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Will they like me? Neural and behavioral responses to social-evaluative feedback in socially and non-socially anxious females

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Abstract

The current study examined neural and behavioral responses to social evaluative feedback processing in social anxiety. Twenty-two non-socially and 17 socially anxious females (mean age = 19.57 years) participated in a Social Judgment Paradigm in which they received acceptance/rejection feedback that was either congruent or incongruent with their prior predictions. Results indicated that socially anxious participants believed they would receive less social acceptance feedback than non-socially anxious participants. EEG results demonstrated that unexpected social rejection feedback elicited a significant increase in theta (4-8 Hz) power relative to other feedback conditions. This theta response was only observed in non-socially anxious individuals. Together, results corroborate cognitive-behavioral studies demonstrating a negative expectancy bias in socially anxiety with respect to social evaluation. Furthermore, the present findings highlight a functional role for theta oscillatory dynamics in processing cues that convey social-evaluative threat, and this social threat monitoring mechanism seems less sensitive in socially anxious females.

Keywords: EEG, feedback, P3, social anxiety, social evaluation, theta power

Introduction

Fear of negative social evaluation is a core symptom of social anxiety disorder (D.M. Clark & Wells, 1995), a prevalent anxiety disorder with a chronic course of development and a precursor of other mental health problems (e.g., depression, substance abuse) (Blanco, Nissenson, & Liebowitz, 2001; Wittchen, 2000). Theoretical models have specified a variety information processing biases that contribute to the maintenance of social anxiety, such as attentional biases (e.g., self-focused attention and increased focus on external threat), as well as anticipatory and post-event processing biases (D. M. Clark & McManus, 2002). It has been argued that these information processing biases are expressed based on the level of threat that is assigned to social-evaluative stimuli that convey judgment to important aspects of self-identity (Dickerson, Gruenewald, & Kemeny, 2004) – a concept recently coined as the *social-evaluative threat principle* (Wong & Rapee, 2016). A large body of work has examined responsivity to lower-order social-evaluative threat stimuli (e.g., behavioral and psychophysiological responsivity to facial expressions), and this work has contributed to the characterization of information processing biases in socially anxious individuals (e.g., initial hypervigilance to threat) (D. M. Clark & McManus, 2002; Mogg & Bradley, 2002). However, the neural mechanisms implicated in processing social-evaluative threat stimuli associated with higher-order social concepts (e.g., social rejection cues from peers) remain poorly understood. The goal of the current study is to offer a detailed examination of the behavioral, as well as electrocortical responses to social-evaluative peer feedback in subclinical socially anxious vs. non-socially anxious females.

Due to the chronicity of a negative-expectancy bias in social anxiety, research has focused to delineate the cognitive mechanisms that instantiate this belief to be scrutinized by others in social situations. By employing paradigms that simulate social-evaluative threat it has been shown that socially anxious individuals predict to be socially rejected more often than non-socially anxious individuals. For example, using the Chatroom task, socially anxious participants believed that a larger proportion of peers would not be interested in chatting with them (Caouette et al., 2015). A similar negative expectancy bias was found using the Island Getaway task. In this paradigm, participants vote to accept or reject co-players from staying on a virtual island, while also receiving similar information from the co-players. Cao et al. (2015) found that participants with social anxiety had lower-peer acceptance expectancies than healthy controls. Recent computational-modeling evidence underscores this negative expectancy bias and highlights a prominent inability to learn from positive feedback in socially anxious individuals (Koban et al., 2017). These authors postulated that socially anxious individuals are less attentive and influenced by positive feedback. These alleged misconceptions about social evaluation might not be easily corrected, which in turn could instantiate the negative expectancy bias and maintain social anxiety symptoms (Koban et al., 2017).

To date, it remains unclear how this negative expectancy bias in socially anxious individuals relates to the processing of social-evaluative feedback in the brain. According to the social-evaluative threat principle (Wong & Rapee, 2016), socially anxious individuals should display heightened reactivity to social-evaluative feedback (e.g., social rejection), since such stimuli would convey a significant threat to the individual’s well-being (Baumeister & Leary, 1995; Eisenberger & Lieberman, 2004). In contrast, the cognitive-behavioral model on social anxiety of Clark and Wells (1995) posits a reduced processing of external social-evaluative threat cues, most likely due to enhanced self-focused attention in socially anxious individuals (Bögels & Mansell, 2004). For example, in anticipation or in response to a social-evaluative stressor, attentional resources in a socially anxious individual can be directed internally (i.e., to physiological cues of arousal, such as elevated heart rate or blushing), or to their behavior and thoughts. Self-focused attention to internal self-relevant stimuli is argued to result in reduced attentional resources to external cues, and limits the processing of external social-evaluative threat (D.M. Clark & Wells, 1995; Rapee & Heimberg, 1997). This interpretation meshes with the idea that socially anxious individuals display increased interoceptive awareness to bodily sensations when they are confronted with a social-evaluative stressor (Durlik, Brown, & Tsakiris, 2014). Heightened interoceptive awareness dedicates increased attentional resources to somatic perception and the inherent subjective perception of anxiety (Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004), which might limit available resources to reorient attentional focus to external stressors in social anxiety (Terasawa, Shibata, Moriguchi, & Umeda, 2013). As a consequence, the enhanced self-focused attention might result in decreased sensitivity to social-evaluative threat.

Neural reactivity associated with processing social-evaluative feedback can offer an objective estimate of whether socially anxious individuals show increased or decreased sensitivity to social-evaluative threat. However, few studies exist on this topic and their results are mixed. These studies examined reactivity of the feedback-related negativity (FRN), a brain potential belonging to a class ERPs generated by the medial prefrontal cortex, and the anterior cingulate cortex (ACC) in particular (van Noordt & Segalowitz, 2012). The FRN is sensitive to feedback communicating an unexpected outcome or indicating that behavior was incorrect (Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997). Using the Island Getaway task, Kujawa et al (2014) found that socially anxious teenagers were more sensitive to social rejection feedback vs. acceptance feedback as indexed by the FRN. In contrast, using a similar paradigm, Cao et al. (2015) found that patients with social anxiety disorder displayed a significantly larger FRN to social acceptance vs. rejection feedback. These inconsistent results might be related the different participant samples used in these studies (e.g., socially anxious teenagers vs. adults with and without social anxiety disorder). Furthermore, both studies examined the FRN in response to social acceptance vs. rejection feedback without taking into account participants' trial-by-trial a-priori predictions about the social-evaluative outcome. It is known from myriad of performance monitoring studies that feedback-related brain activity is sensitive to prediction error (for a review, see Walsh & Anderson, 2012). With respect to the apparent negative expectancy bias in social anxiety, prediction error might be an important factor moderating brain activity to social-evaluative feedback.

A paradigm that allows for examining the effect of expectancies about social evaluation is the Social Judgment Paradigm (SJP), developed by Somerville et al. (2006). In this paradigm, participants are led to believe that they were evaluated by a group of peers based a portrait photograph of the participant. Peers were supposedly asked to indicate whether they would like or dislike the participant based on their first impressions. During the testing session, the participant is shown portrait photographs of these peers and has to predict whether each peer liked or disliked the participant. Thereafter, peer feedback is provided communicating social acceptance or rejection, and is either congruent or incongruent with participants' prior predictions. At the behavioral level, participants are generally optimistic about the social-evaluative outcome, as they predict higher proportions of social acceptance feedback (Dekkers, van der Molen, Gunther Moor, van der Veen, & van der Molen, 2015; van der Molen et al., 2014; van der Veen, van der Molen, van der Molen, & Franken, 2016). At the neural level, ERP studies using this paradigm have found that the FRN is sensitive to unexpected social-evaluative feedback (regardless of valence) and the P3 seems sensitive to expected social acceptance feedback, suggesting reward sensitivity (van der Veen, van der Molen, Sahibdin, & Franken, 2014).

In addition, recent evidence suggests that frontal midline (FM) theta (4-8 Hz) reactivity seems particularly enhanced during processing of unexpected social rejection feedback (van der Molen, Dekkers, Westenberg, van der Veen, & van der Molen, 2017). Source-localization methods revealed that this FM theta response could be localized a broad cingulate network, with prominent activity observed in the dorsal ACC (van der Molen et al., 2017). A vast majority of source-localization studies have identified the dorsal ACC as a main generator of FM theta activity (Asada, Fukuda, Tsunoda, Yamaguchi, & Tonoike, 1999; Ishii et al., 2014; Onton, Delorme, & Makeig, 2005; Young & McNaughton, 2009), and the dorsal ACC and seems to play an important role in a broad neural network – including medial prefrontal cortex and mid/posterior cingulate cortex – that governs FM theta oscillations (Cavanagh & Shackman, 2015; Ishii et al., 2014). Theoretical accounts suggest that FM theta oscillations reflect a general mechanism implicated in cognitive control operations, for example when behavioral adjustment is required after errors or when facing uncertain outcomes (Cavanagh & Frank, 2014; Cavanagh, Zambrano-Vazquez, & Allen, 2012; Shackman et al., 2011). It has been shown that these FM theta-dependent control efforts are not restricted to cognitive processes, but also extend to situations that elicit anxiety (Cavanagh & Shackman, 2015). In this regard, FM theta reactivity to social-evaluative feedback might constitute a neural mechanism of social-evaluative threat processing in the socially anxious brain.

In the current study, we will employ the SJP to examine behavioral and electrocortical responses to social-evaluative feedback processing in socially and non-socially anxious females. We focused on females since they have been shown to be more sensitive to social rejection than men (Benenson et al., 2013; Guyer, McClure-Tone, Shiffrin, Pine, & Nelson, 2009). Also, focusing on females reduces inter-individual variability and allows for better comparison which previous studies on neural correlates of social evaluative feedback processing (Dekkers et al., 2015; van der Molen et al., 2017; van der Molen et al., 2014). In addition to prior studies that have used this paradigm, we will ask participants to provide an estimation about the social-evaluative outcome *prior* to the experiment. This should offer an index of a possible negative expectancy bias in socially anxious participants. Also, we asked participants after the experiment to recall how they thought they were evaluated by peers (e.g., generally positively or negatively), to test for a possible recall bias in socially anxious females (Glazier & Alden, 2017). With respect to the trial-to-trial behavior on the SJP, we hypothesized that non-socially anxious females would be more optimistic about the social-evaluative outcome than socially anxious females (for example, see Dekkers et al., 2015; van der Veen et al., 2016). With respect to neural reactivity to social-evaluative feedback we expected that unexpected social rejection feedback would elicit the strongest theta power response (van der Molen et al., 2017). In addition, we performed source analyses on the theta response to unexpected social rejection feedback, and expected the dorsal ACC to be an important generator of FM theta (see van der Molen et al., 2017). Regarding social anxiety status, two competing hypotheses were tested: If unexpected social rejection feedback was perceived as a social-evaluative threat (cf., Wong & Rapee, 2016), theta power would be higher in socially vs. non-socially anxious participants. In contrast, if socially anxious would display a reduced processing of social-evaluative threat (cf., Clark & Wells, 2005), theta power to unexpected rejection feedback would be lower in socially vs. non-socially anxious participants.

Method

Participants

Participants were selected from 386 female undergraduate students based on their self-reported social anxiety scores obtained with the Liebowitz Social Anxiety Scale (LSAS; Liebowitz, 1987). Participants were assigned to either a non-socially anxious (NSA) group (LSAS scores below 30) or a socially anxious (SA) group (LSAS scores 60 or higher)[1]. Participants were excluded in case of a history of brain trauma, existence of psychiatric

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[1] Participants with LSAS scores below 30 demonstrate no sub-threshold or clinical levels of social anxiety, whereas LSAS scores of 60 or higher have been used to identify individuals with generalized social anxiety disorder Mennin et al. (2002)

disorders other than SAD (*n*=1), use of psychoactive medication (*n*=2), and left-handedness (*n*=3). This LSAS screening yielded 63 female participants that were assigned to either the socially anxious or non-socially anxious group. At the day of testing, the LSAS was administered again to assure that participants still met the abovementioned inclusion criteria regarding group status. Fourteen participants had a LSAS score that did not correspond with their group status and were excluded from further analyses. Additionally, ten participants were excluded due to data recording failures (*n*=2), poor EEG quality (*n*=7), and disbelief in the cover story of the SJP (*n*=1). This resulted in a total sample of 22 LSA participants (mean age = 19.89; *SD* = 1.53) and 17 HSA participants (mean age = 19.57; *SD* = 1.55). Participants had normal or corrected-to-normal vision, provided signed informed consent prior to the experiment, and were rewarded with course credit or 17 Euros for their participation. The protocol of this study was reviewed and approved by the local ethics committee of the Leiden Institute of Psychology.

Procedure

After explaining the EEG procedures and repeating the cover story, participants signed the informed consent form, and were seated in a comfortable chair in a dimly lit and sound attenuated room. The EEG protocol (fixed order) started with a 5-min eyes closed resting-state EEG, which was followed by the SJP and another task of which data have been published elsewhere (Harrewijn, van der Molen, & Westenberg, 2016). After the EEG session, participants completed the LSAS, as well as several other self-report questionnaires to validate that the groups also differed on personality constructs associated with social anxiety[2]. The experiment ended with debriefing the participants about the purpose of the study.

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[2] We measured self-esteem (Rosenberg Self-Esteem Scale; Rosenberg, 1965), fear of negative evaluation (Fear of Negative Evaluation Scale Revised; Carleton, McCreary, Norton, & Asmundson, 2006), fear of positive

Social Judgment Paradigm

The SJP was used as described in van der Molen et al. (2017). Via a cover, story participants were led to believe that they were enrolled in a study on first impressions. All participants submitted a digital personal portrait photograph to the experimenters prior to testing. A group of peers from other universities were supposedly asked to evaluate this photograph and indicate – based on first impressions – whether they liked or disliked the person on the photograph. After approximately two weeks, with a minimum of a week, participants came to the lab for the EEG experiment. Participants were informed that they would be viewing a portrait photograph of each member from the peer panel that evaluated the participant. The task of the participant was to predict whether she thought the peer on the photograph liked or disliked her. After each prediction, the participant received peer feedback communicating social acceptance or rejection. Feedback was either congruent or incongruent with the participants' predictions. In reality, participants were not evaluated by peers, and the fictitious peer feedback was pseudo-randomly generated by the computer. A total of 160 photographs depicting peer faces (50% male) were derived from taking photographs of undergraduates from different universities. These photographs have been obtained in prior studies (Gunther Moor, Crone, & van der Molen, 2010; van der Molen et al., 2014), and were shown on a 17-inch monitor (60 Hz refresh rate; visual angle [width x height] = 4.66° x 6.05°) using E-prime 2.0 stimulus presentation software (Psychology Software Tools, Pittsburgh PA). All peer photographs had a neutral facial expression, as ascertained with the Self-Assessment Manikin (SAM; Bradley & Lang, 1994).

--- insert Figure 1 about here ---

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evaluation (Fear of Positive Evaluation Scale; Weeks, Heimberg, & Rodebaugh, 2008), and depression (Beck Depression Inventory; Beck, Steer, & Brown, 1996). These data are presented in Table 2.

Figure 1 depicts an example of a trial sequence, which started with the presentation of the cue (i.e., photograph of a peer) that remained on the screen during the remainder of the trial. Participants were required to indicate their predictions regarding the social-evaluative outcome by pressing a button with their index finger on the left or right armrest of the chair. The left and right buttons corresponded to expected social acceptance versus rejection feedback, and the button-valence association was counterbalanced across participants. Participants had 3000 ms to provide their feedback predictions. If participants did not respond within this time-window, the words “too slow” appeared on the screen for a duration of 2000 ms, followed by a new trial. If participants did respond on time, the prediction was immediately presented on the computer screen to the left of the peer’s face. Peer feedback was presented after a fixed interval of 3000 ms (from cue onset), to the right of the peer’s face. Peer feedback was pseudorandomly presented, and participants received social rejection feedback on 50% of the trials. A fixation cross was shown in between trial in the middle of the screen for a jittered duration between 500-1000 ms. Participants started the SJP with 10 practice trials, followed by three experimental blocks of 50 trials each. Before and after the SJP, participants were asked to indicate on a visual analogue scale, ranging from 0 (exclusively rejection feedback) to 100 (exclusively acceptance feedback), how they expected to be evaluated (pre-estimate), and how they thought they were evaluated (post-estimate). Participants were debriefed about the cover story at the end of the experiment.

Signal recording and processing

EEG time-series were recorded online between 0.01-100 Hz at a 2048 Hz sampling rate with a Biosemi Active Two system (Biosemi, Amsterdam, the Netherlands) from 64 active scalp electrodes placed in an electrode cap (10/20 placement). Two electrodes placed at the mastoids were used for offline reference. The common mode sense and driven right leg electrodes were used as online reference, which are part of a feedback loop to replace the conventional ground electrode. Two electrodes placed above and below the left eye were used to measure VEOG. HEOG was measured from two electrodes placed at the left and right lateral canthi.

EEG time-series were offline analyzed in BrainVision Analyzer (BVA 2.0.4; Brain Products GmbH, Munich, Germany) for time-frequency and event-related potential analyses (see also van der Molen et al., 2017). Data was down-sampled to 512 Hz, band-pass filtered between 1-40 Hz (including a 50 Hz notch filter) and re-referenced to the average of the left and right mastoid electrodes. A linear derivation method was used to create a single HEOG and VEOG channel based on the existing EOG channels. Epochs were created from -4 s to +4 s surrounding the onset of the feedback stimulus and manually screened for artifacts. Epochs containing artifacts other than eye blinks (e.g., muscular activity, clipping, and movement artifacts) were removed from the data, as well as were trials that contained invalid responses (e.g., responses in the first 100 ms after cue-onset, responses outside the response window and/or multiple responses within the response window). An automatic artifact rejection method was applied that marked artifacts that met the following criteria: a maximum voltage step of 50 µV, a maximum allowed difference of 150 µV in the epoch, as well as activity below 0.5 µV. Thereafter, all epochs were visually inspected and the marked artifacts were rejected (except for noisy channels). Next, a spherical spline interpolation method was used to interpolate noisy channels when needed. This was based on visual inspection and applied to channels that demonstrated excessive drift, clipping or high frequency noise throughout the recordings. On average, 3.85 (SD =2.07) channels were interpolated per participant. The average number of interpolated channels did not differ significantly between anxiety groups (mean difference = 0.90, SD = 0.23, *p* = .18). Thereafter, eye blinks/movements were automatically removed from the data with the Ocular ICA method as implemented in BVA. Table 1 presents the average number of artifact-free epochs used for analyses per group.

--- insert Table 1 about here ---

Time-frequency analyses

A current source density (CSD) transformation was applied to the artifact-free epochs, which yields a reference-free spatially enhanced representation of the direction, location, and intensity of high spatial-frequency activity (Tenke & Kayser, 2012). To extract time-frequency characteristics from the EEG time series, the single trials were convolved with a family of complex Morlet wavelets (van der Molen et al., 2017). Convolution was performed from 1 to 40 Hz in 40 logarithmically spaced steps. The Morlet parameter $C = f(2ps_t)$was set to 5 to obtain an adequate trade-off between time and frequency precision. After the convolution procedure, time-frequency power was extracted from the complex signal: $p(t) = \left(real\left[z(t)\right]^2 + imag\left[z(t)\right]^2\right)$. Power was normalized using a percent-change from the 2100-2400 ms post-feedback window (corresponding to the inter-trial-interval). By collapsing epochs over conditions and groups (Kappenman & Luck, 2016), we observed that theta power was highest at midfrontal electrodes and reached its peak at Fz. For further analyses, theta power was extracted from Fz during a 300-500 ms post-feedback time-window, which is consistent with our prior study (van der Molen et al., 2017)[3].

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[3] This time-window to extract theta power overlaps with both the FRN and P3 components, and likely the total theta oscillatory power (as examined here) reflects the time-frequency reactivity belonging to both these ERP components. Our previous study has indeed found that the time-locked FRN component reflects theta phase reactivity, whereas others have found that the feedback-related P3 is strongly related to delta oscillatory reactivity (Bernat, Nelson, & Baskin-Sommers, 2015). Notably, the fact that theta power has a later (and wider) temporal window than the FRN is likely related to temporal smearing effects due to the wavelet convolution procedure (Cohen, 2014a).

Source-localization analyses

Source-localization of theta power was performed as previously described (van der Molen et al., 2017) using Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011), a Matlab software package documented online and freely available (http://neuroimage.usc.edu/brainstorm). Due to absence of individual MRI anatomies, the ICBM152 default anatomy was used as a tessellated cortical mesh template surface. The Biosemi 64-channel layout (10/10) was co-registered with the MRI anatomy. OpenMEEG softward (Gramfort, Papadopoulo, Olivi, & Clerc, 2010) was used to create a forward model of volume currents, by calculating a symmetric boundary element model (adaptive integration method with default settings was used). The 2100-2400 ms post-feedback interval was used for calculating a noise covariance matrix to estimate the level of noise at the electrodes. Next, using the depth-weighted minimum norm estimate algorithm (Lin et al., 2006) cortically unconstrained source-localization was performed on the single trials. A set of 3x5005 elementary dipoles were distributed over the cortical envelope. Unconstraining the dipole orientations produces a vector source at each grid point in source space. This method avoids noisy and discontinuous features in current source density maps (Uutela, Hamalainen, & Somersalo, 1999), and is particularly useful in the absence of participants' brain anatomy. Since estimating the source current strength is a linear operation, estimating the source of theta power was performed by running time-frequency decomposition directly on the source space (Ambrosini & Vallesi, 2016), using complex Morlet wavelets as outlined before. After averaging over trials, theta source results were normalized via a Z-score transformation relative to the 2100-2400 post-feedback baseline. Z-scores during the 300-500 post-feedback interval were rectified to detect absolute power changes above baseline.

Event-related brain potentials

Feedback-related ERPs (FRN and P3) were extracted from the data by creating 1200 ms epochs, including a 200 ms pre-feedback baseline interval. The FRN was calculated based on peak-to-peak method (Dekkers et al., 2015; Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003; van der Molen et al., 2014). Mean amplitude during the 250-300 ms post-feedback window was extracted, which corresponded with the positive peak prior to the FRN (i.e., the P2 component). Per condition and per subject, these values were subtracted from the FRN, which was calculated based on the mean amplitude in the 300-350 ms post-feedback window that corresponded with peaking of the FRN. The P3 was calculated by extracting the mean amplitude within the 360-460 ms post-feedback window (cf., Luck, 2005). The time-windows used for extracting the mean amplitude of the ERPs were determined by inspection of the grand-averaged ERP, collapsed over conditions and groups (Kappenman & Luck, 2016). This is a recommended procedure to avoid biasing results in favor of obtaining statistically significant results. In accord with prior studies using this paradigm (Dekkers et al., 2015; van der Molen et al., 2017), ERP amplitudes were largest at Fz, and data from this electrode were used for analyses[4].

Statistical procedures

Non-parametric independent-samples Mann-Whitney U tests were used to perform group comparisons on the behavioral (SJP) and self-report personality questionnaires, since these variables violated the normality assumption. A mixed-design repeated measures analysis was used to test group differences in theta power in response to social-evaluative feedback. Feedback Valence (2 levels: Positive, Negative) and Feedback Congruency (2 levels: Expected, Unexpected) were used as within-subjects factor, and Group (SA vs. NSA) was used as between-subjects factor. Theta power was log-transformed, Greenhouse-Geisser

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[4] Prior studies have demonstrated that the P3 effects in this paradigm are most pronounced at the anterior midline (van der Veen et al., 2016; van der Veen et al., 2014). To verify this, we have examined P3 activity from the posterior midline (Pz). These data are included as supplementary material.

correction was applied when appropriate, but uncorrected degrees of freedom were reported for transparency. A Bonferroni correction was applied for post-hoc statistical comparisons. Notably, all theta and ERP variables met assumptions of normality and no outliers were detected.

Statistical analysis of the theta source localization data was performed on the Z-score normalized theta source data. Per subject, per group, theta source data of the unexpected rejection feedback condition was averaged over time (300-500 ms post-feedback) and frequency (4-8 Hz), hereby only considering the spatial dimension. To assess significant group differences in the recruitment of theta power sources between groups, we used nonparametric cluster-based permutation testing (Maris & Oostenveld, 2007), via Fieldtrip's ft_sourcestatistics procedure (Oostenveld, Fries, Maris, & Schoffelen, 2011) as implemented in Brainstorm. First, a cluster-based test-statistic is calculated based on the alpha = 0.05 threshold. Selected samples with a *t*-value larger than 0.05 were clustered based on spatial adjacency. Next, the cluster-level statistic is calculated based on the sum of the *t*-values in each cluster, and the maximum of the cluster-level statistics is used for testing significant group differences. Significance testing was performed via the Monte Carlo method for statistical testing with independent samples *t*-tests. The permutation distribution of cluster-level statistics was approximated by drawing 1000 random permutations of the source data. The cluster method for multiple comparisons was used, and alpha was set at 0.05.

Results

Participant characteristics

Table 2 presents the participant characteristics and results on the self-report questionnaires from the socially and non-socially anxious groups. As expected, groups differed significantly based on their LSAS scores from both measurement occasions. Also, groups differed significantly on personality constructs known to be related to social anxiety (all *p'*s < .0001).

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Behavioral results

Prior to the SJP, participants were asked to estimate the proportion of social acceptance feedback they believed to receive. Socially anxious participants estimated that they would receive social acceptance feedback on 55.3% of the trials, whereas non-socially anxious participants were more optimistic about the social-evaluative outcome and estimated to receive social acceptance feedback on 62.6% of the trials. This was a significant group difference, *U* = 117.5, *Z* = -1.97, *p* = .048. During the task, socially anxious participants did not differ significantly from non-socially anxious participants in their social feedback predictions (mean difference = .04%, *p* = .267), and provided similar response latencies of their feedback predictions (*p*s > .05). After the task, when asked to recall the proportion of social acceptance feedback they had received, socially anxious participants indicated to have received social acceptance feedback on 38.4% of the trials, whereas non-socially anxious estimated this proportion on 45.9% of the trials. Thus, socially anxious participants recalled more rejection feedback than non-socially anxious participants after the SJP, but this group difference was not significant, *U* = 133.5, *Z* = -1.52, *p* = .131. Compared to the actual proportion of social acceptance feedback received (i.e., 50%), both groups demonstrated a significant negativity bias by overestimating the proportion of social rejection feedback received (non-socially anxious group: Z = -2.07, *p* = .039; socially anxious group: *Z* = -3.09, *p* = .002). These data are shown in Table 3.

--- insert Table 3 about here ---

Time-frequency theta power

The mixed design ANOVA yielded a main effect of Feedback Valence, $F(1,37) = 4.54$, $p = .040$, $n_p^2 = .11$, which was included in the significant three-way interaction between Feedback Valence x Feedback Congruency x Group, $F(1,37) = 5.60$, $p = .023$, $n_p^2 = .13$. Follow-up repeated measures ANOVAs revealed a significant interaction effect between Feedback Valence and Feedback Congruency in the non-socially anxious group, $F(1,21) = 8.62$, $p = .001$, $n_p^2 = .29$, which indicated that theta power for unexpected social rejection feedback was significantly larger than in the other conditions (all *p*s < .015). No significant within-subject effects were observed in the socially anxious group (all *p*s > 0.2), nor did we observe a significant between-subject effect, $F(1,37) = 2.81$, $p < .11$, $n_p^2 =.07$. These time-frequency results are shown in Figure 2. Exploratively, we examined the correlation between theta power (unexpected rejection) and the self-report measures (FNE, FPE, BDI, RSES) per group, but no significant associations were found *p*'s > .05). These data are presented as supplementary material S1.

--- insert Figure 2 about here ---

Next, we examined the neural sources that generated the theta power increase during the unexpected social rejection condition. Figure 3 depicts the estimated sources for theta power during the unexpected social rejection condition for both groups. Both in the non-socially anxious and socially anxious groups, probable sources were located in the anterior cingulate cortex (BA 24 and 32) and subgenual cingulate cortex (BA 25). In the non-socially anxious group, additional activity was found in the posterior cingulate cortex (BA 38) and temporal pole (BA 23). Statistical comparison of the z-score normalized theta source activity between groups (for the unexpected rejection condition only) yielded two significant clusters based on cluster-based permutation testing. These clusters (cluster 1: size = 174, $p = 0.04$; cluster 2: size = 196, $p = 0.04$) yielded higher theta source activity in the non-socially anxious group relative to the socially anxious group. These data represent significant group difference averaged over the 300-500 post-feedback window encompassing the primary visual cortex (BA 17 and 18), the posterior cingulate cortex (BA 23) and perirhinal cortex (BA 36).

--- insert Figure 3 about here ---

Feedback-related negativity

Event-related potentials elicited at Fz by social-evaluative feedback are shown in Figure 4. The mixed-design ANOVA yielded a significant main effect of Feedback Congruency, $F(1,37) = 6.85$, $p = .013$, $n_p^2 = .16$. As expected, FRN amplitudes were significantly larger for feedback that was unexpected than expected (mean difference = -1.22 uV). No other main or interaction effects were significant. Also, FRN amplitudes were not significantly different between groups (*p*s >.05).

P300

The mixed-design ANOVA yielded a significant two-way interaction between Feedback Valence and Feedback Congruency, $F(1,37) = 7.54$, $p = .009$, $n_p^2 = .17$. Post-hoc examination of this interaction indicated that P300 amplitude to expected acceptance feedback was significantly larger than for the other feedback types (all *p*s <.05). These P300 data are shown in Figure 4. Exploratively, we examined whether these results were similar for the posterior P3 (as measured at Pz). This analysis revealed a similar significant two-way interaction between Feedback Valence and Feedback Congruency ($p < .05$), but follow-up *t*-tests indicated that P3 amplitude in response to expected acceptance feedback was only larger relative to expected rejection feedback (see supplementary material S2).

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Discussion

The goal of the current study was to offer a detailed examination of the behavioral, as well as electrocortical responses to social-evaluative feedback processing in socially vs. non-socially anxious females. Behaviorally, we observed that before the task, non-socially anxious females were more optimistic about social evaluation by peers than socially anxious females, as indicated by significant a higher proportion of positive feedback expectancies in non-socially anxious females. In contrast to our hypotheses, we did not find differences between groups regarding feedback predictions during the SJP, nor did we find evidence of a significant feedback recall bias suggesting a larger proportion of remembered social rejection feedback in socially anxious females. At the neural level, we found that unexpected social rejection feedback elicited a significant increase in frontal theta power, but this effect was only found in non-socially anxious females. Together, this study offered novel insights into behavioral and neural mechanisms implicated in the processing of social-evaluative threat stimuli subclinical social anxiety.

Positive expectancies about a social-evaluative situation in non-socially anxious participants is in accord with earlier findings suggesting that people have a general positive view on how they will be evaluated by others (Dekkers et al., 2015; van der Molen et al., 2014; van der Veen et al., 2016). Although socially anxious participants expected social acceptance more often than rejection, these estimates were less optimistic than those observed for the non-socially anxious participants. This significant difference in pre-task feedback expectations seems to index a decrement of the positivity bias in socially anxious participants, since their predictions were around the neutral point (i.e., 50%). Furthermore, when asked to recall the proportion of social acceptance vs. rejection feedback received after the SJP, socially anxious participants recalled more rejection than acceptance feedback (38%), but this proportion did not differ significantly from non-socially anxious participants (46%). However, this trend seems in accord with a negative memory bias for self-relevant social evaluation (Caouette et al., 2015). During the SJP, no significant behavioral differences were found between the socially anxious and non-socially anxious groups. This is in contrast with our prior study using this paradigm, where we found that those females with higher fear of negative evaluation took longer in providing their trial-by-trial predictions about the social-evaluative outcome (van der Molen et al., 2014). This was interpreted to reflect increased uncertainty in those individuals with high fear of negative evaluation about the social-evaluative outcome. Future studies should verify this notion, since the current study failed to find evidence for such behavioral uncertainty in socially anxious females.

Brain responses to social evaluation revealed that unexpected social rejection feedback elicited a significant increase in frontal theta power in non-socially anxious females. This result corroborates prior findings using this paradigm in healthy female participants (van der Molen et al., 2017), and underscores that the brain responds to such social threat via a robust change in theta oscillatory dynamics. Using source-localization we were able to demonstrate that the dorsal ACC was the main probable source of this theta response to unexpected social rejection feedback. It has been suggested that the dorsal ACC plays central role in estimating whether it is worth to invest cognitive control in a task. Based on this *Expected Value of Control* account of dorsal ACC function (Shenhav, Botvinick, & Cohen, 2013), unexpected social rejection feedback would be the most threatening feedback stimulus to an individual, and therefore requiring a greater degree of cognitive control to safeguard the individual's well-being. This idea is to a large extent similar to the social-evaluative threat principle in social anxiety (Wong & Rapee, 2016), which suggests that a threat value is assigned to social-evaluative stimuli, and this value would be higher for stimuli that pose a significant threat to the individual. Social-evaluative feedback stimuli, such as unexpected social rejection, are most likely to convey a high threat value and might negatively impact an individual's functioning.

Interestingly, our current theta results suggest that the social threat-monitoring system – as indexed by feedback-related theta reactivity – is *less* responsive to such potentially threatening social feedback stimuli in socially anxious females. This 'blunted' theta reactivity to unexpected rejection feedback might be related to the well-established bias in socially anxious females to expect rejection feedback more often than rejection feedback (D. M. Clark & McManus, 2002; Wong & Rapee, 2016), rendering rejection feedback less surprising. This is in accord with theoretical accounts on prediction error (Alexander & Brown, 2011), that argue that neural response to unexpected feedback would be larger than to expected feedback. We did observe that socially anxious females predicted a significantly larger proportion of rejection feedback pre-task relative to non-socially anxious feedback, which might have resulted in the attenuated neural prediction error response to rejection feedback. However, in keeping with theories on prediction error and cognitive conflict (Cohen, 2014b; den Ouden, Kok, & de Lange, 2012), neural reactivity (e.g., theta or FRN amplitude) would be enhanced in response to unexpected *acceptance* feedback, since this outcome is highly unexpected in socially anxious females, and perhaps more salient due to their prediction bias. However, we did not observe this response in socially anxious females.

Alternatively, this blunted theta reactivity in response to unexpected rejection feedback in socially anxious females could be explained by increased self-focused attention, rendering less attentional resources toward external threat. Although this is a speculative notion since our study did not include any measures to verify self-focused attentional state in our participants, this notion is in keeping with cognitive-behavioral theory on social anxiety (D.M. Clark & Wells, 1995). When confronted with a social stressor, increased self-focused attention would direct attentional resources to internal (e.g., bodily) stimuli (Bögels & Mansell, 2004), reflecting an increased in somatic perception during a social stressful event (Durlik et al., 2014; Terasawa et al., 2013). In turn, this might limit the ability of the saliency system – as indexed by theta oscillatory dynamics – to process unexpected social rejection feedback (an external stressor) as social-evaluative threat. Furthermore, this notion meshes with the theta source activity differences observed between groups. That is, source-localization results revealed that the posterior cingulate cortex (PCC) displayed higher theta reactivity in non-socially vs. socially anxious individuals. It has been argued that a key function of the PCC is to control the balance between internal and external focus of attention (Leech & Sharp, 2014). In this regard, increased PCC reactivity in response to unexpected rejection feedback in non-socially anxious females might track the recruitment of attentional resources to this external social-evaluative threat. Obviously, this interpretation is speculative since we did not include an objective measure to index self-focused attention (or introspective awareness). Therefore, a critical task for future studies is to examine the psychophysiological mechanisms underlying theta power responsivity in both subclinical as well as clinical social anxiety.

The ERPs elicited by social-evaluative feedback were not modulated by social anxiety status. Like previous studies using the SJP, the FRN was sensitive to feedback congruency showing largest amplitudes to feedback that was unexpected (Dekkers et al., 2015; van der Molen et al., 2014). This result is at odds with studies that reported that the FRN was sensitive to valence of social-evaluative feedback (Cao et al., 2015; Kujawa et al., 2014). For example, Kujawa et al. (2014) found that the FRN was larger to social rejection relative to acceptance feedback, and this FRN response to rejection was larger in teenagers with higher levels of social anxiety. However, using a similar paradigm, Cao et al. (2015) found that participants with social anxiety disorder displayed largest FRN reactivity to social acceptance feedback. Findings from these two studies are difficult to reconcile with the current results, since these studies did not take into account participants predictions about the social-evaluative outcome on a trial-by-trial basis. Thus, in future studies it would be valuable to take into account participant’s trial-by-trial expectancies regarding an imminent social-evaluative outcome in paradigms such as the Island Getaway task.

With respect to P3 activity, we found that this feedback component was largest in amplitude in response to expected social acceptance feedback, and reached statistical significance at the anterior midline. This is in accord with two prior ERP studies using the SJP, and has been interpreted as a neural signature of reward processing (van der Veen et al., 2016; van der Veen et al., 2014). This P3 result might seem at odds with studies demonstrating that stimulus probability is an important factor governing P3 generation (i.e., larger P3 in response to infrequent stimuli) (Polich, 2007). However, in the majority of these studies, the probability is not equally matched between stimuli that differ in valence (i.e., error trials are less frequent than correct trials, or rewards are less probable than losses). This impact of feedback probability on the P3 was elegantly demonstrated by Ferdinand et al. (2012). Using a time-estimation paradigm, these authors equally balanced the probability of positive vs. negative feedback. Results showed a significant increase in P3 amplitude in response to infrequent positive feedback relative to infrequent negative feedback. This clearly suggest that processes other than stimulus probability contribute to P3 generation, such as task motivation and/or rewarding attributes of the feedback stimulus. In the current study, the probability of receiving acceptance vs. rejection feedback was also equally balanced. The observation of a larger P3 in response to *expected* social acceptance feedback might be related to a rewarding outcome resulting from an approach-motivated decision-making process (San Martin, 2012; Threadgill & Gable, 2017). That is, the participant first decides whether the peer might have liked or disliked the participant. During this decision-making process, the participant might base her decision on whether or not she cares to be liked by the peer (reflecting an approach vs. avoidance decision). When the participant's expected acceptance is than indeed matched with acceptance of the peer, such an outcome would be rated as more rewarding (and/or relevant in terms of potential social interaction) than when receiving *unexpected* social acceptance feedback (as in this case, the participant had less approach-related tendencies towards this peer). Of course, this interpretation is speculative, since our current study was not designed to explicitly test whether these approach approach-motivated states might have indeed influenced the P3 in response to social feedback. However, it has been widely documented that multiple evaluative processes – other than stimulus probability – contribute to P3 generation, such as stimulus valence, reward magnitude, and task relevance of an outcome (San Martin, 2012). The notion that the feedback-related P3 is sensitive to subjective probability estimates of an outcome, dependent on motivational states, meshes with theoretical accounts on the P3 (Johnson, 1986; Nieuwenhuis, Aston-Jones, & Cohen, 2005; San Martin, 2012), but future studies are encouraged to tease apart these influences and examine their role in P3 generation in a social evaluative context.

A limitation of the current study is that the results are characteristic of subclinical social anxiety, and it remains uncertain whether individuals with social anxiety disorder will display similar blunted reactivity to unexpected social rejection feedback. Such information would further our understanding of the functional significance of theta oscillatory dynamics in processing social threat, as well as its significance as a diagnostic marker. For example, it might be possible that individuals with social anxiety disorder might reveal increased theta power reactivity to social-evaluative feedback. Indeed, a recent study found elevated theta reactivity in social anxiety disorder, albeit in a small clinical sample (Harrewijn, van der Molen, van Vliet, Tissier, & Westenberg, 2018). This would render the current observation of an absence of theta power reactivity to unexpected rejection feedback as a potential mechanism of protective inhibition of negative affect (Tops, Schlinkert, Tjew-A-Sin, Samur, & Koole, 2015). Another limitation is that the current sample consisted of females only. It has been shown that females are more sensitive to social evaluation (Stroud, Salovey, & Epel, 2002), and future work should establish whether males with and without subclinical social anxiety display similar results as those observed in the present study. Finally, our current source-localization results of theta power should be interpreted with some caution since these analyses were not based on the participants' structural MRI images, but based on the template brain anatomy and thus might have introduced localization errors due to variation in head shapes between subjects. Although our current findings correspond nicely with a recent and similar study (van der Molen et al., 2017), future studies are encouraged to use the individual brain anatomies for source-localization when possible.

In conclusion, this study has examined both behavioral and neural responses to social-evaluative feedback processing in females with and without subclinical social anxiety. In accordance with prior cognitive studies, socially anxious females were less optimistic about the social-evaluative outcome than non-socially anxious females. Additionally, socially anxious females displayed a significant attenuation in midfrontal theta reactivity to unexpected social rejection feedback. These findings indicate that ecologically valid paradigms such as the SJP tap into important psychophysiological processes that are characteristic of the etiology of social anxiety. Specifically, we have shown that theta oscillations play a central role in typical and atypical response to social feedback processing, and provide a potential neural mechanism for targeting interventions of social anxiety. An important task for future studies is to examine these behavioral and neural responses to social-evaluative feedback in patients with social anxiety disorder.

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Conflict of interest

The authors report no conflict of interest

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TABLES

Table 1. Number of artifact-free EEG epochs used for analysis.

	NSA (*n* = 22)	SA (*n* = 17)
Expected acceptance	34.39 (5.94)	32.70 (7.79)
Expected rejection	28.65 (6.65)	31.39 (8.55)
Unexpected acceptance	28.17 (5.85)	29.83 (8.79)
Unexpected rejection	34.30 (7.42)	29.39 (8.84)

Note: trials per condition did not differ between groups.

Abbreviations: NSA = Non-Socially Anxious; SA = Socially Anxious

Table 2. Group characteristics

	NSA (*n* = 22)	SA (*n* = 17)	*p*-value
Age	19.89 (1.53)	19.57 (1.55)	$p = .52$
Social anxiety (screening)	17.14 (7.77)	74.35 (12.51)	$p < .001$
Social anxiety (testing)	18.32 (7.02)	80.41 (12.77)	$p < .001$
Fear of Negative Evaluation	14.36 (7.85)	33.76 (7.78)	$p < .001$
Fear of Positive Evaluation	16.68 (11.16)	36.53 (10.84)	$p < .001$
Self-esteem	22.86 (3.01)	15.29 (4.90)	$p < .001$
Depression	5.23 (3.58)	13.94 (6.54)	$p < .001$

Abbreviations: NSA = Non-Socially Anxious; SA = Socially Anxious

Table 3. Behavioral indices of the Social Judgment Paradigm

	NSA (*n* = 22)	SA (*n* = 17)	*p*-value
Pre-task predicted social acceptance (% trials)	62.64 (11.09)	55.29 (10.66)	*p* = .04
Post-task predicted social acceptance (% trials)	45.86 (9.63)	38.41 (13.32)	*p* = .13
On-task predicted social acceptance (no. trials)	80.82 (10.76)	75.35 (17.04)	*p* = .23
On-task predicted social rejection (no. trials)	67.41 (11.62)	73.59 (16.41)	*p* = .18
RT social acceptance predictions (ms)	1517.68 (267.90)	1500.17 (216.32)	*p* = .83
RT social rejection predictions (ms)	1563.04 (309.55)	1528.36 (220.43)	*p* = .70

Abbreviations: NSA = Non-Socially Anxious; SA = Socially Anxious

FIGURES

Figure 1. A schematic of a single trial of the Social Judgment Paradigm.

Figure 2. Feedback-related time-frequency power results from Fz for non-socially anxious (panel A) and socially anxious (panel B) participants. Theta power was higher for unexpected social rejection feedback, but this effect was only significant for non-socially anxious females. Panel C shows the scalp topography of theta power (Hz) for both groups during the social feedback conditions. Panel D depicts log-transformed theta power averages for the four social feedback conditions per group.

Figure 3. Source localization analyses showing theta source activity for socially and non-socially anxious females when receiving unexpected rejection feedback (Panel A). The ACC is a prominent source of feedback related theta power in both groups. Panel B shows statistical differences in theta source activity during processing of unexpected rejection feedback. Theta source activity indicates significantly higher theta activity in the non-socially anxious (NSA) relative to the socially anxious (SA) group.

Figure 4. Event-related brain potentials elicited at Fz by social evaluative peer feedback for non-socially anxious (panel A) and socially anxious (panel B) females. Shaded areas indicate that time-windows to extract the ERP components. Panel C depicts the mean amplitude of the feedback-related negativity. Panel D depicts the mean amplitude of the P300. In both groups, social feedback that was incongruent with participants' predictions elicited largest FRN amplitude. P300 amplitude was significantly largest for expected acceptance feedback in both groups.

SUPPLEMENTARY MATERIAL

SUPPLEMENT 1: Correlation matrices between EEG metrics and self-report questionnaires

Exploratively, Pearson product-moment correlation analyses were performed to test the association between the EEG metrics of unexpected rejection (Theta, FRN) and expected acceptance (P3) with the self-report questionnaires (FNE, FPE, BDI, RSES). No significant associations were observed (Bonferroni corrected for multiple comparisons), all *p*'s > .05 (two-tailed). Separately for both groups, correlation matrices are shown for theta power and the self-report questionnaire results.

Table S1.1. Correlation matrix depicting the association between theta power (unexpected rejection feedback) with the self-report questionnaire data for non-socially anxious females.

Measure	1	2	3	4	5
1. Theta power	-				
2. FNE	-.08	-			
3. FPE	-.06	-.06	-		
4. Depression	-.02	-.11	.49*	-	
5. Self-esteem	-38	-.40	-.17	-.09	-

Note: * significant at $p < 0.05$ (two-tailed).

Table S1.2. Correlation matrix depicting the association between theta power (unexpected rejection feedback) with the self-report questionnaire data for socially anxious females.

Measure	1	2	3	4	5
1. Theta power	-				
2. FNE	.30	---			
3. FPE	.47	.3500	-		
4. Depression	.33	.3800	.57*	-	
5. Self-esteem	-.28	-.63**	-.17-	-.55*	-

Note: * significant at *p* < 0.05 (two-tailed); ** significant at *p* < 0.01 (two-tailed)

SUPPLEMENT 2: Posterior P3 results

A mixed-design repeated measures ANOVA was performed on the posterior midline P3 obtained from channel Pz. A significant two-way interaction between Valence and Congruency was observed, $F(1,37) = 9.02$, $p < .005$, $n_p^2 =.20$. Follow-up *t*-tests indicated that expected acceptance feedback yielded largest P3 amplitudes, but this only reached statistical significance compared to expected rejected feedback (see Figure S1). The group contrast results are plotted in supplementary Table S3.

--- insert Figure S1 here ---

Figure S1. Posterior P3 amplitude measured at Pz. Acceptance feedback yielded larger P3 amplitude than rejection feedback, but this effect was only significant for the expected acceptance (Yes-Yes) vs. expected rejection (No-No) contrast. Abbreviations: Yes-Yes = expected acceptance; Yes-No = unexpected rejection; No-No = expected rejection; No-Yes = unexpected acceptance.

	NSA (*n* = 22)	SA (*n* = 17)	*p*-value
Expected acceptance (Yes-Yes)	8.56 (4.76)	8.08 (3.84)	*p* = .74
Expected rejection (No-No)	7.81 (4.67)	6.28 (.32)	*p* = .15
Unexpected acceptance (No-Yes)	7.81 (4.33)	6.94 (4.09)	*p* = .30
Unexpected rejection (Yes-No)	8.82 (4.76)	6.71 (3.84)	*p* = .53

Table S2. Group contrasts for the posterior P3 (Pz)

Note: mean P3 amplitudes per condition is plotted in microvolt and standard deviation between brackets. NSA = non-socially anxious; SA = socially anxious.