing with the distinction between anticipatory (future-oriented) and consummatory (in-the-moment) anhedonia (Gard et al., 2006), this study demonstrates that anhedonia is associated with a blunted neural representation of delayed rewards rather than immediate rewards. Our finding aligns with recent theories that motivation, which is future-oriented and more associated with anticipatory pleasure, plays a more critical role in anhedonia among nonclinical and clinical populations (Husain & Roiser, 2018; Romer et al., 2015; Treadway & Zald, 2011). Under the cost-benefit framework, motivation refers to the process that facilitates overcoming costs to achieve desired outcomes (Soutschek & Tobler, 2018). Previous studies have reported that anhedonia is associated with less willingness to overcome effort costs for rewards (Ang et al., 2022; Barch et al., 2014; Slaney et al., 2022; Treadway et al., 2009) and inefficient effort allocation in pursuit of rewards (McCarthy et al., 2015; Wen et al., 2024). Our finding extends these studies by demonstrating that anhedonia is susceptible to time costs in pursuit of rewards. Therefore, it is tempting to infer that the abnormal cost-benefit mechanism in anhedonia is similar across different cost domains. Future research is needed to examine this possibility by comparing the cost-benefit mechanism across effort and time domains in anhedonia (Soutschek & Tobler, 2018).

This study should be viewed in the context of several caveats. First, unlike the neural dissociation between immediate and delayed rewards, the high-anhedonia versus low-anhedonia group reported lower levels of anticipatory and consummatory pleasures, as measured by the TEPS. This might be due to the retrospective nature of the questionnaire, resulting in a conflation between anticipatory and consummatory

pleasures. Second, our study lacks behavioral evidence of greater delay discounting as a direct replication of previous investigations. It is necessary to assess both the relative and absolute subjective values of immediate versus delayed rewards to provide a comprehensive understanding of delay discounting in anhedonia. Third, we recruited participants with high and low anhedonia from a nonclinical sample based on their RCPAS scores. Our findings are thus not necessarily in alignment with the investigation in clinical populations suffering from anhedonia-relevant psychiatric disorders such as schizophrenia and depression. Also, our findings may not be directly applicable to the treatment of pathological conditions or to address pathophysiological mechanisms. Future research should examine the relationship between neural delay discounting and anhedonia in clinical samples (Pulcu et al., 2013; Takahashi et al., 2008). Forth, given that our sample consisted of young adults who may still be undergoing brain maturation in regions involved in reward circuits (Barkley-Levenson & Galván, 2014), future research should extend our findings to other age groups to investigate the neurodevelopmental effect on neural delay discounting in anhedonia.

Conclusion

This is the first study to measure neural responses to immediate and delayed rewards in anhedonia using a nonclinical sample. Univariate ERP results demonstrate a neural delay discounting in anhedonia, showing a blunted effect of reward magnitude on the RewP in individuals with high anhedonia when the rewards would be delivered six months later. Multivariate RSA results indicate that the neural delay discounting is associated with a sensitive neural representation of reward time in anhedonia. These results suggest the inability to form mental representations of future positive experiences in anhedonia.

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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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijchp.2024.100542.

References

Ahn, W. Y., Rass, O., Fridberg, D. J., Bishara, A. J., Forsyth, J. K., Breier, A., Busemeyer, J. R., Hetrick, W. P., Bolbecker, A. R., & O'Donnell, B. F. (2011). Temporal discounting of rewards in patients with bipolar disorder and schizophrenia. *Journal of Abnormal Psychology, 120*(4), 911–921. https://doi.org/10.1037/a0023333

Ainslie, G. (1975). Specious reward: A behavioral theory of impulsiveness and impulse control. *Psychological Bulletin, 82*(4), 463–496. https://doi.org/10.1037/h0076860

Ang, Y. S., Gelda, S. E., & Pizzagalli, D. A. (2022). Cognitive effort-based decision-making in major depressive disorder. *Psychological Medicine, 53*(9), 4228–4235. https://doi.org/10.1017/s0033291722000964

Avakian, A. D., & Markou, A. (2012). The neurobiology of anhedonia and other reward-related deficits. *Trends in Neurosciences, 35*(1), 68–77. https://doi.org/10.1016/j.tins.2011.11.005

Barch, D. M., Treadway, M. T., & Schoen, N. (2014). Effort, anhedonia, and function in schizophrenia: Reduced effort allocation predicts amotivation and functional impairment. *Journal of Abnormal Psychology, 123*(2), 387–397. https://doi.org/10.1037/a0036299

Barkley-Levenson, E., & Galván, A. (2014). Neural representation of expected value in the adolescent brain. *Proceedings of the National Academy of Sciences of the United States of America, 111*(4), 1646–1651. https://doi.org/10.1073/pnas.1319762111

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Beck, A. T. (2005). The current state of cognitive therapy: A 40-year retrospective. *Archives of General Psychiatry, 62*(9), 953–959. https://doi.org/10.1001/archpsyc.62.9.953

Beck, A. T., Steer, R. A., & Brown, G. K. (1996). *Manual for the beck depression inventory-II*. San Antonio, TX: Psychologica Corporation.

Cai, X. L., Weigl, M., Liu, B. H., Cheung, E. F. C., Ding, J. H., & Chan, R. C. K. (2019). Delay discounting and affective priming in individuals with negative schizotypy. *Schizophrenia Research, 210*, 180–187. https://doi.org/10.1016/j.schres.2018.12.040

Carver, C. S., & White, T. L. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS Scales. *Journal of Personality and Social Psychology, 67*(2), 319–333. https://doi.org/10.1037/0022-3514.67.2.319

Cherniawsky, A. S., & Holroyd, C. B. (2012). High temporal discounters overvalue immediate rewards rather than undervalue future rewards: An event-related brain potential study. *Cognitive, Affective, & Behavioral Neuroscience, 13*(1), 36–45. https://doi.org/10.3758/s13415-012-0122-x

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dombrovski, A. Y., Szanto, K., Siegle, G. J., Wallace, M. L., Forman, S. D., Sahakian, B., Reynolds, C. F., & Clark, L. (2011). Lethal forethought: Delayed reward discounting differentiates high- and low-lethality suicide attempts in old age. *Biological Psychiatry, 70*(2), 138–144. https://doi.org/10.1016/j.biopsych.2010.12.025

Engelmann, J. B., Maciuba, B., Vaughan, C., Paulus, M. P., & Dunlop, B. W. (2013). Posttraumatic stress disorder increases sensitivity to long term losses among patients with major depressive disorder. *PLoS One, 8*(10), e78292. https://doi.org/10.1371/journal.pone.0078292

Gard, D. E., Gard, M. G., Kring, A. M., & John, O. P. (2006). Anticipatory and consummatory components of the experience of pleasure: A scale development study. *Journal of Research in Personality, 40*(6), 1086–1102. https://doi.org/10.1016/j.jrp.2005.11.001

Goyer, J. P., Woldorff, M. G., & Huettel, S. A. (2008). Rapid electrophysiological brain responses are influenced by both valence and magnitude of monetary rewards. *Journal of Cognitive Neuroscience, 20*(11), 2058–2069. https://doi.org/10.1162/jocn.2008.20134

Green, P., & MacLeod, C. J. (2016). SIMR: An R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution, 7*(4), 493–498. https://doi.org/10.1111/2041-210X.12504

Hatzigiakoumis, D. S., Martinotti, G., Giannantonio, M. D., & Janiri, L. (2011). Anhedonia and substance dependence: Clinical correlates and treatment options [Review] *Frontiers in Psychiatry, 2*. https://doi.org/10.3389/fpsyt.2011.00010.

Horan, W. P., Johnson, M. W., & Green, M. F. (2017). Altered experiential, but not hypothetical, delay discounting in schizophrenia. *Journal of Abnormal Psychology, 126*(3), 301–311. https://doi.org/10.1037/abn0000249

Huang, Y., Hu, P., & Li, X. (2017). Undervaluing delayed rewards explains adolescents' impulsivity in inter-temporal choice: An ERP study. *Scientific Reports, 7*(1). https://doi.org/10.1038/srep42631

Husain, M., & Roiser, J. P. (2018). Neuroscience of apathy and anhedonia: A transdiagnostic approach. *Nature Reviews Neuroscience, 19*(8), 470–484. https://doi.org/10.1038/s41583-018-0029-9

Kirby, K. N., Petry, N. M., & Bickel, W. K. (1999). Heroin addicts have higher discount rates for delayed rewards than non-drug-using controls. *Journal of Experimental Psychology: General, 128*(1), 78–87. https://doi.org/10.1037//0096-3445.128.1.78

Kriegeskorte, N., Mur, M., & Bandettini, P. (2008). Representational similarity analysis—connecting the branches of systems neuroscience. *Frontiers in Systems Neuroscience*. https://doi.org/10.3389/neuro.06.004.2008

Lempert, K. M., & Pizzagalli, D. A. (2010). Delay discounting and future-directed thinking in anhedonic individuals. *Journal of Behavior Therapy and Experimental Psychiatry, 41*(3), 258–264. https://doi.org/10.1016/j.jbtep.2010.02.003

Lenth, R.V. (2022). *Emmeans: Estimated marginal means, aka least-squares means*. In R package version 1.7.1.

Lopez-Gamundi, P., Yao, Y.-W., Chong, T. T. J., Heekeren, H. R., Herrero, E. M., & Pallares, J. M. (2021). The neural basis of effort valuation: A meta-analysis of functional magnetic resonance imaging studies. *Neuroscience & Biobehavioral Reviews, 131*, 1275–1287. https://doi.org/10.1016/j.neubiorev.2021.10.024

Luck, S. J., & Gaspelin, N. (2016). How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology, 54*(1), 146–157. https://doi.org/10.1111/psyp.12639

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

McCarthy, J. M., Treadway, M. T., & Blanchard, J. J. (2015). Motivation and effort in individuals with social anhedonia. *Psychiatry Research, 165*(1), 70–75. https://doi.org/10.1016/j.schres.2015.03.030

Meadows, C. C., Gable, P. A., Lohse, K. R., & Miller, M. W. (2016). The effects of reward magnitude on reward processing: An averaged and single trial event-related

potential study. *Biological Psychology, 118*, 154–160. https://doi.org/10.1016/j.biopsycho.2016.06.002

Miltner, W. H., Braun, C. H., & Coles, M. G. (1997). Event-related brain potentials following incorrect feedback in a time-estimation task: Evidence for a "generic"' neural system for error detection. *Journal of Cognitive Neuroscience, 9*(6), 788–798. https://doi.org/10.1162/jocn.1997.9.6.788

Nusslock, R., & Alloy, L. B. (2017). Reward processing and mood-related symptoms: An RDoC and translational neuroscience perspective. *Journal of Affective Disorders, 216*, 3–16. https://doi.org/10.1016/j.jad.2017.02.001

Olson, E. A., Ahmad, S., Granger, S. J., Ashraf, A., Pizzagalli, D. A., & Rosso, I. M. (2024). Anhedonia and delay discounting: Differing patterns of brain-behavior relationships in healthy control participants versus individuals with posttraumatic stress disorder. *Biological Psychiatry. Cognitive Neuroscience and Neuroimaging, 9*(1), 80–90. https://doi.org/10.1016/j.bpsc.2023.07.013

Olson, E. A., Kaiser, R. H., Pizzagalli, D. A., Rauch, S. L., & Rosso, I. M. (2018). Anhedonia in trauma-exposed individuals: Functional connectivity and decision-making correlates. *Biological Psychiatry. Cognitive Neuroscience and Neuroimaging, 3*(11), 959–967. https://doi.org/10.1016/j.bpsc.2017.10.008

Pelizza, L., & Ferrari, A. (2009). Anhedonia in schizophrenia and major depression: State or trait? *Annals of General Psychiatry, 8*(1). https://doi.org/10.1186/1744-859x-8-22

Pion-Tonachini, L., Kreutz-Delgado, K., & Makeig, S. (2019). The ICLabel dataset of electroencephalographic (EEG) independent component (IC) features. *Data in Brief, 25*. https://doi.org/10.1016/j.dib.2019.104101

Proudfit, G. H. (2015). The reward positivity: From basic research on reward to a biomarker for depression. *Psychophysiology, 52*(4), 449–459. https://doi.org/10.1111/psyp.12370

Pulcu, E., Trotter, P. D., Thomas, E. J., McFarquhar, M., Juhasz, G., Sahakian, B. J., Deakin, J. F. W., Zahn, R., Anderson, I. M., & Elliott, R. (2013). Temporal discounting in major depressive disorder. *Psychological Medicine, 44*(9), 1825–1834. https://doi.org/10.1017/s0033291713002584

Rizvi, S. J., Pizzagalli, D. A., Sproule, B. A., & Kennedy, S. H. (2016). Assessing anhedonia in depression: Potentials and pitfalls. *Neuroscience & Biobehavioral Reviews, 65*, 21–35. https://doi.org/10.1016/j.neubiorev.2016.03.004

Romer, T. K., Whybrow, P. C., & Kringelbach, M. L. (2015). Reconceptualizing anhedonia: Novel perspectives on balancing the pleasure networks in the human brain. *Frontiers in Behavioral Neuroscience, 9*. https://doi.org/10.3389/fnbeh.2015.00049

Schmidt, B., Holroyd, C. B., Debener, S., & Hewig, J. (2017). I can't wait! Neural reward signals in impulsive individuals exaggerate the difference between immediate and future rewards. *Psychophysiology, 54*(3), 409–415. https://doi.org/10.1111/psyp.12796

Slaney, C., Perkins, A. M., Davis, R., Penton-Voak, I., Munafò, M. R., Houghton, C. J., & Robinson, E. S. J. (2022). Objective measures of reward sensitivity and motivation in people with high v. low anhedonia. *Psychological Medicine, 53*(10), 4324–4332. https://doi.org/10.1017/s0033291722001052

Soutschek, A., & Tobler, P. N. (2018). Motivation for the greater good: Neural mechanisms of overcoming costs. *Current Opinion in Behavioral Sciences, 22*, 96–105. https://doi.org/10.1016/j.cobeha.2018.01.025

Takahashi, T., Oono, H., Inoue, T., Boku, S., Kako, Y., Kitaichi, Y., Kusumi, I., Masui, T., Nakagawa, S., Suzuki, K., Tanaka, T., Koyama, T., & Radford, M. H. (2008). Depressive patients are more impulsive and inconsistent in intertemporal choice behavior for monetary gain and loss than healthy subjects-an analysis based on Tsallis' statistics. *Neuro Endocrinology Letters, 29*(3), 351–358.

Treadway, M. T., Buckholtz, J. W., Schwartzman, A. N., Lambert, W. E., & Zald, D. H. (2009). Worth the 'EEfRT'? The effort expenditure for rewards task as an objective measure of motivation and anhedonia. *PLoS One, 4*(8). https://doi.org/10.1371/journal.pone.0006598

Treadway, M. T., & Zald, D. H. (2011). Reconsidering anhedonia in depression: Lessons from translational neuroscience. *Neuroscience & Biobehavioral Reviews, 35*(3), 537–555. https://doi.org/10.1016/j.neubiorev.2010.06.006

Veldhoven, D. T., Roozen, H., & Vingerhoets, A. (2020). The association between reward sensitivity and activity engagement: The influence of delay discounting and anhedonia. *Alcohol and Alcoholism, 55*(2), 215–224. https://doi.org/10.1093/alcalc/agz105

Wang, Z., Li, Q., Nie, L., & Zheng, Y. (2020). Neural dynamics of monetary and social reward processing in social anhedonia. *Social Cognitive and Affective Neuroscience, 15*(9), 991–1003. https://doi.org/10.1093/scan/nsaa128

Wen, H., Wu, M., Wang, Z., Gao, B., & Zheng, Y. (2024). Aberrant effort-based reward dynamics in anhedonia. *Cereb Cortex, 34*(5), bhae193. https://doi.org/10.1093/cercor/bhae193

Whitton, A. E., Treadway, M. T., & Pizzagalli, D. A. (2015). Reward processing dysfunction in major depression, bipolar disorder and schizophrenia. *Current Opinion in Psychiatry, 28*(1), 7–12. https://doi.org/10.1097/yco.0000000000000122

Wing, V. C., Moss, T. G., Rabin, R. A., & George, T. P. (2012). Effects of cigarette smoking status on delay discounting in schizophrenia and healthy controls. *Addictive Behaviors, 37*(1), 67–72. https://doi.org/10.1016/j.addbeh.2011.08.012

Zheng, Y., Guan, C., Wang, Z., Yang, W., & Gao, B. (2023a). Electrocortical correlates of hypersensitivity to large immediate rewards in sensation seeking. *NeuroImage, 284*. https://doi.org/10.1016/j.neuroimage.2023.120456

Zheng, Y., Shi, P., Deng, L., Jiang, H., & Zhou, S. (2023b). Contextual valence influences the neural dynamics of time and magnitude representation during feedback evaluation. *Psychophysiology, 60*(10), e14335. https://doi.org/10.1111/psyp.14335