

Neural dynamics of monetary and social reward processing in social anhedonia

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Abstract

Being characterized by reduced pleasure from social interaction, social anhedonia constitutes a transdiagnostic marker for various psychiatric disorders. However, the neural portrait of social anhedonia remains elusive because of heterogeneities of reward type and reward dynamics in previous studies. The present event-related potential study investigated neural dynamics in response to monetary and social rewards in social anhedonia. Event-related potential responses were examined when a high social anhedonia (HSA, $N = 23$) group and a low social anhedonia (LSA, $N = 26$) group were anticipating and consuming social and monetary rewards. LSA but not HSA participants showed an increased stimulus-preceding negativity (anticipatory phase) and increased reward positivity (consummatory phase) for monetary as compared with social rewards. This group difference could spring from an increased relevance of social rewards or a general decline in affective responding due to a potential association between social anhedonia and depression. Our findings provide preliminary evidence for neural aberrations of the reward system in social anhedonia, which is contingent upon reward type and reward dynamics.

Key words: social anhedonia; reward dynamics; reward type; event-related potentials

Introduction

Anhedonia refers to a lack of interest to pursue rewarding activities and an inability to experience pleasure once obtained, which is associated with anticipatory and consummatory aspects of the reward system, respectively (Rømer Thomsen *et al.*, 2015). Due to its transdiagnostic nature (Rizvi *et al.*, 2018), anhedonia has been included in the Positive Valence System dimension of the Research Domain Criteria (Nusslock and Alloy, 2017), a new classification framework that aims to identify pathophysiological mechanisms common to various psychological diseases (Insel *et al.*, 2010). Therefore, a precise characterization of the

neural correlates underlying anhedonia may contribute to a better understanding of the pathophysiology of relevant psychiatric disorders. Importantly, anhedonia consists of a physical component and a social component (Chapman *et al.*, 1976). Whereas physical anhedonia is associated with decreased pleasure to sensory or physical stimuli, social anhedonia is characterized by reduced pleasure from social interaction (Chapman *et al.*, 1976; Kupferberg *et al.*, 2016). However, this distinction has often been ignored in the literature (Rømer Thomsen *et al.*, 2015), and previous research has mainly focused on anhedonia in general and its physical dimension (Harvey *et al.*, 2007; Wacker *et al.*, 2009). In

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the current study, we focus on reward processing in social anhedonia, which is experiencing a resurgence of interest in recent years (Barkus and Badcock, 2019).

Aberrations in the reward system are central to social anhedonia. Few studies using clinical samples have linked high social anhedonia (HSA) to reduced neural responses during anticipation of monetary rewards in patients with schizophrenia (Vignapiano et al., 2016) but increased brain responses to reward anticipation in individuals with negative schizotypy (Yan et al., 2016), as well as to reduced gray matter volume in the caudate nucleus of the reward system in patients suffering from major depressive disorder (Enneking et al., 2019). More recent research has focused on nonclinical and medication naïve individuals to exclude disease-related confounds. Behaviorally, elevated social anhedonia has been associated with reduced motivation (Wang et al., 2018) and inefficient effort allocation for monetary rewards (McCarthy et al., 2015), reduced reward learning for social instead of monetary rewards (Chevallier et al., 2016), as well as reduced hedonic experience to positive social affective images but not for monetary rewards (Xie et al., 2014). Neuroimaging studies have demonstrated that social anhedonia is related to increased brain responses during mutual liking relative to received liking (Healey et al., 2014) and altered (hypo- or hyper-) neural connectivity in healthy adults (Healey et al., 2014; Yin et al., 2015; Wang et al., 2016).

Taken together, existing findings suggest that although social anhedonia is associated with an aberrant reward system, a clear portrait of this relationship is lacking due to the heterogeneities of the previous studies. One heterogeneity concerns reward type. Previous studies on social anhedonia mostly used either monetary rewards (McCarthy et al., 2015; Karcher et al., 2017; Wang et al., 2018) or social rewards as diverse as affective images (Xie et al., 2014), interpersonally facial expressions (Yin et al., 2015), 'thumbs up' video clips (Chevallier et al., 2016) and social acceptance (Healey et al., 2014). Although a common neural system has been proposed to be implicated in processing social and monetary rewards (Levy and Glimcher, 2012), evidence has emerged that the two types of rewards are processed by distinct neural circuits (Rademacher et al., 2010). Indeed, several studies found that social anhedonia appeared to be more driven by aberrations in processing social rewards than monetary rewards (Xie et al., 2014; Chevallier et al., 2016).

Another heterogeneity is associated with reward dynamics, that is, the multifaceted nature of the reward system. It is well known that reward is not a monolithic construct but includes at least an anticipatory ('wanting') component and a consummatory ('liking') component, which is dissociable at both behavioral and neural levels (Berridge and Robinson, 2003). Therefore, examining the anticipatory and consummatory phases of reward processing in social anhedonia may elucidate whether the aberrant reward system results from reward anticipation, reward consumption or both. Indeed, recent theories highlight that reward deficits underlying anhedonia are more associated with the anticipatory aspect than the consummatory aspect based on the observation of specific aberration in the anticipatory reward processing among various clinical diseases characterized by anhedonia including schizophrenia, major depressive disorder and addiction (Treadway and Zald, 2011; Rømer Thomsen et al., 2015; Nusslock and Alloy, 2017). However, previous studies on social anhedonia focused on either the anticipatory/motivational (McCarthy et al., 2015; Vignapiano et al., 2016; Wang et al., 2018) or the consummatory (Karcher et al., 2017) dimension. A recent functional magnetic

resonance imaging (fMRI) study examined the reward dynamics (anticipatory vs. consummatory processing) in social anhedonia and found that social anhedonia was associated with increased brain activation to monetary gains during the anticipatory phase but not the consummatory phase (Yan et al., 2016). Unfortunately, fMRI may be not suitable to track neural dynamics of reward processing because of its inferior temporal resolution. Specifically, fMRI may conflate neural activity related to temporally close but psychologically distinct processes (e.g. the anticipatory vs. consummatory phase during reward processing).

This issue could be circumvented by the event-related potential (ERP) technique, which possesses a fine-grained time resolution and thus affords the separation of neural processes during the anticipatory and consummatory phases of reward processing (Glazer et al., 2018). Anticipatory reward processing is typically indexed by the stimulus-preceding negativity (SPN), an ERP component that is evident as a slow negative-going negativity with a broad scalp topography during the waiting period of motivational stimuli and is associated with the dopaminergic reward system (Brunia et al., 2011). For consummatory reward processing, the reward positivity (RewP) and the feedback P3 (fb-P3) components are most relevant. The RewP is a relative positivity over frontocentral areas occurring around 300 ms following gain relative to loss feedback and is thought as a neural marker for reward sensitivity (Proudfit, 2015) or reward prediction error (Holroyd and Coles, 2002). The subsequent fb-P3 is a parietal positivity peaking between 300 and 600 ms and is linked to motivational salience during feedback processing (Nieuwenhuis et al., 2005). Using healthy samples, recent ERP studies have demonstrated that monetary and social rewards elicit morphologically similar ERPs during both the anticipatory and consummatory phases of reward processing. Specifically, whereas the SPN and the fb-P3 were found to be enhanced for monetary rewards than social rewards, the RewP seemed to be comparable across reward types (Ait Oumeziane et al., 2017; Distefano et al., 2018; Ait Oumeziane et al., 2019; but see Ethridge and Weinberg, 2018). To our knowledge, only one previous study using a reversal learning task found that the RewP in response to monetary rewards was unaffected by social anhedonia as determined by the Revised Chapman Social Anhedonia Scale (RSAS; Karcher et al., 2017).

The current study aimed to investigate neural dynamics in response to monetary and social rewards in social anhedonia using a nonclinical sample. We examined electrocortical responses in the anticipatory and consummatory phases when an HSA group and a low social anhedonia (LSA) group were anticipating and consuming social and monetary rewards. Based on the research reviewed earlier, we hypothesized that social anhedonia would be associated with an abnormality in reward processing, which should depend on neural dynamics and reward type. Specifically, during the anticipatory phase of reward processing, the HSA group would exhibit a reduced SPN than the LSA group for both monetary and social rewards, based on previous findings of reduced motivation in social anhedonia (McCarthy et al., 2015; Chevallier et al., 2016; Wang et al., 2018). During the consummatory phase, no group differences were expected for the RewP and fb-P3 in response to monetary rewards, as previous research has reported relatively intact consummatory reward processing of monetary rewards in social anhedonia (Yan et al., 2016; Karcher et al., 2017). Consummatory ERP responses to social rewards would be modulated by social anhedonia, but the direction was unclear because both

hypo- and hyper-neural responses have been reported (Healey et al., 2014; Yin et al., 2015; Wang et al., 2016).

To further elucidate the relationship between social anhedonia and electrocortical responses to monetary and social rewards, we examined the between-task association for ERP components and the within-task association between the anticipatory (i.e. the SPN) and consummatory (i.e. the RewP and the fb-P3) ERPs. On the one hand, recent research has indicated that analogous ERPs across monetary and social tasks were moderately correlated with each other (Ait Oumeziane et al., 2017; Ethridge et al., 2017; Distefano et al., 2018), highlighting both the domain-general and the category-specific electrocortical responses. Examining the between-task association may be helpful in determining whether reward deficits in social anhedonia are domain general or category specific. On the other hand, a growing number of studies have established the connectivity between anticipatory and consummatory reward processing by finding that the SPN was correlated with the fb-P3 as well as the RewP (Fuentemilla et al., 2013; Moris et al., 2013; Novak and Foti, 2015; Zheng et al., 2017). Examining such relationship would also be feasible since the connectivity may be modulated by social anhedonia.

Methods

Participants

Forty-nine participants were recruited from a large sample pool of 507 university students (372 females, 135 males) based on their scores on the Chinese version of RSAS (Eckblad et al., 1982; Chan et al., 2012). The RSAS includes 40 true-false statements to assess individual differences in the ability to experience pleasure from social stimuli, resulting in a possible score range of 0–40. A higher score on the RSAS indicates a higher level of social anhedonia. RSAS scores for the original sample pool ($N = 507$) ranged from 1 to 36, with the mean value being 10.54 (s.d. = 6.14). Cronbach's alpha (0.84) revealed good internal consistency for this sample. Similar to previous research (Wang et al., 2016; Gunther et al., 2017), responders with a score greater than 0.8 s.d. above the mean score of their own gender (females: $M = 10.14$, males: $M = 11.64$) were assigned as the HSA group, and those with a score less than 0.8 s.d. below the mean score of their own gender as the LSA group (Figure S1 in the Supplementary Materials). The selection criterion was applied for females and males separately because of the gender imbalance in the current sample. Fifty-three participants were invited to take part in this study. Data from four participants (three from the HSA group and one from the LSA group) were rejected because they exhibited excessive motions and thus discontinued prior to the completion of testing. The final sample thus consisted of 23 participants (14 females, 9 males) for the HSA group and 26 participants (18 females, 8 males) for the LSA group. The sample size was similar to past studies examining reward-related ERP components in physical anhedonia using the categorical between-group design (Padrao et al., 2013; Chen et al., 2018b; Zhou et al., 2019). Furthermore, a sensitivity analysis using the G*Power software (Faul et al., 2007) showed that, with the final sample size of 49, the study had a power of 0.8 to detect a medium-sized effect for the within-between interaction (i.e. the group-by-task interaction for the SPN and RewP) at an alpha level of 0.05 (Figure S2 in the Supplementary Materials). As shown in Table 1, groups were matched in terms of demographic characteristics including gender, age and education level. As expected, the HSA group showed a significantly higher score on the RSAS than the LSA group.

Participants also completed the Snaith Hamilton Pleasure Scale (SHAPS) to measure their consummatory hedonic experience (Snaith et al., 1995), the Temporal Experience of Pleasure Scale (TEPS) to measure their anticipatory and consummatory experiences of pleasures (Gard et al., 2006), the Anticipatory and Consummatory Interpersonal Pleasure Scale (ACIPS) to assess their social capacity to enjoy interpersonal interactions (Gooding and Pflum, 2014), the Social Interaction Anxiety Scale (SIAS) to assess their general fears and feelings of distress in social interactions (Mattick and Clarke, 1998) as well as the Beck Depression Inventory II (BDI-II) to assess their depressive symptoms (Beck et al., 1996). Compared to the LSA group, the HSA group exhibited a reduced capacity to enjoy interpersonal interactions, as indexed by their lower score on the ACIPS. Moreover, the HSA group showed a higher level of physical anhedonia as indexed by the TEPS score than the LSA group, which was driven mainly by the anticipatory component, instead of the consummatory component. Finally, group differences on the BDI-II, SHAPS and SIAS failed to reach significance (Table 1).

All participants received the Structured Clinical Interview for DSM-IV Axis I disorders to ensure that they were free of current or past Axis I disorders (First et al., 1995). Each was right-handed as determined by self-report and had normal or corrected-to-normal vision. All gave signed informed consent prior to the experiment. This study was approved by the Dalian Medical University Institutional Review Board in accordance with the 1989 Helsinki Declaration.

Procedure

Participants completed a monetary reward task and a social reward task with a counterbalanced order. Following each task, participants were instructed to rate their affective responses for the anticipation and consumption of feedback in terms of valence and arousal on a Likert-type scale ranging from 1 (not at all) to 9 (extremely). In addition, they also completed a facial expression categorization task after the reward tasks, which was reported elsewhere (Nie et al., 2020). Participants received credits for participation, plus a feedback-related bonus of ¥40 for the monetary reward task (see details later). They were debriefed at the end of the experiment.

Social reward task

The social reward task was adapted from a previous study (Distefano et al., 2018). Participants were led to believe that they were taking part in a social evaluation study. They were asked to provide a personal portrait photograph prior to the formal experiment and were told that the photograph would be evaluated by a panel of peers from other universities. The panel would judge whether they liked or disliked the participant based on the photograph. Approximately 3 weeks later, participants were invited to perform the electroencephalogram (EEG) experiment. Participants were told that they would see the portrait photos of the peers who had rated them and that their task was to guess which peers liked them.

A total of 160 photographs of peers (80 females, 80 males), which were taken from photographs of voluntary undergraduates with whom participants were not acquainted, were used in the social reward task. Each trial (Figure 1) began with a pair of gender-matched photographs of the peers. Participants were told that one peer liked and the other disliked them and that their goal was to guess which peer liked them by pressing the corresponding button with either their left or right index finger.

Table 1. Demographic characteristics of the sample, including gender, age, education and scale scores ($M \pm s.d.$)

Variable	HSA (N = 23)	LSA (N = 26)	P	Cohen's <i>d</i>
Gender (M/F)	9/14	8/18	0.539	
Age (years)	20.04 ± 1.49	20.08 ± 1.79	0.944	-0.02
Education (years)	13.91 ± 0.90	13.85 ± 0.78	0.782	0.08
RSAS	22.09 ± 3.29	3.73 ± 1.43	<0.001	7.40
ACIPS	70.52 ± 11.50	87.38 ± 9.46	<0.001	-1.61
TEPS				
Total score	80.61 ± 11.32	87.50 ± 12.23	0.047	-0.58
Anticipatory pleasure	35.17 ± 5.77	40.46 ± 6.51	0.004	-0.86
Consummatory pleasure	45.43 ± 10.55	47.04 ± 7.38	0.537	-0.18
SHAPS	22.91 ± 6.70	19.81 ± 5.43	0.080	0.51
BDI-II	7.35 ± 9.89	3.08 ± 4.50	0.053	0.57
BAS/BIS scales				
BAS				
Drive	11.30 ± 1.96	11.69 ± 1.52	0.440	-0.22
Fun seeking	14.22 ± 1.88	14.92 ± 2.31	0.251	-0.33
Reward responsiveness	12.87 ± 1.82	13.00 ± 1.26	0.770	-0.08
BIS	19.70 ± 2.91	19.12 ± 3.35	0.524	0.18
SIAS	33.87 ± 10.16	27.27 ± 13.89	0.067	0.54

Note. HSA = high social anhedonia; LSA = low social anhedonia; RSAS = Revised Social Anhedonia Scale; ACIPS = Anticipatory and Consummatory Interpersonal Pleasure Scale; TEPS = Temporal Experience of Pleasure Scale; SHAPS = Snaith Hamilton Pleasure Scale; BDI-II = Beck Depression Inventory-II; BIS/BAS = Behavioral Inhibition System/Behavioral Activation System; SIAS = Social Interaction Anxiety Scale.

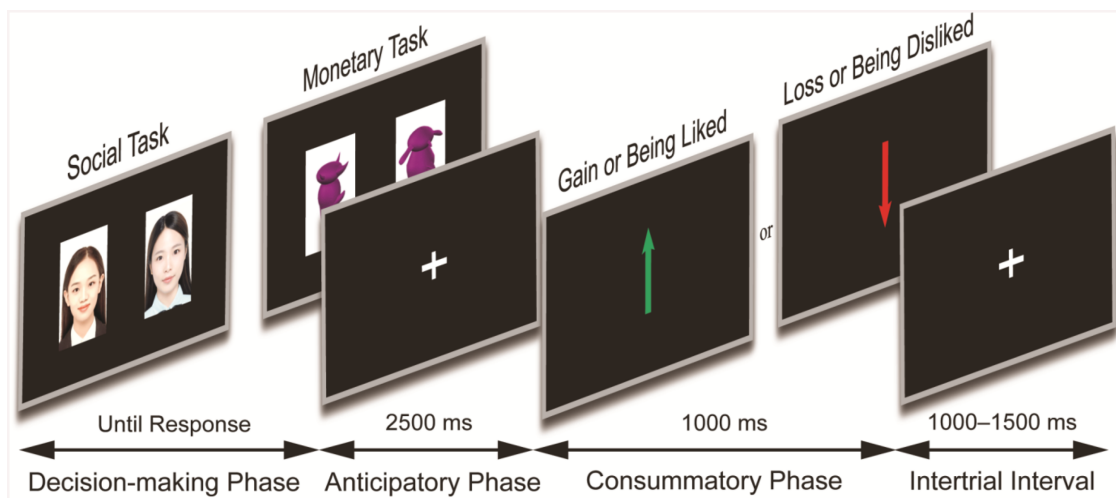


Fig. 1. Trial structure and timeline of the monetary and social reward tasks. In the monetary reward task, participants had to select one of two Greebles, receiving either reward or loss feedback. In the social reward task, they had to select one of two peers, receiving either being liked or being disliked feedback.

The images disappeared upon their response, and a fixation was presented for 2500 ms. Then, an arrow appeared for 1000 ms to indicate the outcome of the current trial. A green arrow pointing upward indicated that the selected peer liked them, resulting in social acceptance; a red arrow pointing downward signaled that the peer disliked them, resulting in social rejection. Unbeknownst to the participants, the outcome of each trial was predetermined and pseudorandom such that they would receive social acceptance on exactly 50% of trials. Each trial ended with an intertrial interval varying between 1000 and 1500 ms. The task consisted of 2 blocks of 40 trials with a rest provided between blocks. Prior to the formal experiment, participants performed a practice block of 12 trials to familiarize themselves with the task.

Monetary reward task

The monetary reward task was similar as the social reward task. It consisted of 160 images of Greebles, which were three-dimensional objects with similar configurations but different appearances (Rossion et al., 2002) and thus were appropriate as a control set for the panel of peers used in the social reward task. On each trial (Figure 1), participants were presented with a pair of images of Greebles. They were told that one Greeble would give them ¥1 and the other would steal ¥0.5 from them and that their goal was to choose the 'good' Greeble to maximize their final money. Trial structure and timeline of the monetary reward task were same as the social reward task. Specifically, the graphic of the two Greebles appeared until a

response was made. Following the response and prior to visual feedback, a fixation was presented for 2500 ms. Visual feedback, either a green arrow indicating a winning of ¥1 or a red one indicating a loss of ¥0.5, then appeared for 1000 ms. The inter-trial interval varied between 1000 and 1500 ms. Similarly, this task started with 12 practice trials, followed by 2 experimental blocks of 40 trials with a rest provided between blocks. During the experimental blocks, the outcome of each trial was predetermined and pseudorandom such that participants succeeded and failed on exactly 50% of trials, resulting in the same bonus money of ¥40 for each participant.

Recording and analysis

EEG was recorded continuously with a left mastoid reference via 64 Ag/AgCl electrodes according to the extended International 10/20 system. The EEG signals were digitized at 32-bit resolution at a sampling rate of 500 Hz. Horizontal electrooculogram (EOG) was recorded as the voltage between two electrodes placed at the lateral canthi of each eye; vertical EOG was recorded as the voltage between two electrodes located above and below the left eye. Both the EEG and EOG signals were amplified using a Neuroscan SynAmp² amplifier with a low-pass of 100 Hz in DC acquisition mode. Electrode impedance was kept under 5 K Ω throughout the experiment.

The EEG data were analyzed using MATLAB 2014a (MathWorks, US) and EEGLAB toolbox (Delorme and Makeig, 2004). Given the DC acquisition mode, the data were linearly detrended to remove the overall mean value of the EEG data (DC offsets), which was performed using a function called removedc.m in ERPLAB toolbox (Lopez-Calderon and Luck, 2014). The data were then rereferenced to the average activity of the two mastoids. For SPN analysis, the raw EEG was filtered with a high pass of 0.01 Hz (roll-off 6 dB/octave) and then was epoched from -4000 to 1500 ms relative to feedback onset, with the activity from -3500 to -3000 ms serving as the baseline. The interval for the baseline was early to exclude the confounding influences of movement-related potentials. For RewP and fb-P3 analyses, the raw EEG was filtered with a high pass of 0.1 Hz (roll-off 6 dB/octave) and then was epoched from -2000 to 2000 ms relative to feedback onset, with the activity from -200 to 0 ms serving as the baseline. After epoch artifacts were rejected automatically using the Fully Automated Statistical Thresholding algorithm (Nolan et al., 2010), epoched data were subjected to an infomax independent component analysis (Delorme and Makeig, 2004). Individual components were then inspected, and blink components were removed. Finally, the ERPs of

interest (i.e. the SPN, the RewP and the fb-P3) were averaged separately across trials for each condition. A series of independent samples t-tests on the number of artifact-free trials revealed no significant group differences ($P > 0.25$) for each ERP component and task condition (Table 2). For visualization only, the anticipatory ERP waveforms were filtered with a low-pass cutoff at 7 Hz and the consummatory ERP waveforms with a low-pass cutoff at 30 Hz, as implemented in the ERPLAB toolbox.

ERP components were measured using a region-of-interest (ROI) approach. Measurement parameters were determined based on averaged ERP waveforms and topographic maps over all conditions across groups, which thus was orthogonal to the conditions of interest (Luck and Gaspelin, 2017). The SPN was measured as the mean voltage during four time-windows (-2000 to -1500 ms, -1500 to -1000 ms, -1000 to -500 ms, -500 to 0 ms) over a centroparietal ROI (CP1, CPz, CP2, Pz). We measured the temporal dynamics of the SPN (i.e. -2000-0 ms) because previous research has demonstrated that different SPN phases may reflect distinct cognitive states (Moris et al., 2013; Ohgami et al., 2014; Seidel et al., 2015). The RewP was isolated using the difference-score method, which has been recommended in a recent meta-analysis of RewP studies to avoid component overlap (Sambrook and Goslin, 2015). Specifically, the RewP was quantified as the mean voltage from 220 to 300 ms of the difference waveforms between positive and negative feedback (i.e. being liked minus being disliked feedback for the social reward task and gain minus loss feedback for the monetary reward task) over a frontocentral ROI (Fz, FC1, FCz, FC2). The fb-P3 was measured as the mean voltage from 330 to 430 ms relative to feedback onset over a centroparietal ROI (CP1, CPz, CP2, Pz).

ERP data were analyzed separately with a mixed repeated-measures analysis of variance (ANOVA). The SPN data were analyzed using group (HSA vs. LSA) as a between-subject factor and task (Social vs. Monetary) and time window (Time 1 vs. Time 2 vs. Time 3 vs. Time 4) as within-subject factors. The RewP and fb-P3 data were analyzed with a Group \times Task ANOVA and a Group \times Task \times Valence (Positive: monetary gain and being liked vs. Negative: monetary loss and being disliked) ANOVA, respectively. Greenhouse-Geisser epsilon correction was applied for the violation of sphericity assumption, and the Bonferroni procedure was used for post hoc comparisons. Moreover, the Pearson's correlation was used to examine the between-task association for each ERP and the within-task association between the anticipatory (i.e. the SPN) and consummatory (i.e. the RewP and the fb-P3) ERPs within each task.

Table 2. The number of artifact-free trials in each task condition for each component as a function of group ($M \pm$ s.d.)

	HSA (N = 23)	LSA (N = 26)	P	Cohen's d
SPN				
Monetary	76.30 \pm 1.96	77.23 \pm 8.21	0.601	-0.15
Social	78.04 \pm 1.26	77.69 \pm 1.62	0.406	0.24
RewP and fb-P3				
Monetary gain	37.91 \pm 1.12	38.50 \pm 3.71	0.470	-0.21
Monetary loss	38.57 \pm 1.47	39.38 \pm 3.80	0.336	-0.28
Social like	38.70 \pm 0.82	38.31 \pm 1.49	0.274	0.32
Social dislike	39.13 \pm 0.92	38.96 \pm 1.18	0.583	0.16

Note. HSA = high social anhedonia; LSA = low social anhedonia.

Result

Behavioral and self-reported data

Overall decision-making time was $M = 2428.11$ ms (s.d. = 1331.36), which was comparable between groups and between tasks, as revealed by the absence of significant main and interaction effects ($P_s > 0.25$).

Valence and arousal rating data were analyzed separately with a Group \times Task ANOVA for feedback anticipation and a Group \times Task \times Valence ANOVA for feedback consumption (Table 3). Figure 2 shows the rating data of valence and arousal for feedback anticipation and consumption. As shown in Table 3, the delivery of positive feedback was rated as more pleasant and more arousing than negative feedback, as reflected by two significant main effects of valence. A significant interaction between task and valence was obtained for the valence rating data of feedback delivery. Post hoc comparisons revealed that being liked was rated as more pleasant than earning money ($P = 0.041$), whereas being disliked and losing money were rated as unpleasant to a similar extent ($P = 0.211$).

Electrophysiological data

Figure 3 illustrates grand-averaged ERP waveforms and topographic maps during the anticipatory and the consummatory phases across the monetary and the social reward tasks as a function of group. During the anticipatory phase, the SPN was elicited as a broad, slow wave with a centroparietal distribution in each condition across groups, as well as a frontotemporal distribution with a right hemispheric preponderance. During the consummatory phase, the RewP was evidenced as a relative positivity over frontocentral areas, which was followed by a pronounced fb-P3 component with a centroparietal distribution.

Anticipatory ERP: the SPN component. The SPN increased its amplitude as the feedback approached, as reflected by a sig-

nificant main effect of time window, $F(3, 141) = 39.63$, $P < 0.001$, $\eta_p^2 = 0.46$. This SPN gradient effect was more pronounced for the social reward task than for the monetary reward task as revealed by a significant interaction between task and time window, $F(3, 141) = 13.05$, $P < 0.001$, $\eta_p^2 = 0.22$. Bonferroni-corrected comparisons revealed that the SPN in the social reward task increased linearly as the arrival of the feedback ($P_s < 0.003$). In contrast, the SPN in monetary reward task was larger during the last time window (i.e. -500 to 0 ms) than other time windows ($P_s < 0.001$), with no differences between other time windows ($P = 0.052$ – 0.232).

The SPN was more negative in the monetary reward task than in the social reward task, $F(1, 47) = 17.63$, $P < 0.001$, $\eta_p^2 = 0.27$. Although the main effect of group was not significant, $F(1, 47) = 2.88$, $P = 0.097$, $\eta_p^2 = 0.06$, the interaction of group and task was significant, $F(1, 47) = 4.74$, $P = 0.035$, $\eta_p^2 = 0.09$. As shown in Figure 4A, post hoc comparisons revealed that the SPN was more negative for the monetary reward task than for the social reward task in the LSA group (-5.22 ± 0.72 vs. -2.46 ± 0.55 μV , $P < 0.001$). In contrast, the SPN was comparable for the monetary and the social reward tasks in the HSA group (-2.87 ± 0.76 vs. -1.99 ± 0.59 μV , $P = 0.172$). Between-group comparisons revealed that the HSA group relative to the LSA group exhibited a reduced SPN in the monetary reward task ($P = 0.030$) but not in the social reward task ($P = 0.568$).¹

Consummatory ERPs: the RewP and the fb-P3 components. The ANOVA performed on RewP data revealed no significant main effects of task, $F(1, 47) = 1.93$, $P = 0.172$, $\eta_p^2 = 0.04$, and group, $F(1, 47) = 0.34$, $P = 0.565$, $\eta_p^2 = 0.01$. However, there was a significant interaction between group and task, $F(1, 47) = 4.75$, $P = 0.034$, $\eta_p^2 = 0.09$. As illustrated in Figure 4B, post hoc comparisons revealed that the HSA group showed comparable RewPs across the monetary and the social reward tasks (2.85 ± 0.77 vs. 3.20 ± 0.67 μV , $P = 0.590$). In contrast, the LSA group elicited a larger RewP in the monetary reward than the social reward task

Table 3. Summary of the analysis of variance performed on rating data

Source	Df	F	P	η_p^2
Anticipatory valence				
Group	(1, 47)	0.51	0.479	0.01
Task	(1, 47)	2.84	0.099	0.06
Group \times Task	(1, 47)	2.84	0.099	0.06
Anticipatory arousal				
Group	(1, 47)	0.12	0.730	<0.01
Task	(1, 47)	0.05	0.831	<0.01
Group \times Task	(1, 47)	0.60	0.443	0.01
Consummatory valence				
Group	(1, 47)	3.62	0.063	0.07
Task	(1, 47)	0.52	0.477	0.01
Valence	(1, 47)	123.62	<0.001	0.73
Group \times Task	(1, 47)	0.11	0.747	<0.01
Group \times Valence	(1, 47)	3.17	0.082	0.06
Task \times Valence	(1, 47)	4.08	0.049	0.08
Group \times Task \times Valence	(1, 47)	0.74	0.394	0.02
Consummatory arousal				
Group	(1, 47)	3.09	0.085	0.06
Task	(1, 47)	1.07	0.307	0.02
Valence	(1, 47)	35.60	<0.001	0.43
Group \times Task	(1, 47)	0.08	0.776	<0.01
Group \times Valence	(1, 47)	3.19	0.081	0.06
Task \times Valence	(1, 47)	0.13	0.722	<0.01
Group \times Task \times Valence	(1, 47)	0.41	0.525	0.01

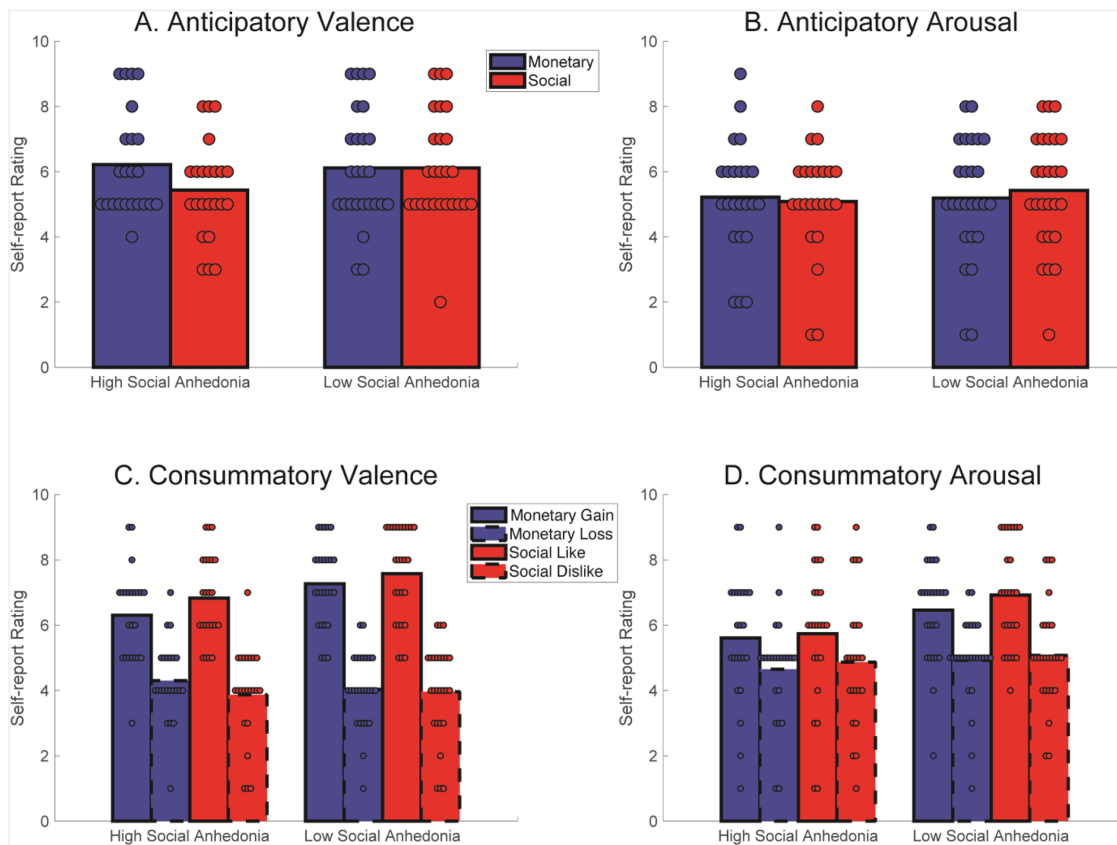


Fig. 2. Rating data for (A) anticipatory valence, (B) anticipatory arousal, (C) consummatory valence and (D) consummatory arousal of the monetary and the social reward tasks as a function of social anhedonia. Bars and dots represent mean and individual rating values, respectively, for each condition as a function of group.

(3.28 ± 0.72 vs. 1.74 ± 0.63 μV , $P = 0.012$). Between-group comparisons revealed no significant differences between the HSA group and the LSA group for both the monetary reward task ($P = 0.685$) and the social reward task ($P = 0.119$).²

With regard to the fb-P3, there was a significant main effect of task, $F(1, 47) = 30.86$, $P < 0.001$, $\eta_p^2 = 0.40$, with the fb-P3 being more positive in the monetary reward task than the social reward task. The main effect of valence was also significant, $F(1, 47) = 4.54$, $P = 0.04$, $\eta_p^2 = 0.09$, revealing that the fb-P3 was enhanced for positive (i.e. monetary gain and being liked) compared to negative (i.e. monetary loss and being disliked) feedback. No other significant effects were obtained ($P = 0.227$ – 0.712).

Correlations between tasks and between ERPs within tasks. Table 4 shows Pearson's correlations between the ERPs elicited in the two tasks and the anticipatory and consummatory ERPs within each task.³ There were 14 correlations (3 for between-task and 4 for within-task within each of the 2 groups), demanding the Bonferroni-adjusted significance level of $P < 0.003$ ($0.05/14$), to test on an overall error rate of 0.05. On this significance level, significant positive correlations were observed between the monetary and the social reward tasks across groups for both the SPN and fb-P3. Although the RewP was significantly correlated between the monetary and the social reward tasks in the HSA group, further inspection of scatter plots showed that this effect was driven by two outliers. After removing the outliers, the correlation became nonsignificant on

the Bonferroni-adjusted significance level, $r = 0.50$, $P = 0.021$. With respect to the relationship between the anticipatory and consummatory ERPs, the correlation between the SPN and the fb-P3 was marginally significant across tasks for the LSA group but was far from being significant for the HSA group. In addition, between- and within-task correlation coefficients were not significantly different between the HSA group and the LSA group ($z = -1.09$ – 1.77 , $P = 0.077$ – 0.958).

Discussion

To our knowledge, this is the first study examining reward dynamics (anticipatory vs. consummatory phases) underlying monetary and social reward processing in social anhedonia with a nonclinical sample. We adopted a social reward task and a monetary reward task, which were matched in terms of trial structure and visual characteristics. Anticipatory reward processing was indexed by the SPN, whereas consummatory reward processing was indexed by the RewP and fb-P3. Our main hypothesis was that the abnormal reward processing of social anhedonia would depend on reward type and reward dynamics. We obtained two major findings. First, during the anticipatory phase, the LSA group but not the HSA group exhibited an increased SPN for monetary rewards compared to social rewards. Second, during the consummatory phase, the RewP was increased for monetary relative to social rewards, which was found for the LSA but not the HSA group. In the following sections, the discussion is organized alongside these main findings.

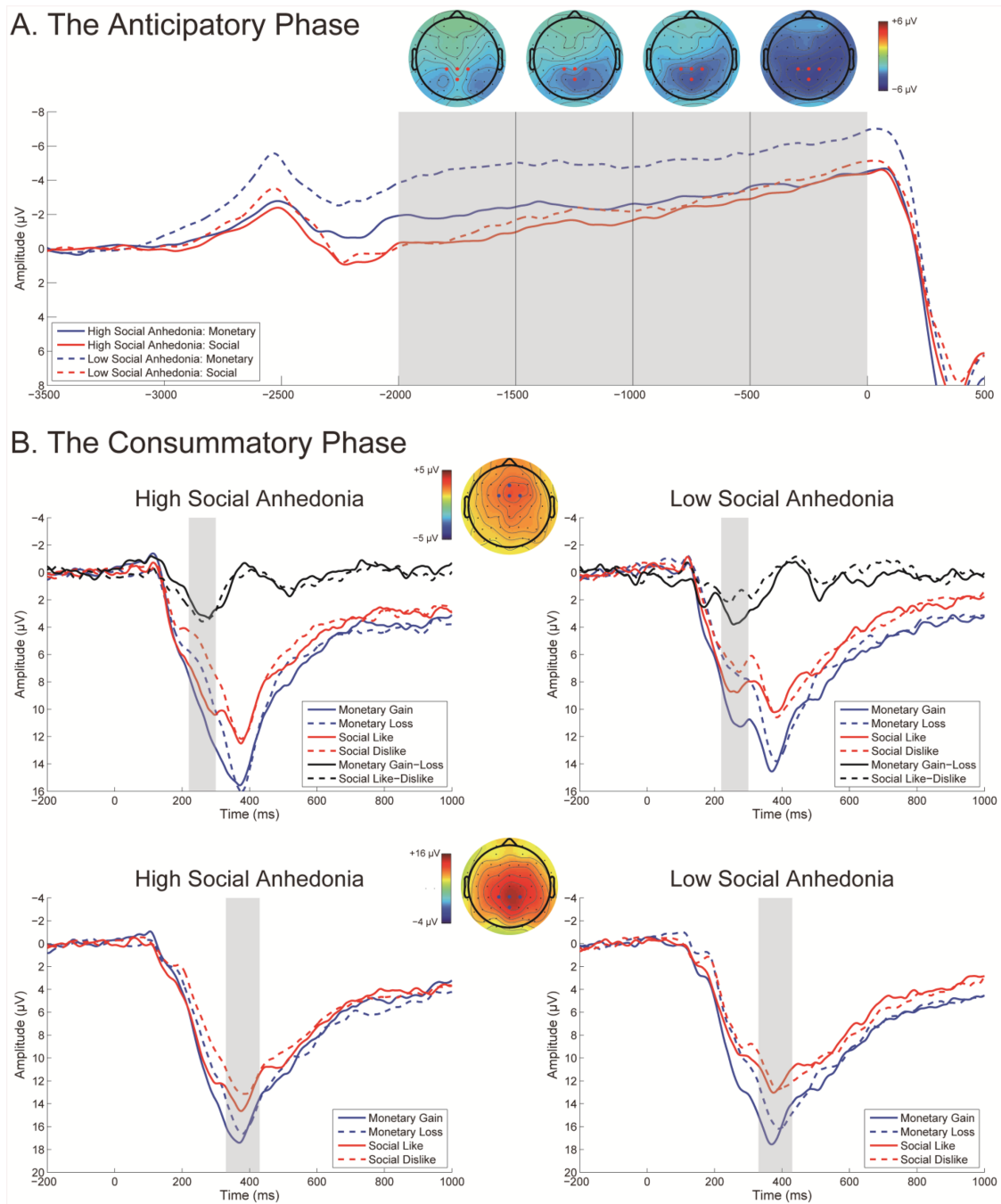


Fig. 3. Grand-averaged ERP waveforms as a function of social anhedonia during (A) the anticipatory phase and (B) the consummatory phase of the monetary and the social reward tasks. The shaded areas demarcate the time windows during which the SPN (−2000 to 0 ms), the RewP (220–300 ms) and the fb-P3 (330–430 ms) were scored. Topographical maps for the ERP components are also displayed, and the colored dots overlaid on the maps indicate the ROIs selected for analysis.

During the anticipatory phase, the SPN was larger for monetary rewards than for social rewards, which was observed for the LSA group but not for the HSA group. The SPN is related to the motivational salience of feedback stimuli, as evidenced by its enhanced amplitudes for large versus small reward-magnitude conditions (Mattox et al., 2006; Zheng and Liu, 2015; Zheng et al., 2017) and for high versus low self-related conditions (Masaki et al., 2010; Mei et al., 2018; Chen et al., 2018a). Therefore, our SPN findings may reflect a higher level of motivational salience for monetary rewards than for social rewards among individuals

without social anhedonia. In contrast, those with elevated social anhedonia exhibited similar motivational salience during the reward anticipation (as indexed by the SPN) across reward domains. In other words, the finding that the SPN was comparable for both reward types in the HSA group might be attributable to impairments in the ability to distinguish between rewards of different magnitude. Further between-group comparisons revealed that the HSA relative to the LSA group elicited a reduced SPN for monetary rewards, which is consistent with previous findings that increased social anhedonia in a nonclinical sample

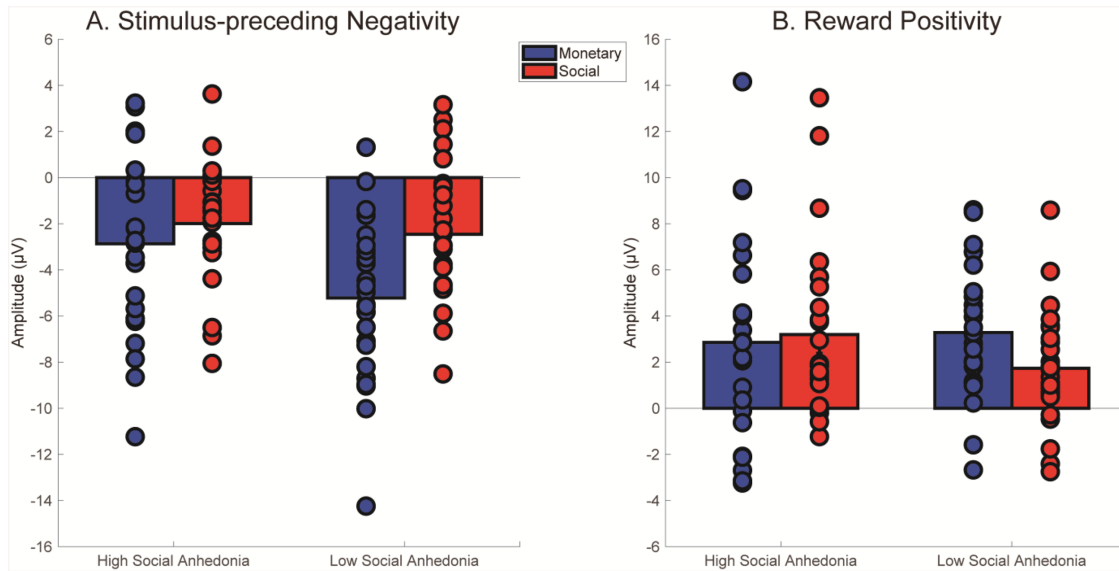


Fig. 4. Stripcharts of Group \times Task interaction for (A) the SPN and (B) the RewP. Bars and dots represent mean and individual amplitude values, respectively, for each condition as a function of group.

Table 4. Correlations of ERPs within and between the monetary and the social reward tasks

		Within task						
		Between task			Monetary		Social	
		SPN SPN	RewP RewP	fb-P3 fb-P3	SPN RewP	SPN fb-P3	SPN RewP	SPN fb-P3
HSA	<i>r</i>	0.62	0.73	0.71	-0.08	-0.27	-0.19	-0.28
	<i>P</i>	0.002	<0.001	<0.001	0.728	0.214	0.397	0.195
LSA	<i>r</i>	0.61	0.37	0.84	-0.25	-0.44	-0.15	-0.55
	<i>P</i>	0.001	0.065	<0.001	0.222	0.026	0.467	0.003

Note: HSA = high social anhedonia; LSA = low social anhedonia. The SPN was from 500 to 0 ms relative to feedback onset; the fb-P3 was collapsed across positive and negative feedback. The 14 correlations demand the Bonferroni-adjusted significance level of $P < 0.003$ ($0.05/14$) to test on an overall error rate of 0.05. The significant between-task correlation of the RewP in the HSA group was driven by two outliers. After removing the outliers, the correlation became nonsignificant.

was associated with reduced motivation (as indexed by less willingness to expend effort) for monetary rewards (Wang et al., 2018). Given that the effort-based motivation can be selectively predicted by the SPN elicited during anticipation of monetary rewards (Zhang et al., 2017), it is possible that the blunted anticipatory reward response may be contributable to the reduced motivation to pursue rewards in social anhedonia (Treadway and Zald, 2013; Rømer Thomsen et al., 2015). Furthermore, a recent study found that a reduced P3 in response to monetary cues was correlated with HSA in patients with schizophrenia (Vignapiano et al., 2016). Our SPN findings extend this study to demonstrate that the anticipatory deficit also occurs during unresolved expectation for monetary rewards with a healthy sample.

In contrast with our prediction, however, the SPN elicited during anticipation of social rewards was comparable between groups. To our knowledge, this is the first ERP study to examine the anticipatory response for motivationally social stimuli in social anhedonia. Our results suggest that neural anticipation for social rewards may be intact in social anhedonia, reflecting a floor effect caused by the relatively low salience of social rewards in this study. This finding is consistent with a previous behavioral study using an affective incentive delay (AID)

task and finding similar anticipatory sensitivity towards positive social affective images between individuals with social anhedonia and healthy controls (Xie et al., 2014). However, our finding is inconsistent with another fMRI study reporting that physical anhedonia is associated with reduced neural responses in the anticipatory phase of the AID task (Chan et al., 2016). This discrepancy may be attributable to methodological differences between the two studies. In the Chan et al. study, the authors focused on physical anhedonia by adopting an AID task during which positive social affective images were obtainable upon fast responses. In contrast, we focused on social anhedonia by employing a social evaluation task where social acceptance (being liked) or social rejection (being disliked) was available upon deliberate decisions. Alternatively, it is possible that the 'normal' SPN for the social task in the HSA group reflects an enhanced anticipation for social rejection among individuals with HSA. Specifically, it is unknown that whether participants in the current task were anticipating a social reward or a social punishment because of the high uncertainty (50%) of feedback stimuli. People with elevated social anhedonia may be hypersensitivity to social rejection during an uncertain situation, thus enhancing the amplitude of the SPN. This possibility dovetails with previous findings that anhedonia (as measured

by the SHAPS) was positively correlated with neural responses to social exclusion in the amygdala, insula, and ventrolateral prefrontal cortex (Kumar *et al.*, 2017). The current ERP data cannot adjudicate between the two possibilities. The valence of social anticipation in social anhedonia should be clarified in future research by collecting participants' subjective predictions (social acceptance vs. social rejection) prior to their anticipation at the trial level (Somerville *et al.*, 2006).

During the consummatory phase, the RewP (isolated using the difference score approach) was larger for monetary rewards than for social rewards in the LSA group. In contrast, the RewP was comparable across reward types in the HSA group. These results indicate that social anhedonia is associated with less sensitive neural responses for monetary versus social rewards during the consummatory phase. One explanation for our RewP findings is attributable to prediction error, that is, the difference between the predictive value of future outcomes and their realized value (Schultz *et al.*, 1997). It is well established that the prediction error signal can be tracked by the RewP with its amplitude increasing as a function of reward prediction error (Holroyd and Coles, 2002). Given the pessimistic (negative) expectation of self-related events observed in anhedonia-related depression (Rief and Joermann, 2019; Kube *et al.*, 2020), individuals high in social anhedonia might be less likely to believe that they would be evaluated positively. When they received social rewards, a large prediction error (i.e. better than expected) might be generated, which was accompanied by a relatively large RewP. This possibility echoes prior findings that social anhedonia is characterized by greater neural responses to social acceptance (Healey *et al.*, 2014) and positive self-relevant stimuli (Keedwell *et al.*, 2005) in the medial prefrontal cortex (including the anterior cingulate cortex), the most likely neural generator of the RewP (Gehring and Willoughby, 2002; Holroyd and Coles, 2002). Indeed, as shown in Figure 3, the disappeared effect of reward type in individuals with elevated social anhedonia seemed to be driven by an enhanced RewP in response to social rewards, rather than by a reduced RewP in response to monetary rewards. Specifically, whereas monetary rewards elicited comparable RewP amplitudes across groups (2.85 vs. 3.28 μ V), the RewP for social rewards was numerically larger for the HSA than the LSA group (3.20 vs. 1.74 μ V). Consistent with our findings, a recent study found comparable RewPs for monetary rewards between people with extremely elevated social anhedonia and healthy controls (Karcher *et al.*, 2017). However, it should be noted that although the RewP was numerically larger for the HSA than the LSA group, the difference failed to reach significance as revealed by between-group comparisons. It is possible that the effect of social anhedonia on the RewP of social prediction error may not be that strong in a nonclinical sample. Indeed, when BDI scores were included as a covariate in the ANOVA model, the group-by-task interaction for the RewP became marginally significant (Table S1 in the Supplementary Materials), which is consistent with the established finding of the blunted RewP during feedback processing in depression (Keren *et al.*, 2018). Future research should extend our findings to clinical populations with schizophrenia or major depressive disorder.

Our rating and correlation results also merit discussion. First, it should be noted that the effects of the group-by-task interactions were not observed for self-reported rating data. Instead, the HSA group showed marginally lower affective ratings than the LSA group irrespective of task. On the one hand, our data indicate that subjective assessment of anticipation and consumption is a less sensitive measure and/or does not necessarily

reflect implicit processes as indexed by the reward-related ERP components. On the other hand, the fact that both groups differed in terms of arousal and valence suggests a more general decline in affective response in social anhedonia (Leung *et al.*, 2010; Hooker *et al.*, 2014). Second, it seems worth mentioning that the SPN and the fb-P3 appeared marginally related in the LSA but not HSA group. Compatible with previous studies (Fuentemilla *et al.*, 2013; Pornpattananangkul and Nusslock, 2015; Novacek *et al.*, 2016), the correlation between the SPN and the fb-P3 in the LSA group suggests a common motivational significance across the anticipatory and consummatory reward processing among individuals without social anhedonia. However, this connection was disrupted in the HSA group across the monetary and social reward tasks, supporting a general uncoupling between 'wanting' and 'liking' responses in social anhedonia (Pizzagalli, 2014). Presumably, this uncoupling is possibly driven by the aberrant anticipatory processing due to the group difference found for the SPN instead of the fb-P3. Interestingly, our TEPS results also revealed that the two groups differed in the anticipatory but not consummatory experiences of pleasures. Therefore, the relation between anticipation and consumption may be an interesting direction for further research in social anhedonia.

Several limitations of this study should be noted. First, although we tried to match the monetary and social reward tasks in terms of trial structure and physical properties, the subjective value of the two reward types may still be divergent, resulting in different motivational salience across tasks. Second, the effect of social evaluation (being liked vs. being disliked) in the current study might be relatively weak because (1) social evaluation was made by a panel of peers from other universities, and we failed to measure mutual liking (being liked by someone participants also liked) during social evaluation (Healey *et al.*, 2014); (2) social evaluation was delivered by colored arrows instead of, for example, smiling faces. Third, the absence of a control condition with no rewards makes it difficult to exclude more general effects between the HSA and LSA groups, which should be addressed in future research.

In conclusion, our data provide preliminary evidence for neural aberrations of the reward system in social anhedonia, which is contingent upon reward type and reward dynamics. Specifically, social anhedonia is associated with reduced electrocortical responses for monetary rewards during the anticipatory phase as indexed by the SPN and less sensitive neural responses for monetary versus social rewards during the consummatory phase as indexed by the RewP. These neural aberrations may result from an increased relevance of social rewards or a general decline in affective responding due to a potential association between social anhedonia and depression. Our findings will facilitate more targeted interventions for relevant clinical diseases characterized by social anhedonia.

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Declaration of interest

All authors have declared that no competing interests exist.

Supplementary data

Supplementary data are available at SCAN online.

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1 We also measured the readiness potential (RP) as the mean activity from –3000 to –2500 ms relative to feedback onset (i.e. 500 ms before response execution) over central areas (C1, Cz, C2) to examine motor preparation between the HSA and LSA groups. A Group \times Task ANOVA performed on RP data revealed that the RP was enhanced in the monetary reward task ($-2.32 \pm 0.22 \mu\text{V}$) compared to the social reward task ($-1.23 \pm 0.24 \mu\text{V}$), $F(1, 47) = 20.36$, $P < 0.001$, $\eta_p^2 = 0.30$, and was increased for the LSA group ($-2.25 \pm 0.27 \mu\text{V}$) relative to the HSA group ($-1.31 \pm 0.29 \mu\text{V}$), $F(1, 47) = 5.61$, $P = 0.022$, $\eta_p^2 = 0.11$. These results indicate that the SPN results could not be explained by movement-related differences as indexed by the RP.

2 We run an ANCOVA on the SPN and RewP data separately, with TEPS scores as a covariate, because of statistically significant group differences in this variable. The results revealed that the two-way interaction between group and task remained significant for both the SPN, $F = 4.76$, $P = 0.034$, $\eta_p^2 = 0.09$, and the RewP, $F = 4.30$, $P = 0.044$, $\eta_p^2 = 0.09$.

3 We selected the SPN during the time window of 500 to 0 ms relative to feedback onset, which was maximal, as revealed by the significant main effect of time window. The fb-P3 was collapsed across positive and negative feedback, due to the nonsignificant interaction between task and valence.