Behavioral, neural, and psychiatric correlates of social feedback

Brent I. Rappaport1, Autumn Kujawa2, Kodi B. Arfer3, Samantha Pegg2, Danielle Kelly4, Joan L. Luby4, & Deanna M. Barch1,4,5

1 Psychological & Brain Science, Washington University in St. Louis

2 Department of Psychology & Human Development, Vanderbilt University

3 Center for HIV Identification, Prevention, and Treatment Services, University of California

4 Department of Psychiatry, School of Medicine, Washington University in St. Louis

5 Department of Radiology, School of Medicine, Washington University in St. Louis

Author note

1 Psychological & Brain Science, Washington University in St. Louis, St. Louis, MO  
2 Department of Psychology & Human Development, Vanderbilt University, Nashville, TN  
3 Center for HIV Identification, Prevention, and Treatment Services, University of California, Los Angeles, Los Angeles, CA  
4 Department of Psychiatry, School of Medicine, Washington University in St. Louis, St. Louis, MO  
5 Department of Radiology, School of Medicine, Washington University in St. Louis, St. Louis, MO

The authors made the following contributions. Brent I. Rappaport: Conceptualization, Formal Analysis, Writing - Original Draft Preparation, Writing - Review & Editing; Autumn Kujawa: Methodology, Conceptualization, Writing - Review & Editing; Kodi B. Arfer: Software, Writing - Review & Editing; Samantha Pegg: Formal Analysis, Writing - Review & Editing; Danielle Kelly: Writing - Review & Editing, Supervision, Resources, Funding acquisition; Joan L. Luby: Resources, Funding acquisition, Writing - Review & Editing; Deanna M. Barch: Conceptualization, Supervision, Resources, Funding acquisition, Writing - Review & Editing.

Correspondence concerning this article should be addressed to Brent I. Rappaport, One Brookings Drive St. Louis, MO 63130. E-mail: [brappaport@wustl.edu](mailto:brappaport@wustl.edu)

Abstract

Problems responding to peer feedback and disrupted interpersonal relationships arise in numerous psychiatric disorders; yet heterogeneity and homogeneity across disorders suggests both common and unique mechanisms of impaired social function. Identifying brain correlates of these disruptions could help explain diagnostic comorbidies as well as unique pathways, thus informing more individualized treatments. However, studies seeking to understand the link between psychological and neural mechanisms often have to rely on reverse inference assumptions to match psychological processes to brain activity. One hypothesis is that social feedback is processed similar to other forms of feedback. Thus, we aimed to test such assumptions by examining the correspondence between the brain’s response and behavioral performance on a reward and loss task, as well as to examine the relationship between the brain’s response to peer acceptance and rejection and depression and social anxiety severity. The sample consisted of 114 16–19-year-olds who received virtual peer acceptance or rejection feedback in an event-related potential (ERP) task. We used principal component analysis to identify the reward positivity (RewP) and feedback negativity (FN) ERP components and measured the mean amplitude. Hypotheses were tested using multiple regression models, including covariates. Structural equation modeling was used to test the overall fit of all proposed hypotheses to the data. We found that the FN was positively related to behavioral loss avoidance. We found a relationship between the RewP and depression severity that, while non-significant, was of a similar magnitude to prior studies. Exploratory analyses showed a positive relationship between the RewP and socioeconomic status (SES). These findings suggest greater support for inferences about negative social feedback being processed similar to loss (e.g., FN to rejection relates to behavioral loss avoidance) than to ideas about positive social feedback and reward processing . The novel exploratory finding, if replicated, provides a potential mechanism linking SES and risk for psychopathology.

*Keywords:* social feedback, ERP, depression, social anxiety, reward, reward positivity, feedback negativity

*Word count:* X

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# Introduction

Problems forming and maintaining interpersonal relationships are associated with physical health problems and increased mortality risk (House et al., 1988). Such problems arise in numerous psychiatric disorders (Association, 2013; Kennedy & Adolphs, 2012). Responding properly to social feedback is a key element of effective social function. Here, social feedback is used to refer to the receipt of socially relevant information (e.g., being accepted or rejected by a conspecific). Individuals must use such feedback to learn and alter their behavior, and respond in a prosocial manner that elicits the desired response in another person. Clinically, patients with different disorders often present with complaints of dysfunction in their interpersonal relationships, which often results in reduced contact with others. However, we know relatively little about the psychological and neural processes involved in responding to social feedback, nor about shared and unique disruptions across disorders. Thus, the goal of the current study was to test the hypothesis that social feedback is processed similarly to other forms of reward and loss feedback, and to assess shared and dissociable relationships to anxiety and depression.

Recent studies of social feedback (i.e. acceptance and rejection) have suggested that the brain responds to acceptance much like monetary rewards (Distefano et al., 2018; Wake & Izuma, 2017). However, other studies have shown weak relationships between brain responses to social and monetary rewards (Ethridge et al., 2017), differential responses depending on participants’ age (Rademacher et al., 2014), or differential relationships as a function of prior peer victimization (Rappaport et al., 2019). Although some researchers have suggested that the brain responds to rejection much like physical pain (Naomi I. Eisenberger, 2012; Naomi I. Eisenberger et al., 2003; Naomi I. Eisenberger & Lieberman, 2004; Lieberman & Eisenberger, 2015), this proposition has recently been called into question by two independent meta-analyses (S. Cacioppo et al., 2013; Vijayakumar et al., 2017), among others (Somerville et al., 2006; Woo et al., 2014). Instead, an alternative hypothesis is that rejection is akin to loss. As defined in the Research Domain Criteria matrix, loss refers to: *“a state of deprivation of a motivationally significant con-specific, object, or situation. Loss may be social or non-social and may include permanent or sustained loss of…loved ones, or relationships”* (*NIMH Definitions of the RDoC Domains and Constructs*, n.d.). In fact, S. Cacioppo et al. (2013) found greater BOLD signal in the insula to social exclusion and Vijayakumar et al. (2017) found greater BOLD signal in the ventral striatum–both of which are regions implicated in processing negative affect (Hamilton et al., 2011; Palaniyappan, 2012) and loss (Canessa et al., 2013; Dugré et al., 2018; Liu et al., 2011; Oldham et al., 2018; Tom et al., 2007). Thus, a hypothesis that may be compatible with both the pain theories of rejection and recent meta-analyses is that social rejection is processed similarly to other forms of loss.

## The reverse inference problem

To test such hypotheses about the psychological processes implicated in the response of social feedback, studies thus far have typically relied on *affirmation of the consequent* (J. T. Cacioppo et al., 2003) or *reverse inference*: *“the inference of a psychological process from an observed pattern of brain activity”* (Amodio, 2010). For example, despite suggestions that similar brain regions are activated to social acceptance and monetary reward, drawing the conclusion that the reward system is implicated in responding to social acceptance from such findings is problematic since similar patterns of brain activation could reflect different psychological processes. As such, studies are needed that test whether the brain’s response to such feedback is associated with behavioral measures (Poldrack, 2006)–in this case indexing response to reward or loss–providing converging evidence of dysfunction in the hypothesized psychological process. If so, it suggests a function of that brain activity in reward/loss responsivity; if not it calls into question prior conclusions made using reverse inference. Thus, the current proposal aims to test whether the brain’s reward/loss system responds to social acceptance and rejection feedback.

## Using event-related potentials (ERP) to study social feedback

Neural systems that process reward and loss involve a host of brain regions that work in a coordinated fashion, just as any other social function (Amodio, 2010), to process and respond to social feedback. FMRI studies have begun to identify regions active in response to social exclusion (S. Cacioppo et al., 2013; Vijayakumar et al., 2017). In complementary research, event-related potentials (ERPs)—-EEG signals time-locked to a stimulus onset—-provide a robust way to understand the timing of neural responses associated with social feedback by examining specific ERP components thought to reflect brain activity to acceptance (reward positivity [RewP]) and rejection (feedback negativity [FN]) (Luck & Kappenman, 2012; Proudfit, 2015; Regan, 1989). Given the complexity of brain responses to social feedback, the temporal resolution of ERP may be well suited to identifying individual differences in brain responses as compared to methods with worse temporal but better spatial resolution (Amodio et al., 2014). Moreover, ERPs directly measure brain activity (Gratton & Fabiani, 2001), rather than its indirect consequence with a hemodynamic response in fMRI. Furthermore, ERP allows participants to sit upright rather than still and supine in a scanner, lending it greater ecological validity (Amodio et al., 2014). These factors together suggest that ERP is an excellent method for measuring individual differences in brain responsivity to social feedback.

## Social Feedback Processing in Depression and Anxiety

As noted above, different types of psychpathology involve disruptions in interpersonal relationships and reduced social engagement. However, these same endpoints may be due to different underlying mechanisms across individuals. For instance, individuals may withdraw because they experience less pleasure from interacting with other people or negative self-esteem, out of fear of rejection (or negative evaluation more generally), or for both reasons (see Rubin et al. (2009) for a review). Such heterogeneity and homogeneity across disorders suggests both common and unique mechanisms of impaired interpersonal relationships. Homogeneity is exemplified by multiple disorders sharing deficits. For example, both depression and social anxiety are associated with heightened sensitivity to social rejection (Burklund et al., 2017; Cohen et al., 2016; Gao et al., 2017; Groschwitz et al., 2016; Harrewijn et al., 2017; Heeren et al., 2017; Hsu et al., 2015; Kujawa et al., 2014; Malejko et al., 2018; Silk et al., 2014). However, only depression, not social anxiety (Kujawa et al., 2017; Pegg et al., 2019), is also associated with blunted neural responses to social acceptance and inclusion (Davey et al., 2011; Kujawa et al., 2017; Zhang et al., 2017). Studying the neural processes at play in responding to social feedback can help us understand whether these similar behavioral outcomes (i.e. reduced time spent with others) is due to common or distinct psychophysiological mechanisms. Thus, although these two dimensions of psychopathology are related to deficits in responding to social feedback, they may do so via both shared and distinct mechanisms, necessitating more individualized treatments. To test such hypotheses, transdiagnostic studies are needed to distinguish common from unique neural and behavioral deficits in social feedback response across psychiatric disorders.

## Current study

The current study aims to address the key questions outlined above. Specifically, first we test reverse inference assumptions by analyzing the relationship between individual differences in RewP and FN magnitude to social acceptance and rejection feedback and separate behavioral individual differences of bias towards rewards and avoidance of losses. Testing whether individual or group differences in brain activity are also related to a converging behavioral measure constrains the interpretation of the brain activation (Poldrack, 2006). Second, we test diagnostic homogeneity and heterogeneity by analyzing the relationship between individual differences in RewP and FN magnitude to social acceptance and rejection feedback and severity of depression and social anxiety symptoms. Third, we test for the presence of a relationship between behavioral bias towards rewards and away from losses and severity of depression and social anxiety, aiding in the interpretation of the previous analyses. This would provide converging evidence of our proposed nomological network between the ERP, behavioral, and psychopathology measures.

# Methods

## Participants

Participants were drawn from the Preschool Depression Study (PDS), a prospective longitudinal investigation of young children and their families conducted at a midwestern university in the United States (Luby et al., 2009). Details of recruitment have been previously reported (Luby et al., 2014, 2009). To briefly summarize, 3- to 6-year-olds were recruited from primary care practices and preschools/daycares throughout the St. Louis metropolitan region using a validated screening checklist (Preschool Feelings Checklist; Luby et al. (2004)) to oversample preschoolers with symptoms of depression and healthy controls. Children were excluded if they presented with chronic illness, marked speech and/or language delays and/or neurologic or autism spectrum disorders. Parental written consent and child assent were obtained before participation and the local Institutional Review Board approved all procedures. These 306 children have participated in up to 10 in person clinical and behavior assessments and five neuroimaging assessments. An additional 40 currently healthy children were added at school age and have participated in up to five clinical and behavior assessments and five neuroimaging assessments. Participants completed all measures of the current study during the tenth and most recent assessment wave of the PDS. Of those, 175 participated in the most recent wave, with 118 participants completing the social feedback task. Of those, one participant was excluded due to technical errors during the social feedback task, and two participants were excluded due to intelligence quotients (IQ) below 70. Of those 115 remaining participants, 99 had completed and had usable data for the behavioral reward/loss task, 110 had completed a self-report measure of depression, and 115 had completed a self-report measure of social anxiety.

## Measures

### Depression severity.

Depression severity was measured using the Child Depression Inventory–2 (CDI-2) (Kovacs, 1992) for participants less than 18 years-old and Beck Depression Inventory–II (BDI–II) (Dozois et al., 1998) for participants 18 years-old and older. The CDI-2 includes 28 items scored on a three point Likert scale. The BDI-II includes 21 items scored on a four point Likert scale. Both measures assess self-reported depression symptoms in the past 2 weeks and have excellent internal consistency (CDI-2: =0.91; BDI-II: =0.91) and test-retest reliability (CDI-2: =0.89; BDI-II: =0.93) (Beck et al., 1996; Dozois et al., 1998; Kovacs, 1992).

### Social anxiety severity.

Social anxiety severity was measured using the Social Interaction Anxiety Scale (SIAS-6) and Social Phobia Scale (SPS-6) (Peters et al., 2012)—a scale that combines the two scales and was developed as an abbreviated version of the full SIAS/SPS (Mattick & Clarke, 1998) using Item Response Theory modeling. This scale includes 6 items rated on a five point Likert scale from each of the SIAS-6 and SPS-6, comprising one total scale. The SIAS/SPS-6 assesses self-reported current symptoms of social anxiety/phobia (with no specific time frame given) and has excellent internal consistency ( > 0.90) and test-retest reliability ( > 0.91) (Mattick & Clarke, 1998; Osman et al., 1998).

### Covariates.

Covariates in multiple regression models included age at time of task, sex, race (Caucasian, African American, or Multiracial), Hispanic ethnicity, and socioeconomic status (i.e., income-to-needs ratio). Income to needs ratio from the most recent available assessment wave was used. Supplemental analyses also included recent psychotropic medicine use as a covariate, however 9 participants were missing this data. All categorical variables (i.e., sex, race, Hispanic ethnicity, and psychotropic medicine use) were dummy coded and all continuous variables (i.e. reward bias, loss avoidance, RewP, FN, depression severity, social anxiety severity, age, socioeconomic status) were standardized to aid in interpretation of regression estimates.

## Procedure

### Social feedback ERP task.

The Island Getaway task was used to measure brain responses to social feedback. For the task, participants are told they are playing a game with 11 co-players in which they are travelling in the Hawaiian Islands, and at each island, have to vote whether they want each co-player to continue on with them to the next island, followed by feedback on how co-players voted for them. Participants review information about each co-player (e.g., gender, location, personal preferences) and enter information that they are told is similarly reviewed by each co-player. Participants complete 6 rounds of “voting,” during which they vote whether to “keep” or “kick out” each co-player, and following each vote receive feedback as to whether that co-player voted to accept (“keep”) or reject (“kick out”) them (Figure 1). After each round, participants are told that one of the co-players had been sent out, and after completing the sixth round, participants are informed that they made it to the “Big Island.” Participants receive 51 trials of feedback: 25 acceptance and 25 rejection, and one randomly selected trial—a unique strength of this particular task (over tasks of only social rejection or exclusion) that yields reliable measurements of brain activity to social acceptance and rejection feedback. Co-players are randomly assigned a voting pattern for each participant such that 2 co-players reject the participant on most rounds, 2 co-players accept the participant on most rounds, and the remaining 7 co-players are equally likely to accept or reject the participant. Following the task, participants complete a brief post-task questionnaire assessing engagement in the task. This task has been validated in early adolescent, late adolescent, and young adult samples (Ethridge et al., 2017; Ethridge & Weinberg, 2018; Kujawa et al., 2017; Pegg et al., 2019).

### Behavioral reward bias and loss avoidance task.

To measure reward bias and loss avoidance we used the Probabilistic Incentive Learning Task (PILT), specifically two modified versions (Heerey et al., 2008; Pizzagalli et al., 2005), here termed PILT-Positive and PILT-Negative, to assess reward bias and loss avoidance respectively. These tasks have been used in adult and pediatric samples (Heerey et al., 2008; Luking et al., 2016b, 2015; Luking, Neiman, et al., 2015; Pizzagalli et al., 2005, 2008). In each trial, participants perform a perceptual discrimination and indicate whether a long or short stimulus was briefly presented (Figure 1). For the PILT-P, a portion of correct responses receive gain feedback while, for the PILT-N, a portion of incorrect responses receive loss feedback. For both tasks, one of the two responses (i.e. short or long, termed the RICH response) is scheduled to receive three times the amount of feedback as the alternative (LEAN) response. This leads to preferentially selecting the RICH response in the PILT-P (reward bias) and avoiding the RICH response in the PILT-N (loss avoidance) (Luking, Pagliaccio, et al., 2015; Luking, Neiman, et al., 2015; Pizzagalli et al., 2005, 2008).

Participants complete 20 practice trials, followed by two blocks of 60 trials each. Feedback was presented in a pseudo-random order, so that no more than three trials in a row could receive feedback. As in prior studies, individual trials with reactions times (RT) faster than 150ms or slower than 2500ms, or greater than or less than 3 standard deviations from the participant’s mean RT were excluded. Response bias (log b) assesses behavioral responsiveness to feedback. Responses were coded such that more positive values on the PILT-P task indicate a greater propensity to select the RICH (i.e. rewarded) stimulus and more positive values on the PILT-N task indicate a greater propensity to select the LEAN (i.e. non-punished) stimulus.

### EEG Acquisition and Processing.

Continuous EEG was recorded using the BrainVision ActiChamp, 32 channel active channel amplifier system (BrainVision LLC, Morrisville, NC, USA). Electrodes were mounted in an elastic cap using a subset of the International 10/20 System sites (FP1, F3, F7, FC1, FC5, FT9, C3, T7, CP1, CP5, TP9, P3, P7, O1, Fz, Cz, Pz, Oz, FP2, F4, F8, FC2, FC6, FT10, C4, T8, CP2, CP6, P4, P8, TP10, O2), with a ground electrode located at FPz. The electrooculogram (EOG) generated from blinks and eye movements is recorded from five facial electrodes. The EEG is sampled at 500 Hz and all signals digitized on a computer. All data was re-referenced to the average of Tp9 and Tp10 and band-pass filtered from 0.1 to 30 Hz. The EEG was corrected for EOG artifacts (Gratton et al., 1983) and physiological artifacts removed using an automatic procedure with a maximum allowed voltage step of 50 µV within a 400 ms interval length, maximum absolute difference between any two points of 175 µV, and a minimum allowed activity of 0.50 µV within a 100 ms interval length. The EEG is segmented into 1000 ms epochs, beginning 200 ms before and ending 800 ms after feedback onset. ERPs are averaged for acceptance and rejection feedback, and baseline corrected to activity 200 ms prior to feedback.

## Data Analysis

Data analysis plans were pre-registered following data collection but prior to data analysis (osf.io/x8rdh). Those analyses that were not pre-registered are included in the exploratory analyses section of the results.

### Multivariate outliers.

Mahalanobis distance was calculated among all measures used in confirmatory analyses (i.e. reward positivity, feedback negativity, reward bias, loss avoidance, depression severity, social anxiety severity) and used to identify and exclude multivariate outliers with a threshold of *p*<0.001 (=1). This resulted in a final sample of =114.

### PCA.

Temporospatial principal component analysis (PCA) was conducted using the EP Toolkit (Dien, 2010b). A temporal PCA was conducted first, using a Promax rotation to rotate a simple structure in the temporal domain (Dien, 2010a, 2012; Dien et al., 2007) and included time points from each participant’s averaged data as variables and participants, recording sites, and trial types as observations. To identify factors accounting for substantial variance, a Scree plot (Cattell, 1966) was generated and a parallel test (Horn, 1965) conducted comparing a Scree of the dataset to that of a fully random dataset. We identified 15 temporal factor (TF) that accounted for a larger proportion of variance than the random dataset, and thus were retained. Next, a spatial PCA was conducted using Infomax rotation to rotate the spatial factors to independence (Dien, 2010a) and included all recordings sites as variables and participants, trial types, and temporal factor scores as observations. We identified 3 spatial factors (SF), resulting in 45 factor combinations accounting for a total 34.8% of the variance. Factor scores were converted to voltages and robust analysis of variance was conducted on factors that accounted for greater than 1% of variance to identify factors that meaningfully distinguish acceptance and rejection feedback, yielding 11 factors. Peak latency and electrode location were used to identify the RewP/FN component at temporal factor 2-spatial factor 1 (TF2/SF1). Data was imported from Brain Vision Analyzer to R (R Core Team, 2020) for all further computations.

ERP activity in the RewP significantly differed between the acceptance and rejection conditions (, 95% CI , , ). The RewP was calculated as the mean activity 50ms before and 50ms after the peak latency (344ms, time window of 294-394ms) at the peak electrode (FP2; see Figure 2). In line with previous work and recommendations (Meyer-Lindenberg & Tost, 2012), residual scores for the RewP response to acceptance accounting for the response to rejection were calculated, producing scores uncorrelated with the response to rejection. Likewise, residual scores for the FN response to rejection accounting for the response to acceptance were calculated, producing scores uncorrelated with the response to acceptance. This produces RewP and FN scores that are correlated (=0.83) but not inverses of one another and isolates mean amplitude in the ERP unique to acceptance or rejection. A non-difference score measure (e.g., mean amplitude to acceptance without accounting for activity to rejection) is confounded by activity throughout the brain unrelated to the acceptance stimulus. Results of the PCA also suggested the presence of the P2 (peak latency: 212ms, time window of 162-262ms) and N1 (peak latency: 174, time window of 124-224ms) components, both of which also significantly differed between the acceptance and rejection conditions (P2: , 95% CI , , ; N1: , 95% CI , , ).

### Multiple imputation of missing data.

MCAR analyses showed that there was not significant evidence to reject the hypothesis that the data were missing completely at random (MCAR; *p*=0.22). Thus, multiple imputation was conducted using the ‘MICE’ package (van Buuren & Groothuis-Oudshoorn, 2011) in R. Ten imputations were generated using predictive mean matching of the variables of interest (i.e. depression severity, social anxiety severity, reward positivity, feedback negativity, reward bias, and loss avoidance), covariates (age, sex, SES, race, ethnicity), and other measures that were collected concurrently and a priori considered to inform missing data in depression severity (e.g., major depressive disorder diagnosis on the KSADS, social anxiety disorder diagnosis on the KSADS, BAS child drive, BAS child fun seeking, BAS child reward responsiveness–revised, BIS child–revised, and the Pleasure Scale for Children) and behavioral reward bias/loss avoidance (accuracy on the PILT-P and PILT-N, NIH Toolbox list sorting, pattern completion, picture sequencing, picture vocabulary, flanker).

### Multiple regression models.

Following multiple imputation, measures were standardized in each of the 10 imputations. Multiple regression models were conducted and estimates were pooled across the imputations using the ‘miceadds’ package (Robitzsch & Grund, 2020).

Multiple regression models were used to test all three primary hypotheses. For example, two models tested the first hypothesis. In one model, reward bias and loss avoidance were included as predictors, along with covariates, and the RewP as the outcome (see equation 1 below). The other model included the same predictors but included the FN as the outcome (see equation 2 below). These models allow for estimation of the amount of unique variance in the ERP component activity accounted for by reward bias and loss avoidance, controlling for covariates.

An identical structure was used to test the second and third hypotheses. That is, in models testing the second hypothesis, depression and social anxiety severity were included as predictors and the RewP as the outcome in the first model, and the FN as the outcome in the second model. In models testing the third hypothesis, depression and social anxiety severity were included as predictors and reward bias as the outcome in the first model, and loss avoidance as the outcome in the second model.

### Structural equation model of hypotheses.

A structural equation model (SEM) of all three hypotheses was modeled using the ‘lavaan’ package version 0.6.7 (Rosseel, 2012) to determine whether the hypotheses demonstrated an overall improvement in model fit over null model (i.e. one that assumed that all of the hypothesized relationships were null). By simultaneously testing the predicted associations between all variables, this model will account for within-subject shared variance across, for example, ERP components (i.e. RewP & FN), while testing its predicted associations with reward bias and loss avoidance and with the psychopathology measures. Model fit was assessed two ways. First, measures of absolute model fit—root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR)—were compared to established guidelines (RMSEA & SRMR < 0.08) to determine goodness of fit (Hooper et al., 2008). Second, measures of relative model fit—comparative fit index (CFI), Akaike Information Criteria (AIC), Bayesian Information Criteria (BIC)—were compared to a reduced model (with higher CFI and lower AIC and BIC indicating better model fit) (Hooper et al., 2008).

# Results

## Confirmatory analyses

### Association between RewP/FN and reward bias and loss avoidance.

Multiple regression models showed that the RewP to social acceptance feedback was not significantly associated with behavioral reward bias. However, the FN to social rejection feedback was significantly related to behavioral loss avoidance (Table 3), such that a greater negative deflection to rejection feedback was associated with a greater behavioral avoidance of the punished response in the PILT-N task. Zero order correlations further confirmed this pattern of results (Table 2), though at trend level (=0.20, 95% CI [-0.02, 0.41], *p*=0.07). Moreover, these results were consistent when accuracy (i.e. participants’ ability to correctly discriminate between the stimuli) was included in the model (Table S#). Results from supplemental analyses including recent psychotropic medication use were largely consistent, except that the FN to rejection was associated with loss avoidance at trend levels (=0.23, 95% CI [-0.01, 0.46], *p*=0.06, Table S#).

### Association between RewP/FN and depression and social anxiety severity.

Multiple regression models showed that the RewP to social acceptance feedback was not significantly associated with depression severity, nor was the FN to social rejection feedback significantly associated with depression or social anxiety severity (see Table 3). Zero order correlations further confirmed this pattern of results (Table 2), however, the effect size of the correlation between the RewP and depression severity (=-0.08, 95% CI [-0.27, 0.11], *p*=0.41) was comparable to two large prior studies using indepedent samples (=-0.10, total =643; Kujawa et al. (2017); Pegg et al. (2019)). Results from supplemental analyses including recent psychotropic medication use were consistent (Table S#).

### Association between Reward bias/loss avoidance and depression and social anxiety severity.

Multiple regression models showed that reward bias was not significantly associated with depression severity, nor was loss avoidance significantly associated with depression or social anxiety severity (see Table 4). Zero order correlations further confirmed this pattern of results (Table 2). Results from supplemental analyses including recent psychotropic medication use were consistent (Table S#).

### Structural equation modeling of hypotheses.

Structural equation models, modeling all hypotheses simlutaneously, supported the pattern of results reported above. The hypothesized model showed good fit according to absolute model fit indices (RMSEA=0.08, SRMR=0.03), but it did not show significant improvement in model fit over the simplified model (see Table 5).

## Exploratory analyses

### Socioeconomic status.

Multiple regression models showed that income to needs ratio was significantly positively associated with the RewP (not the FN) when reward bias and loss avoidance were included as predictors (=0.26, 95% CI [0.02, 0.49], *p*=0.03), and that the association was trending when current depression and social anxiety severity were included as predictors (=0.20, 95% CI [-0.01, 0.42], *p*=0.06). Follow up analyses showed that income to needs was indeed positively associated with the RewP, and not the FN, in zero-order correlations (RewP: =0.23, 95% CI [0.04, 0.41], *p*=0.02; FN: =0.11, 95% CI [-0.08, 0.29], *p*=0.25). Because income to needs significantly differed between races in our sample (*F*(2,111)=17.14, *p*<.001) and recent discussion in the field about the imperfectness of reports on participants’ race in identifying risk factors and equity gaps (Ioannidis et al., 2021), we also examined models in which race was omitted as a covariate. In these models, income to needs is significantly positively associated with the RewP covarying for reward bias, loss avoidance, depression severity, and social anxiety severity (=0.27, 95% CI [0.06, 0.48], *p*=0.01).

Multiple regression models also showed that income to needs ratio was significantly positively associated with behavioral reward bias (=0.23, 95% CI [0.00, 0.46], *p*=0.05) and significantly negatively associated with loss avoidance (=-0.35, 95% CI [-0.58, -0.12], *p*=0.00) (Table #). That is, reduced income to needs ratio was related to reduced bias towards rewarding stimuli and greater avoidance of the punished response. Zero order correlations further confirmed this pattern of results (Table 2), though at trend level for reward bias (Reward bias: =0.18, 95% CI [-0.02, 0.37], *p*=0.08; Loss avoidance: =-0.31, 95% CI [-0.51, -0.12], *p*=0.00). Moreover, these results were consistent when accuracy (i.e. participants’ ability to correctly discriminate between the stimuli) and recent psychotropic medication use was included in the model (Table S#).

### Other ERP components.

We also examined exploratory ERP components. The temporospatial PCA yielded one component similar to the P2 and one similar to the N1. Exploratory analyses revealed that neither the P2 nor N1 were significantly associated with reward bias or loss avoidance, nor with depression or social anxiety severity (Table S#).

# Discussion

As the first to assess the relationship between ERP responses to social feedback and behavioral performance on reward/loss tasks, the current study sought to test hypotheses that a) the RewP and FN ERP components observed in response to social feedback reflect reward and loss system function respectively, b) depression and social anxiety have shared and distinct mechanisms of interpersonal relationship problems, and c) that depression and social anxiety have shared and distinct mechanisms of dysfunction in responding to rewards and losses. The results of the current study show mixed support for these hypotheses.

## RewP/FN and behavioral reward bias and loss avoidance

For the first hypotheses, the FN was related to behavioral loss avoidance, such that a greater response to social rejection was related to a greater loss avoidance. This lends support for our hypothesis that social rejection reflects loss. Rejection and exclusion experiences have been shown to elicit BOLD signal in the caudate and ventral striatum (S. Cacioppo et al., 2013; Vijayakumar et al., 2017)–two regions implicated in response to other types of losses (Breiter et al., 2001; Seymour et al., 2007). Moreover, studies of life events have categorized social rejection/separation experiences as losses or even humiliations (Kendler et al., 2003). Thus, it is likely that the brain’s response to social rejection uses systems more generally implicated in response to loss.

At the same time, the RewP was unrelated to behavioral reward bias. This also calls into question potential assumptions that the RewP to social acceptance reflects reward related processes. Indeed, a prior study found weak relationships between brain responses to social and monetary rewards (i.e. RewP) in emerging adults (*r*(46)=0.16, *p*=0.27) and early adolescents (*r*(37)=0.28, *p*=0.09; Ethridge et al. (2017)), and a subset of the current sample showed weak correlations as well (*r*(54)=0.04, *p*=0.76; unpublished data, see Rappaport et al. (2019) for methods). However, differences in the structure of the social reward task have led to a more correlated social and monetary RewP (*r*(114)=0.26, *p*<0.01; Distefano et al. (2018)). Further studies using convergent behavioral measures of reward processing and brain measures of neural response to social acceptance are needed to establish the conditions under which brain responses to social and other types of rewards are similar and different.

One potential and intruiging explanation is that there are a number of psychological processes that occur when one experiences social acceptance, with the reward system as only one of those processes. For example, one review proposed that there is a period of attentional orienting to the feedback, followed my the emotional appraisal of the feedback, and finally resulting in emotion regulation (Wang et al., 2017). Such theories are supported by the presence of different ERP components identified in the current study (i.e. N1, P2, RewP/FN), and another review supporting the presence of multiple processes in response to rewards (Glazer et al., 2018). However, such conclusions again rely on reverse inference. Thus, future studies will need to assess the relationship between these brain signals and converging behaviors to better determine their function.

## RewP/FN and depression and social anxiety severity

We did not find support for significant relationships between the RewP and FN and depression and social anxiety symptoms. One possibility is that blunted RewP and heightened FN responses may reflect risk factors for future depression and/or social anxiety (Kujawa & Burkhouse, 2017; Masten et al., 2011) rather than indicators of a current depressive or socially anxious state. In fact, prospective studies have found that the RewP interacts with stressful life events to predict later depression (Burani et al., 2021; Goldstein et al., 2020; Mackin et al., 2019; Pegg et al., 2019). The clinical literature supports different forms of social rejection (e.g., peer victimization, romantic breakups, parental rejection) as risk factors for depression (Copeland et al., 2013; Kendler et al., 2003; Monroe et al., 1999; Rapee, 1997; Slavich et al., 2009). Therefore, greater sensitivity (i.e. heightened FN) to rejection, in combination with greater experiences of interpersonal rejection, may lead to depression.

## Reward bias/loss avoidance and depression and social anxiety severity

Finally, we did not find that depression and social anxiety severity were related to behavioral reward bias or loss avoidance. This was surprising given previous evidence that these constructs are affected, particularly in depression (Luking, Pagliaccio, et al., 2015; Luking, Neiman, et al., 2015; Pizzagalli et al., 2008; Vrieze et al., 2013; Whitton et al., 2016). Rather than be related cross-sectionally to depression or social anxiety severity, one possibility is that impaired reward processing is more of a trait associated with risk, particularly for depression, making them risk factors of future psychopathology. This is supported by studies showing that a history of depression is related to impaired reward processing (Pechtel et al., 2013; Rappaport et al., 2020), and that reward processing dysfunction predicts depressive symptoms (Gotlib et al., 2010; Luking et al., 2016a; McCabe et al., 2012; Stringaris et al., 2015). Although the PDS study includes data about past psychopathology of the current sample, we were concerned that such exploratory analyses would require too many comparisons. Further, past assessments of social anxiety are limited, since the SIAS/SPS was not collected prior to the current wave.

## SES and brain response to social acceptance

The results also suggested some interesting avenues for further exploration. We had not predicted a priori that SES (as operationalized as income-to-needs ratio) would be associated with the RewP and FN. We chose to include this in the multiple regression model to control for the established relationship between income-to-needs and psychopathology (Barch et al., 2016; Gilman, 2002). Thus, it is intriguing that we found a positive relationships between SES and RewP to social feedback. We are not aware of any prior literature examining relationships between socioeconomic status and brain response to social feedback, making this a highly novel and intruding finding. There is a robust literature indiciating that low SES is related to greater risk for psychopathology (CITE). Given that lower SES was associated with a reduced RewP to positive social feedback, one specupossibility is that poverty confers risk for psychopathology at least partially through social anhedonia. This could lead to social withdrawal and greater social isolation, which is already exacerbated in impoverished youth (Eckhard, 2018; Sletten, 2010), and subsequently depression (Bruce & Hoff, 1994). If blunted responses to social acceptance is in fact a risk factor for future depression (Burani et al., 2021; Goldstein et al., 2020; Mackin et al., 2019; Olino et al., 2015; Pegg et al., 2019), then this illustrates a potential causal pathway whereby poverty leads to blunted responses to social acceptance, which in turn leads to depression.

## SES and behavioral reward bias and loss avoidance

Another novel finding was that lower SES was associated with less behavioral reward bias and greater loss avoidance on the PILT. This represents another intriguing avenue for future research, as it suggests another potential pathway through which poverty confers risk for psychopathology. Adolescents with fewer monetary resources may be more sensitive to loss. That is, adolescents with lower SES may seek to avoid potential losses, perhaps even at the expense of receiving rewards. Intriguing, an enhanced response to losses has been associated with depression risk (Luking et al., 2016a, 2015). Thus, if lower SES is associated with greater sensitivity to loss and a blunted response to reward, this could confer risk factor for developing depression, If these findings are replicated, future studies should seek to examine the mechanisms responsible for and the outcomes of the link between poverty, blunted responses to social acceptance, and blunted reward bias and enhanced loss avoidance.

## Strengths and limitations

This study represents an important step in our understanding of the function of the brain’s response to social feedback, and how that function is different in depression and social anxiety. The current study has a number of strengths, including a) the preregistration of hypotheses, procedures, and analyses (osf.io/x8rdh), b) testing of reverse inference assumptions, c) use of dimensional measures of depression and social anxiety, and d) robust multiple regression and structural equation modeling analyses that include demographic covariates, including low SES, which itself has been related to psychopathology risk (Barch et al., 2016; Gilman, 2002). Moreover, this study provides intriguing exploratory findings that could have implications for our understanding of how poverty affects processing of social acceptance feedback.

These strengths must also be considered in light of the current study’s limitations. First, our study may have been under-powered to detect the hypothesized relationships. Post-hoc power analyses suggested that the sample (=114) has 92% power to detect moderate effects (=0.15), and 75% power to detect smaller effects (=0.10), at an adjusted alpha of 0.025 with two predictors of interest and six covariates in the multiple regression. Furthermore, we were under-powered to detect a correlation between the RewP to social acceptance and depression severity at the effect size found in two prior studies (=-0.10 ) (Kujawa et al., 2017; Pegg et al., 2019). That being said, finding a similar effect size among three independent studies of adolescents–one of which was preregistered–suggests that this may represent a true population effect albeit of small magnitude. Second, one may take issue with our use of multiple regressions as overly conservative. To guard against potential Type II error, we also examined zero-order correlations between the variables of interest. These correlations largely converged with the results of the regression models. Third, convergence of the current findings with studies using other behavioral measures of reward and loss are needed to verify whether or not these ERP components truly represent engagement of reward and loss systems. Fourth, although boasting greater temporal resolution, subcortical processing of social feedback may be affected in depression and social anxiety. ERP measures would be able to detect downstream consequences in cortical regions (e.g., insula, cortical networks; Rappaport and Barch (2020)), however it may be limited in detecting subcortical origin of such individual differences (e.g., in the subgenual ACC or striatum; Silk et al. (2014)). FMRI, however, carries its own limitations. The low temporal resolution of fMRI would limit the ability to distinguish between the different processes thought to underlie the response to social feedback. Further, fMRI risks reducing psychological phenomena to specific regions of interest. Future studies using both ERP and fMRI methods will be able to address this.

## Conclusions

Overall, the current findings replicate and extend prior studies. These findings lend support to the assumption that brain responses to social rejection reflect functioning of loss-related systems. At the same time, further investigation is warranted to support the assumption that brain response to social acceptance reflect functioning of reward-related systems. Although non-significant in the current study, the finding of a consistent, albeit small, relationship between depression and brain response to social acceptance across now three independent studies is notable. Finally, the exploratory findings that lower socioeconomic status was related to greater blunting of the brain response to social acceptance, as well as reduced behavioral reward bias and enhanced loss avoidance, offers evidence of a potential novel mechanism linking poverty with psychopathology. Together these findings represent an important step in alleviating problems in interpersonal relationships.

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