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Neural response to monetary and social feedback demonstrates differential associations with depression and social anxiety

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Abstract

An aberrant neural response to rewards has been linked to both depression and social anxiety. Most studies have focused on the neural response to monetary rewards, and few have tested different modalities of reward (e.g. social) that are more salient to particular forms of psychopathology. In addition, most studies contain critical confounds, including contrasting positive and negative feedback and failing to disentangle being correct from obtaining positive feedback. In the present study, 204 participants underwent electroencephalography during monetary and social feedback tasks that were matched in trial structure, timing and feedback stimuli. The reward positivity (RewP) was measured in response to correctly identifying stimuli that resulted in monetary win, monetary loss, social like or social dislike feedback. All monetary and social tasks elicited a RewP, which were positively correlated. Across all tasks, the RewP was negatively associated with depression and positively associated with social anxiety. The RewP to social dislike feedback, independent of monetary and social like feedback, was also associated with social anxiety. The present study suggests that a domain-general neural response to correct feedback demonstrates a differential association with depression and social anxiety, but a domain-specific neural response to social dislike feedback is uniquely associated with social anxiety.

Key words: anxiety; depression; event-related potentials; reward; social

Introduction

Depression and social anxiety disorder are two of the most prevalent forms of psychopathology (Kessler *et al.*, 2005). Childhood and adolescence are critical periods for the emergence of symptoms and syndromes (Merikangas *et al.*, 2011), which often persist into adulthood (Weissman *et al.*, 1999), and women are disproportionally impacted relative to men (Hankin *et al.*, 1998; Lewinsohn *et al.*, 1998). Both disorders have been associated with a number of adverse consequences, including academic difficulties, health problems and social dysfunction (Birmaher *et al.*, 1996; Aderka *et al.*, 2012), and significant economic burden (Luppa *et al.*, 2007; Baxter *et al.*, 2014). Overall, depression and social anxiety are significant public health concerns, and it is critical to better understand their etiopathogenesis to improve early identification, prevention and treatment.

Abnormalities in reward circuitry are central to several etiological models of depression (Treadway and Zald, 2011; Russo and Nestler, 2013; Pizzagalli, 2014). For example, functional

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magnetic resonance imaging (fMRI) studies have indicated that blunted striatal activation to rewards in both youth and adults is associated with concurrent depressive disorders and symptoms (Forbes *et al.*, 2006; Steele *et al.*, 2007; Pizzagalli *et al.*, 2009), family history (i.e. risk) of depression (Gotlib *et al.*, 2010) and future disorders and symptoms (Morgan *et al.*, 2013; Hanson *et al.*, 2015; Stringaris *et al.*, 2015). However, a recent meta-analysis has raised questions about fMRI-based brain activity in depression (Müller *et al.*, 2017).

Event-related potentials (ERPs) have also been employed to examine the neural response to rewards in depression. A majority of these studies have examined the reward positivity (RewP), a frontocentral component that occurs ∼250–350 ms following feedback indicating monetary gain relative to loss (Proudfit, 2015). The RewP is hypothesized to reflect the activation of a reinforcement learning system (Holroyd and Coles, 2002) and has demonstrated convergent validity with other indicators of reward sensitivity, including self-report and behavioral measures (Bress and Hajcak, 2013) and fMRI-based activation in the medial prefrontal cortex and striatum (Carlson *et al.*, 2011; Becker *et al.*, 2014). The RewP has most often been examined during the doors task, in which participants are asked to guess which door contains a monetary prize, while the other door contains a monetary loss. A number of studies have indicated that a blunted RewP during the doors task is associated with multiple measures of depression and risk, including current depressive disorders and symptoms in youth and adults (Foti and Hajcak, 2009; Bress *et al.*, 2012; Liu *et al.*, 2014; Burani *et al.*, 2019), familial history of depression in youth (Foti *et al.*, 2011; Kujawa *et al.*, 2014b) and future disorders and symptoms in youth and adults (Bress *et al.*, 2013; Nelson *et al.*, 2016; Mulligan *et al.*, 2019).

Abnormalities in information processing, including reward circuitry, have also been implicated in the development of anxiety disorders (Silk *et al.*, 2012; Harrewijn *et al.*, 2017). Interestingly, fMRI research has indicated that social anxiety and behavioral inhibition are associated with increased striatal activation to rewards in children and adolescents (Guyer *et al.*, 2006; Bar-Haim *et al.*, 2009; Lahat *et al.*, 2018). A larger RewP has also been associated with greater social anxiety symptoms in children (Kessel *et al.*, 2014).

The relationship between neural response to rewards and psychopathology has largely been examined using monetary reward. However, there has been a growing interest in examining other forms of reward (e.g. social) that might be more salient to conditions like depression and social anxiety (Guyer *et al.*, 2012; Jarcho *et al.*, 2015). fMRI research has indicated that there is a common, domain-general neural system involved in information processing for both non-social and social rewards (Izuma *et al.*, 2008; Lin *et al.*, 2012; Daniel and Pollmann, 2014). However, other studies have also indicated dissociable, domain-specific neural networks for monetary and social reward (Rademacher *et al.*, 2010; Chan *et al.*, 2016).

Depression and social anxiety have disparate patterns of neural activation to social rewards. For example, adults with depression have decreased anterior insula activation to monetary rewards but increased activation to social feedback (Sankar *et al.*, 2019). Moreover, youth with depression have increased activation in a number of regions, including the amygdala, subgenual anterior cingulate, anterior insula and nucleus accumbens, to social rejection (Silk *et al.*, 2014), but youth with a parental history of depression have reduced striatal and anterior cingulate cortex activation to social rewards (Olino *et al.*, 2015). Behavioral inhibition and social anxiety in adolescents have a more consistent relationship with increased striatal activation to both monetary (Guyer *et al.*, 2006) and social feedback (Jarcho *et al.*, 2015; Quarmley *et al.*, 2019).

ERP research has also begun to examine the neural response to social feedback and reward via a variety of experimental paradigms (Kujawa *et al.*, 2014a; Flores *et al.*, 2015; van der Veen *et al.*, 2016; Distefano *et al.*, 2018). In the limited number of studies that compared well-matched experimental paradigms, the RewP to monetary and social feedback in adults was of similar magnitude and positively correlated, consistent with at least a partial domain-general neural system (Distefano *et al.*, 2018; Ait Oumeziane *et al.*, 2019). Moreover, depression and social anxiety have demonstrated differential relationships with the RewP to social feedback such that a blunted RewP in adolescents and adults has been associated with greater depressive symptoms (Kujawa *et al.*, 2017; Distefano *et al.*, 2018), but a larger RewP in children and adults has been associated with social anxiety disorder and greater symptoms (Kujawa *et al.*, 2014a; Cao *et al.*, 2015). Across both fMRI and ERP research, initial evidence has emerged suggesting that an aberrant neural response to rewards might represent a mechanism that is differentially associated with depression and social anxiety.

There are a number of critical confounds and limitations in the literature comparing the neural response to monetary and social rewards in relation to depression and social anxiety. For example, nearly all studies contrast positive (e.g. winning money and social acceptance) and negative (e.g. losing money, social rejection) valence feedback, making it difficult to determine which condition(s) actually contribute to the aberrant neural response to rewards. In addition, no studies have disentangled the intrinsically rewarding experience of being correct from obtaining positive feedback in relation to depression and social anxiety. Finally, most studies contained a relatively small sample and were underpowered to adequately examine the relationship between this mechanism and individual differences in symptoms.

The present study provided a comprehensive evaluation of the neural response to monetary and social feedback in relation to depression and social anxiety. Adult participants completed monetary and social feedback tasks that were matched in trial structure, timing and feedback stimuli in a counterbalanced order. For each task, participants were instructed to correctly identify the door or peer that would provide positive feedback (win money/social like), and another where the goal was to correctly identify the door or peer that would provide negative feedback (lose money/social dislike). The RewP was measured in response to correctly identifying stimuli that resulted in monetary win, monetary loss, social like or social dislike feedback. Participants also completed self-report measures of depression and social anxiety symptoms. We hypothesized that the RewP would be larger to correct feedback compared to incorrect feedback across all four tasks. Moreover, consistent with a domain-general neural system, we hypothesized that the RewP would be positively correlated across all four tasks. We also hypothesized that a blunted RewP would be associated with greater depression symptoms, while a larger RewP would be associated with greater social anxiety symptoms. However, we did not make a hypothesis whether this relationship would be domain general or domain specific.

Method

Participants

A sample of 204 undergraduate students participated for course credit. The sample was college aged (M = 19.92 years old; SD = 2.50), contained 130 (63.7%) females and was racially/ethnically diverse (45.1% Asian, 5.9% Black, 26.5% Caucasian, 10.8% Latino and 11.8% 'Other'). Informed consent was obtained prior to participation, and all procedures were approved by the local Institutional Review Board.

Measures

Inventory of depression and anxiety symptoms. The Inventory of Depression and Anxiety Symptoms—Expanded Version (IDAS-II; Watson *et al.*, 2012) is a 99-item factor-analytically derived self-report inventory of empirically distinct dimensions of depression and anxiety symptoms. Each item assesses symptoms over the past two weeks on a five-point Likert scale ranging from 1 (not at all) to 5 (extremely). The present study focused on the 10-item dysphoria scale (Cronbach's $\alpha = 0.88$), which is the most discriminant symptom dimension of depression, and the 6-item social anxiety scale (Cronbach's $\alpha = 0.86$).

Stimuli

The social feedback task stimuli were identical to a previous investigation (Distefano *et al.*, 2018) and consisted of 120 images of age-matched peers (60 females) compiled from multiple sources [National Institute of Mental Health's Child Emotional Faces picture set (Egger *et al.*, 2011), internet databases of non-copyrighted images and photographs of college-aged individuals]. Variability in the appearance of the social stimuli was necessary in order to corroborate task deception, which suggested participants were being evaluated by actual peers. All images were cropped to a standardized size (3.5 in. width × 4.5 in. height) and occupied ~8° of visual space horizontally and 10° vertically for participants seated ~24 in. from the monitor. Each trial slide contained a pair of either male peers or female peers (60 pairs of male faces and 60 pairs of female faces), pictured from their shoulders up, with a positive facial expression and a solid background.

Procedure

Participants were told that they would complete a social evaluation study with peers at different universities across the USA. Participants were asked to provide a digital photo of themselves that was purportedly uploaded to a study database. Participants believed that once this photograph was uploaded, peers would receive a text message on their cell phone asking them to view the photo and indicate whether they thought they would 'like' or 'dislike' the participant. Participants were told that later in the experimental session, after enough time had elapsed for the purported peers to have rated their photo, they would be asked to guess which peers 'liked' and 'disliked' them. Participants were also told that they would be completing monetary guessing tasks.

Monetary and social feedback tasks. See Jin *et al.* (2019) for a detailed description of the procedure and experimental tasks. All tasks were administered using Presentation software (Neurobehavioral Systems, Inc., Albany, CA, USA) in a counterbalanced order. In the monetary win task, each trial began with the presentation of two identical doors. Participants were told that there were three possible scenarios for each trial: (i) both doors contained a $0.25 monetary win, (ii) one door contained a $0.25 monetary win while the other door resulted in a break even outcome (i.e. neither win nor lose) or (iii) both doors resulted in a break even outcome. Participants were told that the goal was to try and guess which door contained the monetary win. The image of the doors was presented until the participant made a selection. After stimulus offset, a fixation cross (+) was presented for 1000 ms, and then feedback was presented on the screen for 2000 ms. Correct selection of the monetary win door resulted in a $0.25 monetary win, indicated by a green arrow pointing upward (↑). Incorrect selection of the break-even door resulted in no monetary win, indicated by a white horizontal dash (-). Feedback was pre-programed to generate an equal number of win and break even trials. The feedback stimulus was followed by a fixation cross presented for 1500 ms, immediately followed by the message 'Click for next round'. This prompt remained on the screen until the participant responded with a button press to initiate the next trial. The task consisted of 30 total trials (15 of each outcome).

In the monetary loss trials, trial structure and timing was identical to the monetary win trials, but participants were told that the goal was to try and guess which door contained a $0.25 monetary loss. Correct selection of the monetary loss door resulted in a $0.25 monetary loss, indicated by a red arrow pointing downward (↓). Incorrect selection of the break-even door resulted in no monetary loss, indicated by a white horizontal dash (-).

The social like and dislike tasks were identical to the monetary win and loss tasks, respectively, except pictures of gender-matched peers (i.e. two male faces or two female faces) were presented instead of doors. There were an equal number of trials with male and female peers across the social like and social dislike tasks (30 each, 60 total). In the social like trials, participants were told that there were three possible situations for each trial: (i) both people said that they would like the participant, (ii) one person said that they would like the participant while the other person never rated the participant or (iii) neither person rated the participant. Participants were told that the goal was to try and guess which person said they would like the participant. Correct selection of the person who said they would like the participant was indicated by a green arrow pointing upward (↑). Incorrect selection of the person who never rated the participant was indicated by a white horizontal dash (-).

In the social dislike trials, trial structure and timing was identical to the social like trials, but participants were told that the goal was to try and guess which person said they would dislike the participant. Correct selection of the person who said that they would dislike the participant was indicated by a red arrow pointing downward (↓). Incorrect selection of the person who never rated the participant was indicated by a white horizontal dash (-).

EEG recording and processing. Continuous EEG was recorded using an elastic cap with 34 electrode sites (32 standard channels plus FCz and Iz) placed according to the 10/20 system. Electrooculogram (EOG) was recorded using four additional facial electrodes: two placed ~1 cm outside of the right and left eyes and two placed ~1 cm above and below the right eye. All electrodes were sintered Ag/AgCl electrodes. Data were recorded using the ActiveTwo system (BioSemi, Amsterdam, Netherlands). The EEG was digitized with a sampling rate of 1024 Hz using a low-pass fifth order sinc filter with a half-power cutoff of 204.8 Hz. A common mode sense active electrode producing a monopolar (non-differential) channel was used as recording reference.

EEG data were analyzed using BrainVision Analyzer 2.1 (Brain Products, Gilching, Germany). Data were referenced offline to the average of left and right mastoids, band-pass filtered (0.1–30 Hz) and corrected for eye movement artifacts (Gratton *et al.*, 1983). Epochs containing a voltage greater than 50 μV between sample points, a voltage difference of 300 μV within a segment or a maximum voltage difference of less than 0.50 μV within 100 ms intervals were automatically rejected. Additional artifacts were identified and removed based on visual inspection. Feedback-locked epochs were extracted with a duration of 1000 ms, including a 200 ms pre-stimulus and 800 ms post-stimulus interval. The 200 ms pre-stimulus interval was used as the baseline.

A current source density (CSD) transform (order of splines = 5, maximal degree of Legendre polynomial = 10; λ smoothing parameter = 10^{-5}) was applied to the data to compute an estimate of the surface Laplacian based on the EEG voltage across the scalp electrodes. Laplacian data are relatively free from activities originating from remote sources, and the adverse effects of volume conduction on the EEG are considerably attenuated (Vidal *et al.*, 2003). Feedback-locked ERPs were averaged separately for each condition of the monetary win task (win *vs* break-even), monetary loss task (loss *vs* break-even), social like task (like *vs* did not rate) and social dislike task (dislike *vs* did not rate). The visual examination of the ERP response to monetary and social feedback indicated that the RewP occurred between 200 and 300 ms following feedback at electrode Fz, where the difference between feedback outcomes (correct *vs* incorrect) was the greatest (see Supplementary data).

To better isolate the RewP from surrounding ERP components (e.g. P200, P300), a principal component analysis (PCA) was also conducted on the CSD-transformed data at electrode Fz (see Supplementary data). As shown in Figure 1, the PCA-derived TF4 (2.5% of the variance) resembled the temporal characteristics of the RewP and was extracted for all subsequent analyses. TF4 was translated back into the original CSD-transformed voltage scale (i.e. $\mu V/m^2$).

Data analysis

The ERP response during the monetary and social feedback tasks was examined with a task (monetary *vs* social) × valence (positive *vs* negative) × outcome (correct *vs* incorrect) repeated measures analysis of variance (ANOVA). Pearson's *r* correlations were examined between the ΔRewP for each condition using residuals (i.e. monetary win independent of break even, monetary loss independent of break even, social like independent of did not rate and social dislike independent of did not rate). The ΔRewP was quantified using residuals, as opposed to subtraction-based difference scores, as they help isolate neural activity that is unique to the condition of interest and provide a more reliable measure (Ethridge and Weinberg, 2018).

A task × valence × outcome analysis of covariance (ANCOVA) was conducted, with dysphoria and social anxiety symptoms entered as simultaneous covariates (see Supplementary data for more details about analytical strategy). In addition, all follow-up analyses involving dysphoria or social anxiety symptoms involved symptom residuals (i.e. dysphoria independent of social anxiety and social anxiety independent of dysphoria). All analyses were conducted in IBM SPSS Statistics, Version 26.0 (Armonk, NY, USA).

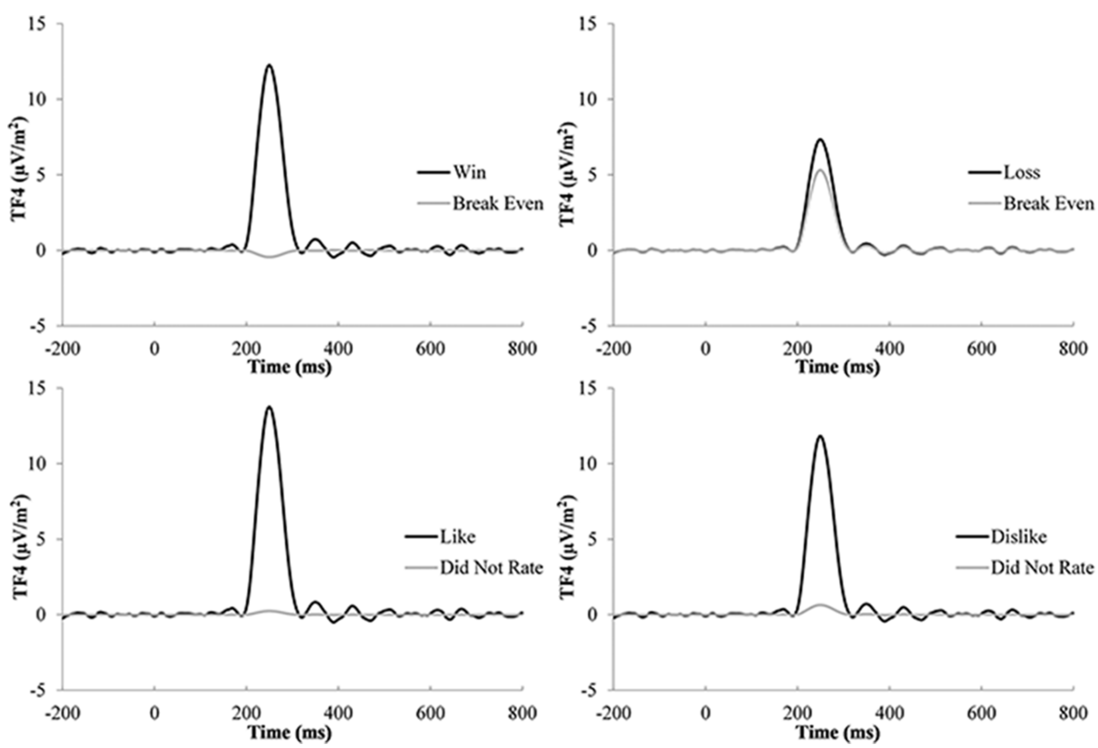

Fig. 1. ERP waveforms for TF4 at electrode Fz for the monetary win, monetary loss, social like, and social dislike tasks.

Results

Monetary and social tasks

Results indicated a main effect of outcome, $F(1, 203) = 226.04$, $P < 0.001$, $\eta_p^2 = 0.53$, type × outcome, $F(1, 203) = 28.23$, $P < 0.001$, $\eta_p^2 = 0.12$ and valence × outcome interactions, $F(1, 203) = 49.81$, $P < 0.001$, $\eta_p^2 = 0.20$, which were qualified by a type × valence × outcome interaction, $F(1, 203) = 32.63$, $P < 0.001$, $\eta_p^2 = 0.14$. The type × valence × outcome interaction was followed-up by conducting separate valence × outcome repeated-measures ANOVAs for each type of task (i.e. monetary and social).

For monetary trials, results indicated a main effect of outcome, $F(1, 203) = 99.40$, $P < 0.001$, $\eta_p^2 = 0.33$, which was qualified by a valence × outcome interaction, $F(1, 203) = 76.38$, $P < 0.001$, $\eta_p^2 = 0.27$. For win trials, the ERP response to win feedback was greater (i.e. more positive) compared to the ERP response to break even feedback, $F(1, 203) = 183.75$, $P < 0.001$, $\eta_p^2 = 0.48$. For loss trials, the ERP response to loss feedback was also greater compared to the ERP response to break even feedback, $F(1, 203) = 4.29$, $P = 0.04$, $\eta_p^2 = 0.02$, but this increase was greater for the win trials compared to the loss trials.

For social trials, results indicated a main effect of outcome, $F(1, 203) = 202.37$, $P < 0.001$, $\eta_p^2 = 0.50$, which was qualified by a valence × outcome interaction, $F(1, 203) = 4.22$, $P = 0.04$, $\eta_p^2 = 0.02$. For like trials, the ERP response to like feedback was greater compared to the ERP response to did not rate feedback, $F(1, 203) = 178.26$, $P < 0.001$, $\eta_p^2 = 0.47$. For dislike trials, the ERP response to dislike feedback was also greater compared to the ERP response to did not rate feedback, $F(1, 203) = 111.80$, $P < 0.001$, $\eta_p^2 = 0.36$, but this increase was greater for the like trials compared to the dislike trials.

Overall, these results suggest that the ERP response to correct feedback was greater compared to the ERP response to incorrect feedback across all four tasks. However, this increase (representing the ΔRewP) was greater for monetary win *vs* loss trials, and social like *vs* dislike trials.

Within-subject correlations

As shown in Table 1, the ΔRewP residual for monetary win, monetary loss, social like and social dislike feedback demonstrated weak to moderate positive correlations with each other.

Symptoms

Across all participants, 5.9% of participants had dysphoria symptom scores that exceeded the diagnostic clinical cut-off for major depressive disorder, and 8.4% of participants had social anxiety scores that exceeded the diagnostic clinical cutoff for social phobia (Stasik-O'Brien *et al.*, 2019). As expected, dysphoria and social anxiety symptoms were moderately correlated, $r(204) = 0.66$, $P < 0.001$.

Table 1. Pearson's *r* between TF4 residuals for monetary win and loss and social like and dislike feedback

	1	2	3	4
Monetary win	–	0.38***	0.42***	0.40***
Monetary loss		–	0.22**	0.37***
Social like			–	0.48***
Social dislike				–

Note. ** $p < .01$, *** $p < .001$.

Symptom analyses indicated dysphoria × outcome, $F(1, 201) = 5.87$, $P = 0.016$, $\eta_p^2 = 0.03$, and social anxiety × outcome interactions, $F(1, 201) = 7.53$, $P = 0.007$, $\eta_p^2 = 0.04$. To follow-up each interaction, the ERP response to the correct feedback (i.e. monetary win, monetary loss, social like and social dislike feedback) was averaged and then the ERP response to the incorrect feedback (i.e. monetary no win [break-even], monetary no loss [break-even], social did not rate [during like trials] and social did not rate [during dislike trials] feedback) was averaged. Next, a residual was calculated for the ERP response to correct feedback (independent of the ERP response to incorrect feedback) to quantify a ΔRewP residual. In addition, residuals were calculated for dysphoria symptoms (independent of social anxiety symptoms) and social anxiety symptoms (independent of dysphoria symptoms). Finally, Pearson's *r* correlations were conducted between the RewP residual and the dysphoria and social anxiety residuals. As shown in Figure 2, results indicated that a smaller ΔRewP was associated with greater dysphoria symptoms, $r(204) = -0.21$, $P = 0.003$, whereas a larger ΔRewP was associated with greater social anxiety symptoms, $r(204) = 0.18$, $P = 0.01$.

Results also indicated a type × valence × outcome × social anxiety interaction, $F(1, 201) = 9.42$, $P = 0.002$, $\eta_p^2 = 0.05$. To follow-up this interaction, residuals were calculated for the ΔRewP to monetary win, monetary loss, social like and social dislike feedback, independent of all other conditions. Next, Pearson's *r* correlations were conducted between the ΔRewP residuals and the social anxiety residual (independent of dysphoria symptoms). As shown in Figure 2, results indicated that an increased ΔRewP to social dislike feedback was associated with greater social anxiety symptoms, $r(204) = 0.16$, $P = 0.022$. There were no significant correlations between the ΔRewP to monetary win, $r(204) = 0.10$, $P = 0.18$, monetary loss, $r(204) = -0.04$, $P = 0.54$ and social like, $r(204) = -0.05$, $P = 0.47$, feedback and social anxiety symptoms.

Discussion

The present study examined the neural response to monetary and social feedback in relation to depression and social anxiety symptoms. Results indicated that correctly identifying stimuli that resulted in monetary win, monetary loss, social like and social dislike feedback elicited RewPs that were positively correlated with each other. Across all tasks, the RewP to correct feedback demonstrated the opposite relationship with depression and social anxiety symptoms such that a smaller RewP was associated with greater depression symptoms, whereas a larger RewP was associated with greater social anxiety symptoms. In addition, a larger RewP to social dislike feedback was uniquely associated with greater social anxiety symptoms. The present study provides initial evidence that a domain-general neural response to correct feedback is differentially associated with depression and social anxiety, but a domain-specific neural response to social dislike feedback is uniquely associated with social anxiety.

There are a number of different experimental paradigms that are currently used in the reward-processing literature. However, the ability to make a refined and more specific interpretation of neural reward responses is often hampered by critical design confounds. For example, a number of studies have examined the

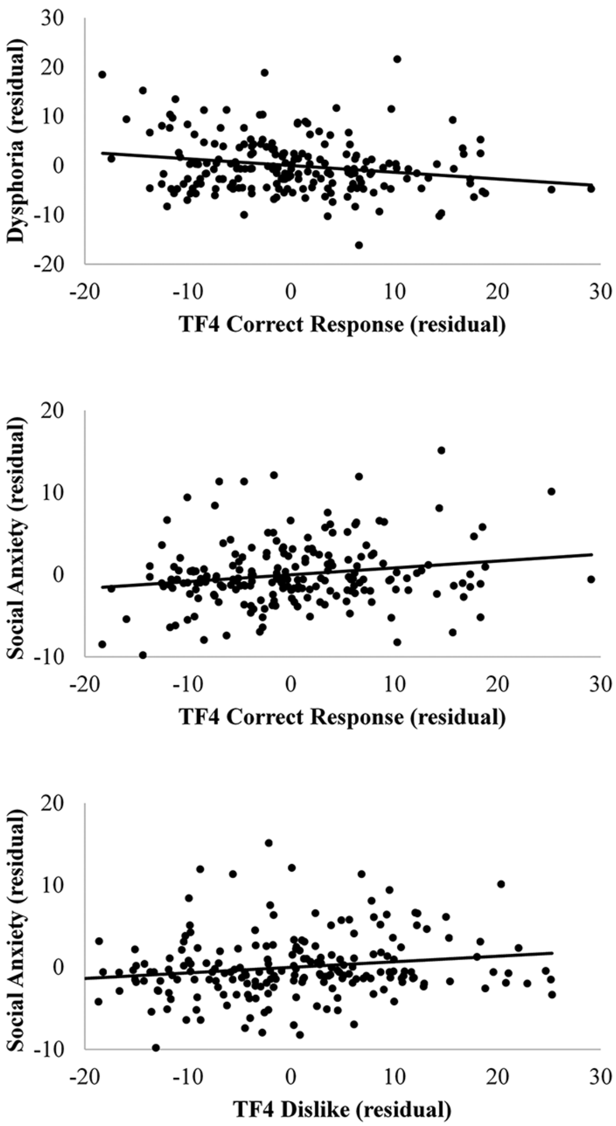

Fig. 2. Scatterplots displaying the association between TF4 and both dysphoria and social anxiety symptoms.

neural response to social feedback but failed to include a non-social comparison condition (Kujawa *et al.*, 2014a; van der Veen *et al.*, 2016) or compared paradigms that are not matched on basic task properties (Ethridge *et al.*, 2017). The presence of these confounds potentially impedes the ability to make a domain-specific interpretation of the results. In addition, many studies directly compare the neural response to positive and negative valence feedback (Proudfit, 2015; Distefano *et al.*, 2018), making it difficult to know if an aberrant neural response is due to the positive stimuli, negative stimuli or both. Finally, the RewP is an ERP component that is elicited in as part of a mesocortical dopamine system central to reinforcement learning (Holroyd and Coles, 2002), but there is often a confound between making a correct decision and receiving positive feedback. Interestingly, a recent investigation found that the RewP is elicited even in the context of a non-monetary doors task (Tunison *et al.*, 2019). The application of multiple experimental tasks across different domains might be necessary to make more specific conclusions about what aspects of a neural response to rewards impact its relationship with psychopathology.

The present study employed a novel set of experimental paradigms that addressed many of the key confounds in the reward-processing literature. The RewP was elicited in response to both monetary and social domains across both positive and negative valence feedback and was positively correlated across all tasks. These results are consistent with several fMRI (Izuma *et al.*, 2008; Lin *et al.*, 2012; Daniel and Pollmann, 2014) and ERP (Distefano *et al.*, 2018; Ait Oumeziane *et al.*, 2019) studies signifying that there is a domain-general neural circuit involved in reinforcement learning and reward processing. The strength of the positive correlations was in the weak to moderate range, suggesting that each neural response also contained variance that was unique to that particular domain. Overall, the results demonstrate that the RewP reflects both domain-general and domain-specific aspects of reward processing.

The present study adds to a growing literature indicating that a blunted RewP is associated with expression and risk for depression. However, the present study provides novel evidence suggesting that the relationship might be the result of a domain-general neural system implicated in functions like reinforcement learning and reward processing. These results are in contrast to a previous investigation that found a domain-specific relationship between the RewP to social feedback from female peers and depression symptoms in female participants (Distefano *et al.*, 2018). The present study had too few trials to differentiate between male and female feedback during the social tasks, and future studies should include more trials to examine this important contextual factor.

While these results are consistent with a domain-general neural system that underlies the relationship between the RewP and depression, this may not be the case for all neural and physiological measures. Indeed, in a time–frequency analysis of the same data from the present study, lesser delta activity to social feedback and greater theta activity to monetary feedback were associated with greater depressive symptoms (Jin *et al.*, 2019). Similarly, an fMRI-based study that used the same experimental paradigms found domain-specific relationships between the neural response to social reward and depression symptoms (Quarmley *et al.*, 2019). Therefore, the RewP might best index the domain-general, while other neural and physiological measures might better represent the domain-specific, aspects of reward circuitry that are associated with depression.

The present study also found that the neural response to social dislike feedback was uniquely associated with greater social anxiety symptoms. Thus, both domain-general and domain-specific neural responses to negative social feedback were associated with social anxiety. These results are consistent with previous studies that have shown that both a greater neural response to monetary reward (Bar-Haim *et al.*, 2009; Lahat *et al.*, 2018) and social rejection/dislike feedback (Jarcho *et al.*, 2015; Quarmley *et al.*, 2019) are associated with social anxiety.

The present study had several limitations that warrant consideration. First, the sample included college students, and additional research is needed to determine if the results generalize to other populations, such as children/adolescents and treatment-seeking clinical populations. Second, the RewP to correct loss feedback was much smaller in mean activity relative to the other conditions, and this is possibly due to the condition instruction containing conflicting motivations. Specifically, participants were asked to choose the door that contained a monetary loss, which meant that both outcomes contained something rewarding (i.e. they were correct but lost money *vs* they were wrong but did not lose money). This is an inverse problem to the confound implicit in traditional reward-processing tasks, in which positive outcomes include two rewarding features, and underscores the need for careful consideration when interpreting even seemingly straightforward results in reward-processing domains. Moreover, the present study instructed participants on their goal for each task (e.g. pick the door that contains the monetary win) but did not explicitly evaluate this in each participant. Thus, it is possible that, while instructed to pick the door with the monetary loss, participants might have attempted to achieve the opposite goal (i.e. pick the door with the break-even outcome). Third, the feedback stimuli were consistent across all social and monetary tasks, but within each task, there were differences in the stimuli indicating a correct (up green arrow) and incorrect (down red arrow) response. Such stimulus-based differences could have contributed to differences in the neural response. Future studies should consider matching the feedback stimuli on as many characteristics as possible to eliminate the possibility that physical characteristics contribute to differences in the neural response. Finally, all measures were collected using a cross-sectional design, and it is difficult to make any causal or temporal conclusions regarding the relationship between the neural response to reward and psychopathology.

In conclusion, the present study provides novel evidence that a domain-general neural response to correct feedback is differentially associated with depression and social anxiety, but a domain-specific neural response to social dislike feedback is uniquely associated with social anxiety. This study also highlights that there are several important confounds and task features that need to be taken into consideration when attempted to make domain-specific conclusions about the role of the neural response to rewards in relation to psychopathology. Additional research is needed to replicate these results across different samples (e.g. children/adolescents) and in relation to other forms of psychopathology that have been associated with reward system dysfunction.

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Conflict of interest

The authors have no conflicts of interest to report.

Supplementary data

Supplementary data are available at *SCAN* online.

References

Aderka, I.M., Hofmann, S.G., Nickerson, A., Hermesh, H., Gilboa-Schechtman, E., Marom, S. (2012). Functional impairment in social anxiety disorder. *Journal of Anxiety Disorders*, **26**, 393–400.

Ait Oumeziane, B., Jones, O., Foti, D. (2019). Neural sensitivity to social and monetary reward in depression: clarifying general and domain-specific deficits. *Frontiers in Behavioral Neuroscience*, **13**, 1–16.

Bar-Haim, Y., Fox, N.A., Benson, B., *et al.* (2009). Neural correlates of reward processing in adolescents with a history of inhibited temperament. *Psychological Science*, **20**, 1009–18.

Baxter, A.J., Vos, T., Scott, K.M., Ferrari, A.J., Whiteford, H.A. (2014). The global burden of anxiety disorders in 2010. *Psychological Medicine*, **44**, 2363–74.

Becker, M.P.I., Nitsch, A.M., Miltner, W.H.R., Straube, T. (2014). A single-trial estimation of the feedback-related negativity and its relation to BOLD responses in a time-estimation task. *The Journal of Neuroscience*, **34**, 3005–12.

Birmaher, B., Ryan, N.D., Williamson, D.E., *et al.* (1996). Childhood and adolescent depression: a review of the past 10 years. Part I. *Journal of the American Academy of Child and Adolescent Psychiatry*, **35**, 1427–39.

Bress, J.N., Smith, E., Foti, D., Klein, D.N., Hajcak, G. (2012). Neural response to reward and depressive symptoms in late childhood to early adolescence. *Biological Psychology*, **89**, 156–62.

Bress, J.N., Foti, D., Kotov, R., Klein, D.N., Hajcak, G. (2013). Blunted neural response to rewards prospectively predicts depression in adolescent girls. *Psychophysiology*, **50**, 74–81.

Bress, J.N., Hajcak, G. (2013). Self-report and behavioral measures of reward sensitivity predict the feedback negativity. *Psychophysiology*, **50**, 610–6.

Burani, K., Mulligan, E.M., Klawohn, J., Luking, K.R., Nelson, B.D., Hajcak, G. (2019). Longitudinal increases in reward-related neural activity in early adolescence: evidence from event-related potentials (ERPs). *Developmental Cognitive Neuroscience*, **36**, 100620.

Cao, J., Gu, R., Bi, X., Zhu, X., Wu, H. (2015). Unexpected acceptance? Patients with social anxiety disorder manifest their social expectancy in ERPs during social feedback processing. *Frontiers in Psychology*, **6**, 1–10.

Carlson, J.M., Foti, D., Mujica-Parodi, L.R., Harmon-Jones, E., Hajcak, G. (2011). Ventral striatal and medial prefrontal BOLD activation is correlated with reward-related electrocortical activity: a combined ERP and fMRI study. *NeuroImage*, **57**, 1608–16.

Chan, R.C.K., Li, K., Zeng, Y.W., *et al.* (2016). Distinct processing of social and monetary rewards in late adolescents with trait anhedonia. *Neuropsychology*, **30**, 274–80.

Daniel, R., Pollmann, S. (2014). A universal role of the ventral striatum in reward-based learning: evidence from human studies. *Neurobiology of Learning and Memory*, **114**, 90–100.

Distefano, A., Jackson, F., Levinson, A.R., Infantolino, Z.P., Jarcho, J.M., Nelson, B.D. (2018). A comparison of the electrocortical response to monetary and social reward. *Social Cognitive and Affective Neuroscience*, **13**, 247–55.

Egger, H.L., Pine, D.S., Nelson, E., *et al.* (2011). The NIMH Child Emotional Faces Picture Set (NIMH-ChEFS): a new set of children's facial emotion stimuli. *International Journal of Methods in Psychiatric Research*, **20**, 145–56.

Ethridge, P., Kujawa, A., Dirks, M.A., *et al.* (2017). Neural responses to social and monetary reward in early adolescence and emerging adulthood. *Psychophysiology*, **54**, 1786–99.

Ethridge, P., Weinberg, A. (2018). Psychometric properties of neural responses to monetary and social rewards across development. *International Journal of Psychophysiology*, **132**, 311–22.

Flores, A., Münte, T.F., Doñamayor, N. (2015). Event-related EEG responses to anticipation and delivery of monetary and social reward. *Biological Psychology*, **109**, 10–9.

Forbes, E.E., Christopher May, J., Siegle, G.J., *et al.* (2006). Reward-related decision-making in pediatric major depressive disor der: an fMRI study. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, **47**, 1031–40.

Foti, D., Kotov, R., Klein, D.N., Hajcak, G. (2011). Abnormal neural sensitivity to monetary gains versus losses among adolescents at risk for depression. *Journal of Abnormal Child Psychology*, **39**, 913–24.

Foti, D., Hajcak, G. (2009). Depression and reduced sensitivity to non-rewards versus rewards: evidence from event-related potentials. *Biological Psychology*, **81**, 1–8.

Gotlib, I.H., Hamilton, J.P., Cooney, R.E., Singh, M.K., Henry, M.L., Joormann, J. (2010). Neural processing of reward and loss in girls at risk for major depression. *Archives of General Psychiatry*, **67**, 380–7.

Gratton, G., Coles, M.G.H., Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, **55**, 468–84.

Guyer, A.E., Nelson, E.E., Perez-Edgar, K., *et al.* (2006). Striatal functional alteration in adolescents characterized by early childhood behavioral inhibition. *Journal of Neuroscience*, **26**, 6399–405.

Guyer, A.E., Choate, V.R., Pine, D.S., Nelson, E.E. (2012). Neural circuitry underlying affective response to peer feedback in adolescence. *Social Cognitive and Affective Neuroscience*, **7**, 81–92.

Hankin, B.L., Abramson, L.Y., Moffitt, T.E., Silva, P.A., McGee, R., Angell, K.E. (1998). Development of depression from preadolescence to young adulthood: emerging gender differences in a 10-year longitudinal study. *Journal of Abnormal Psychology*, **107**, 128–40.

Hanson, J.L., Hariri, A.R., Williamson, D.E. (2015). Blunted ventral striatum development in adolescence reflects emotional neglect and predicts depressive symptoms. *Biological Psychiatry*, **78**, 598–605.

Harrewijn, A., Schmidt, L.A., Westenberg, P.M., Tang, A., van der Molen, M.J.W. (2017). Electrocortical measures of information processing biases in social anxiety disorder: a review. *Biological Psychology*, **129**, 324–48.

Holroyd, C.B., Coles, M.G.H. (2002). The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, **109**, 679–709.

Izuma, K., Saito, D.N., Sadato, N. (2008). Processing of social and monetary rewards in the human striatum. *Neuron*, **58**, 284–94.

Jarcho, J.M., Romer, A.L., Shechner, T., *et al.* (2015). Forgetting the best when predicting the worst: preliminary observations on neural circuit function in adolescent social anxiety. *Developmental Cognitive Neuroscience*, **13**, 21–31.

Jin, J., Sabharwal, A., Infantolino, Z.P., Jarcho, J.M., Nelson, B.D. (2019). Time-frequency delta activity to social feedback demonstrates differential associations with depression and social anxiety symptoms. *Frontiers in Behavioral Neuroscience*, **13**, 1–13.

Kessel, E.M., Kujawa, A., Proudfit, G.H., Klein, D.N. (2014). Neural reactivity to monetary rewards and losses differentiates social from generalized anxiety in children. *Journal of Child Psychology and Psychiatry*, **56**, 792–800.

Kessler, R.C., Chiu, W.T., Demler, O., Merikangas, K.R., Walters, E.E. (2005). Prevalence, severity, and comorbidity of 12-month DSM-IV disorders in the National Comorbidity Survey Replication. *Archives of General Psychiatry*, **62**, 617–27.

Kujawa, A., Arfer, K.B., Klein, D.N., Proudfit, G.H. (2014a). Electrocortical reactivity to social feedback in youth: a pilot study of the Island Getaway task. *Developmental Cognitive Neuroscience*, **10**, 140–7.

Kujawa, A., Proudfit, G.H., Klein, D.N. (2014b). Neural reactivity to rewards and losses in offspring of mothers and fathers with histories of depressive and anxiety disorders. *Journal of Abnormal Psychology*, **123**, 287–97.

Kujawa, A., Kessel, E.M., Carroll, A., Arfer, K.B., Klein, D.N. (2017). Social processing in early adolescence: associations between neurophysiological, self-report, and behavioral measures. *Biological Psychology*, **128**, 55–62.

Lahat, A., Benson, B.E., Pine, D.S., Fox, N.A., Ernst, M. (2018). Neural responses to reward in childhood: relations to early behavioral inhibition and social anxiety. *Social Cognitive and Affective Neuroscience*, **13**, 281–9.

Lewinsohn, P.M., Gotlib, I.H., Lewinsohn, M., Seeley, J.R., Allen, N.B. (1998). Gender differences in anxiety disorders and anxiety symptoms in adolescents. *Journal of Abnormal Psychology*, **107**, 109–17.

Lin, A., Adolphs, R., Rangel, A. (2012). Social and monetary reward learning engage overlapping neural substrates. *Social Cognitive and Affective Neuroscience*, **7**, 274–81.

Liu, W.H., Wang, L.Z., Shang, H.R., *et al.* (2014). The influence of anhedonia on feedback negativity in major depressive disorder. *Neuropsychologia*, **53**, 213–20.

Luppa, M., Heinrich, S., Angermeyer, M.C., König, H.-H., Riedel-Heller, S.G. (2007). Cost-of-illness studies of depression: a systematic review. *Journal of Affective Disorders*, **98**, 29–43.

Merikangas, K.R., He, J., Burstein, M., *et al.* (2011). Service utilization for lifetime mental disorders in U.S. adolescents: results of the National Comorbidity Survey-Adolescent Supplement (NCS-A). *Journal of the American Academy of Child and Adolescent Psychiatry*, **50**, 32–45.

Morgan, J.K., Olino, T.M., McMakin, D.L., Ryan, N.D., Forbes, E.E. (2013). Neural response to reward as a predictor of increases in depressive symptoms in adolescence. *Neurobiology of Disease*, **52**, 66–74.

Müller, V.I., Cieslik, E.C., Serbanescu, I., Laird, A.R., Fox, P.T., Eickhoff, S.B. (2017). Altered brain activity in unipolar depression revisited: meta-analyses of neuroimaging studies. *JAMA Psychiatry*, **74**, 47–55.

Mulligan, E.M., Flynn, H., Hajcak, G. (2019). Neural response to reward and psychosocial risk factors independently predict antenatal depressive symptoms. *Biological Psychology*, **147**, 107622.

Nelson, B.D., Perlman, G., Klein, D.N., Kotov, R., Hajcak, G. (2016). Blunted neural response to rewards as a prospective predictor of the development of depression in adolescent girls. *American Journal of Psychiatry*, **173**, 1223–30.

Olino, T.M., Silk, J.S., Osterritter, C., Forbes, E.E. (2015). Social reward in youth at risk for depression: a preliminary investigation of subjective and neural differences. *Journal of Child and Adolescent Psychopharmacology*, **25**, 711–21.

Pizzagalli, D.A., Holmes, A.J., Dillon, D.G., *et al.* (2009). Reduced caudate and nucleus accumbens response to rewards in unmedicated individuals with major depressive disorder. *The American Journal of Psychiatry*, **166**, 702–10.

Pizzagalli, D.A. (2014). Depression, stress, and anhedonia: toward a synthesis and integrated model. *Annual Review of Clinical Psychology*, **10**, 393–423.

Proudfit, G.H. (2015). The reward positivity: from basic research on reward to a biomarker for depression. *Psychophysiology*, **52**, 449–59.

Quarmley, M.E., Nelson, B.D., Clarkson, T., White, L.K., Jarcho, J.M. (2019). I knew you weren't going to like me! Neural response to accurately predicting rejection is associated with anxiety and depression. *Frontiers in Behavioral Neuroscience*, **13**, 1–11.

Rademacher, L., Krach, S., Kohls, G., Irmak, A., Gründer, G., Spreckelmeyer, K.N. (2010). Dissociation of neural networks for anticipation and consumption of monetary and social rewards. *NeuroImage*, **49**(4), 3276–85.

Russo, S.J., Nestler, E.J. (2013). The brain reward circuitry in mood disorders. *Nature Reviews Neuroscience*, **14**, 609–25.

Sankar, A., Yttredahl, A.A., Fourcade, E.W., *et al.* (2019). Dissociable neural responses to monetary and social gain and loss in women with major depressive disorder. *Frontiers in Behavioral Neuroscience*, **13**, 1–11.

Silk, J.S., Siegle, G.J., Lee, K.H., Nelson, E.E., Stroud, L.R., Dahl, R.E. (2014). Increased neural response to peer rejection associated with adolescent depression and pubertal development. *Social Cognitive and Affective Neuroscience*, **9**, 1798–807.

Silk, J.S., Davis, S., McMakin, D.L., Dahl, R.E., Forbes, E.E. (2012). Why do anxious children become depressed teenagers? The role of social evaluative threat and reward processing. *Psychological Medicine*, **42**, 2095–107.

Stasik-O'Brien, S.M., Brock, R.L., Chmielewski, M., *et al.* (2019). Clinical utility of the inventory of depression and anxiety symptoms (IDAS). *Assessment*, **26**, 944–60.

Steele, J.D., Kumar, P., Ebmeier, K.P. (2007). Blunted response to feedback information in depressive illness. *Brain*, **130**, 2367–74.

Stringaris, A., Vidal-Ribas Belil, P., Artiges, E., *et al.* (2015). The brain's response to reward anticipation and depression in adolescence: dimensionality, specificity, and longitudinal predictions in a community-based sample. *American Journal of Psychiatry*, **172**, 1215–23.

Treadway, M.T., Zald, D.H. (2011). Reconsidering anhedonia in depression: lessons from translational neuroscience. *Neuroscience and Biobehavioral Reviews*, **35**, 537–55.

Tunison, E., Sylvain, R., Sterr, J., Hiley, V., Carlson, J.M. (2019). No money, no problem: enhanced reward positivity in the absence of monetary reward. *Frontiers in Human Neuroscience*, **13**, 1–5.

van der Veen, F.M., van der Molen, M.W.J.W., van der Molen, M.W.J.W., Franken, I.H.A. (2016). Thumbs up or thumbs down? Effects of neuroticism and depressive symptoms on psychophysiological responses to social evaluation in healthy students. *Cognitive, Affective & Behavioral Neuroscience*, **16**, 836–47.

Vidal, F., Burle, B., Bonnet, M., Grapperon, J., Hasbroucq, T. (2003). Error negativity on correct trials: a reexamination of available data. *Biological Psychology*, **64**, 265–82.

Watson, D., O'Hara, M.W., Naragon-Gainey, K., *et al.* (2012). Development and validation of new anxiety and bipolar symptom scales for an expanded version of the IDAS (the IDAS-II). *Assessment*, **19**, 399–420.

Weissman, M.M., Wolk, S., Wickramaratne, P., *et al.* (1999). Children with prepubertal-onset major depressive disorder and anxiety grown up. *Archives of General Psychiatry*, **56**, 794–801.