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RESEARCH ARTICLE

Associations between peer stress in early adolescence and multiple event-related potentials elicited during social feedback processing

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Abstract

Interpersonal stress in adolescence has been associated with alterations in neural responses to peer feedback, and increased vulnerability to psychopathology. However, it is unclear whether the associations of interpersonal problems with neural responses are global across event-related potentials (ERPs) or might result in alterations only in specific ERPs. We examined associations between multiple informants of peer stress (self-reported, parent-reported, and peer-reported) and multiple ERPs (N1, P2, RewP, and LPP) to social feedback in a sample of 46 early adolescents (aged 12–13 years). Reports of peer stress were only moderately correlated with one another, indicating different informants capture different aspects of peer stress. Regressions using informant reports to predict ERPs revealed greater parent-reported peer stress was associated with a smaller RewP, whereas self-reported stress was associated with a smaller P2, to acceptance. In contrast, greater peer-reported stress was associated with *larger* P2, RewP, and LPP to acceptance. Findings suggest that different sources of stress measurement are differentially associated with ERPs. Future research using social feedback-related ERPs should consider multiple sources of information as well as multiple ERP components across the time-course of feedback processing, to gain a clearer understanding of the effects of peer stress on neural responses to feedback.

KEYWORDS
LPP, N1, P2, peer victimization, RewP, social feedback

1 | INTRODUCTION

Adolescence is a period of increased neural plasticity, during which experiences can have lasting influences on brain function and affective behavior (e.g., Griffin, 2017; Guyer et al., 2016; Tottenham & Galvan, 2016). In particular, adolescence is associated with both greater exposure to stressors and greater reactivity to stressors compared with other developmental periods (e.g., Lupien et al., 2009; Tottenham & Galvan, 2016). An important potential source of stress in adolescence is negative interactions with peers. Numerous studies have highlighted the importance of peers during early adolescence: adolescents spend increased time with peers, report greater concerns about peer approval (e.g., Larson et al., 2002; Nelson et al., 2005) and display increased neural and physiological responses to social evaluation compared with children and young adults (e.g., Somerville et al., 2013). Adverse social experiences, or peer stress, can take many forms, including conflict, exclusion, rejection, and victimization. There is evidence that peer stress can have potent effects on physical health and functioning both in the short term (Schacter, 2021) and long term (Copeland et al., 2014). One proposed mechanism for these effects is through neural responses to social feedback. Interpersonal stress with peers in adolescence has been associated concurrently with variation in neural responses to socially-evaluative feedback (e.g., Rappaport et al., 2019; Swartz et al., 2019). These neural alterations may in turn result in heightened vulnerability to subsequent interpersonal and emotional difficulties in later adolescence (e.g., Mastern et al., 2012) and adulthood (e.g., Eisenberger et al., 2007; Flores et al., 2018).

However, effectively processing and responding to social information involves multiple steps (e.g., Crick & Dodge, 1994), such as encoding, then interpreting the information, determining a response, and enacting a behavioral response. Diverse regions of the brain are activated by socially evaluative feedback, including the anterior cingulate cortex, medial prefrontal cortex, amygdala, striatum, and insula (Achterberg et al., 2016, 2017, 2018; Gunther Moor et al., 2010; Olino et al., 2015; Somerville et al., 2006). This suggests a need to examine multiple distinct neural processes following receipt of social feedback to understand whether experiences of interpersonal stressors such as peer victimization show similar associations with different processing stages. Thus, the goal of this study was to examine how multiple event-related potentials (ERPs) elicited by social feedback might be associated with peer stress in adolescence.

1.1 | Event-related potentials

A social evaluation task for assessment of neural responses to feedback from peers is the Island Getaway task, which requires participants to vote to accept or reject coplaying peers and also receive acceptance or rejection feedback from those peers (Kujawa et al., 2014). Previous work examining ERPs elicited in this task, in early adolescents and adults, indicates that multiple components sensitive to social evaluation are evident after feedback: a rejection-sensitive N1 and a series of reward-sensitive components including the P2, the reward positivity (RewP), and the late positive potential (LPP; Ethridge et al., 2017; Kujawa et al., 2017; Weinberg et al., 2022). However, the majority of studies using this task have focused on the RewP, a central positivity in the waveform peaking between approximately 250 and 350 ms after stimuli presentation that is sensitive to receipt of rewarding feedback (see review by Proudfit, 2015). The RewP is typically larger in response to positive feedback compared with negative feedback, and the magnitude of the RewP is correlated with activity in the ventral striatum (Carlson et al., 2011).

There is also evidence that, although the RewP can be elicited by many different types of reinforcers (e.g., money, food, and social approval), there are only modest correlations between the RewPs following these different tasks and reinforcers (Ait Oumeziane et al., 2019; Banica et al., 2022; Ethridge et al., 2017; Springer et al., 2021). These data suggest that the magnitude of the RewP may not reflect domain-general reward sensitivity, but may instead be category specific (i.e., sensitive to reward types), as different rewards differ in their salience across individuals. In addition, the type of task and reward appear to affect associations between the RewP and target variables (Banica et al., 2022; Ethridge et al., 2017; Freeman et al., ; Rappaport et al., 2019). For instance, unlike the RewP following monetary rewards, the RewP elicited in the Island Getaway task appears to relate specifically to social anhedonia and not other facets of anhedonia (Banica et al., 2022), and, unlike the monetary RewP, the social RewP predicts interpersonal behaviors in the Island Getaway game (Weinberg et al., 2020).

In prior research, the RewP elicited by monetary reward appears to be associated with social stress—both acute laboratory social stressors such as the Montreal Imaging Stress Task (Ethridge et al., 2020) and cumulative peer stress from participants' daily lives (Ethridge et al., 2018) are linked to a smaller RewP—however, these studies were conducted in adults, and following monetary incentives. There is emerging evidence that peer victimization experienced in early childhood has been associated with a blunted RewP to social acceptance in young adults (Rappaport et al., 2019). Similarly, in adolescents, fMRI studies have shown that acute social stress can result in blunted patterns of neural activity in the striatum (e.g., Lincoln et al., 2019), suggesting that social stress influences activation of neural circuits implicated in reward processing.

However, less is known about associations between interpersonal stress and other ERP components elicited in response to socially evaluative feedback. A considerable strength of ERP methods is their temporal resolution, allowing researchers to parse distinct patterns of social and cognitive activity (Amodio et al., 2014), which may be impacted by the experience of interpersonal stress. One such ERP component is the N1, a negative-going component maximal between 90 and 200 ms after the presentation of a stimulus, reflecting visual processing and attention orientation (e.g., Sur & Sinha, 2009). The N1 also appears to be a measure of attention to emotional information (e.g., Olofsson et al., 2008). In the Island Getaway task, a larger N1 is observed in adolescents following rejection feedback than acceptance feedback and appears to be a measure of early attentional engagement with negative feedback (Babinski et al., 2019). In the same study, 10–15-year olds with greater self-reported rejection sensitivity also showed an increased N1 to rejection in the Island Getaway task (Babinski et al., 2019), suggesting individual differences in the salience of rejection feedback can influence the N1. These processes may be shaped by early social experiences—for instance, a larger N1 to rejection was found in 12-year olds who had lower quality maternal relationships in early childhood (Kujawa et al., 2020). With regard to stress, studies using laboratory-induced stressors in adults have shown an enhanced N1 to nonsocial visual stimuli (Qi et al., 2018; Shackman et al., 2011), supporting the view that stress can influence early attentional processes. However, it is not clear whether chronic real-world stress in early adolescents might also show the same association with the rejection-sensitive N1.

Following the N1 is the P2, occurring approximately 100–250 ms after feedback presentation. In cue-based behavioral feedback studies, the P2 is maximal over fronto-central electrodes and is associated with early attentional processes that discriminate between reward and punishment (e.g., Holroyd et al., 2011; Wischnewski & Schutter, 2019). The P2 is larger in anticipation of, and in response to, social rewards than nonrewards and is sensitive to individual differences in early aspects of reward processing (Flores et al., 2015). Although the P2 and RewP are similar in their spatial distribution and are temporally proximal to one another, there may also be important functional differences between them. For instance, interventions targeting attention have been shown to modulate the P2 but not the RewP, suggesting a difference in how reward processing is captured by the two ERPs (Sylvain et al., 2020). Importantly, analyses across age groups have revealed that adolescents have a larger P2 to rewards than adults, suggesting that rewarding stimuli elicit a stronger response in this time-window in youth (Wang et al., 2020). Further evidence also suggests that variation in the P2 reflects individual differences in the salience of social feedback: young adults who met criteria for social anxiety disorder (SAD), a disorder characterized by excessive concerns regarding social evaluation, showed *smaller* P2 to acceptance and rejection compared to healthy controls (Cao et al., 2015). However, it is unclear if chronic social stress exposure in adolescents might be similarly associated with the P2.

Like the P2 and the RewP, the LPP is a positive-going deflection in the ERP and is measured from approximately 400 ms after stimulus onset and extending to 1000 ms and beyond (e.g., Brown et al., 2012; Schupp et al., 2000). The LPP is associated with sustained attention to motivationally salient stimuli; a larger LPP is elicited in response to more emotionally arousing stimuli compared to neutral stimuli (e.g., Cuthbert et al., 2000; Codispoti, Micucci, & Cesarei, 2020; Hajcak & Foti, 2020). In the Island Getaway task, the LPP is typically enhanced to acceptance feedback compared to rejection feedback (e.g., Kujawa et al., 2017). In previous adult studies using other tasks, both acute laboratory-induced stress (Rubin et al., 2012) and stress from childhood maltreatment (Sandre et al., 2018) have been associated with an enhanced LPP to threatening social information. However, it is not yet clear how social stress specifically might affect the acceptance-sensitive LPP elicited in the Island Getaway task, nor whether interpersonal stress would show associations with this marker of sustained attention to peer evaluation in early adolescents. In sum, there is a need to examine multiple ERP components reflecting distinct processing steps, in order to clarify how social stressors might be associated with variation in distinct stages of social information processing in this sensitive developmental period.

1.2 | Measures of peer stress

There are multiple ways to assess peer stress in adolescents. Self-report is commonly used, but difficulties with peers can also be assessed with peer reports or parental reports, and multi-informant report may provide a richer portrait of adolescents' experiences with their peers (Dirks et al., 2010). However, although reports from these different sources are typically positively correlated, the magnitude of these associations tends to be modest (e.g., Branson & Cornell, 2009; Cornell & Brockenborough, 2004; Kushner & Tackett, 2017; Putallaz et al., 2007; Zimmer-Gembeck & Webb, 2017). These low levels of agreement are likely not an indication of low-quality information from one or more sources, however, as measures deriving from these distinct sources tend to be both reliable and valid (Card & Hodges, 2008; Goodman, 2001; Ladd & Kochenderfer-Ladd, 2002). Instead, it likely reflects the fact that informants have access to different aspects of youth's interpersonal experiences (Dirks et al., 2012). For instance, peer-nominated peer victimization scales may best capture forms of interpersonal stress that are most visible and salient to other adolescents in a target child's social milieu (e.g., Card & Hodges, 2007; 2008), whereas self-report, and to some extent parent report, may capture not only these more public experiences, but also the experiences of children who encounter more subtle forms of exclusion, or who primarily experience stress in close friendships. Hence, each informant's report can provide unique insight into the target child's social interactions.

Consistent with this, reports from different informants have been shown to be associated with different outcomes (Dirks et al., 2012). For instance, peer-reported peer victimization may better predict early adolescents' behavioral outcomes (e.g., aggression), whereas self-reported peer victimization appears more strongly with self-reported symptoms of anxiety and depression (e.g., Brendgen et al., 2016; Graham et al., 2003). However, the majority of studies assessing associations between neural response to peer feedback and peer stress has relied on a single informant. Thus, it is not clear how different aspects of peer stress captured by different informant reports might be reflected in adolescents' neural processing of social acceptance or rejection from peers.

1.3 | Present study

The aim of this study, therefore, was to examine associations between multiple ERP components and peer stress reported by multiple informants—self-report, parent-report, and peer-report. Based on prior work showing self-reported and parent-reported peer stress are associated with a blunted RewP in both adolescents and emerging adults (e.g., Ethridge et al., 2018; Rappaport et al., 2019), we predicted that we would also observe this in our sample. Because we are not aware of studies looking at peer report and the RewP, our hypotheses here were necessarily more tentative, but we expected that greater peer-reported peer stress would also be associated with a smaller RewP. We further hypothesized that measures of stress from these different sources of information would each account for unique variance in the RewP, and, when considered together, would account for more overall variance in the RewP than a single predictor, as they would provide a fuller picture of peer stress for our adolescent sample. Given the lack of prior work on associations between the LPP and peer stress, our analyses for this component were exploratory. However, consistent with prior evidence that the N1 and P2 are sensitive to stressful life experiences, we expected that higher peer stress scores might be associated with a larger N1 following social rejection and a smaller P2 in response to social acceptance.

2 | METHOD

2.1 | Participants

Fifty-one adolescent participants were drawn from a larger sample of youth attending Grade 7 at a high school in a large Canadian city. Participants were retained for analyses if they took part in the laboratory-based EEG study and had usable EEG data. We excluded participants from the sample due to task technical failure ($n = 1$), not completing the task ($n = 4$), or having missing data in the peer stress measures ($n = 1$). The final sample consisted of 46 participants (34.8% male, $M_{Age} = 12.7$, $SD_{Age} = 0.44$, 91.3% identified as White, 2.2% each identified as Chinese and Caribbean, and 4.3% other or mixed ethnicity). Participants received a $50 gift card as compensation for their time upon completion of the study. Self- and parent-reported data were collected when participants completed a daily diary procedure for the larger parent study, between November and June of the school year, whereas peer-reported data were obtained in class during March and April of the school year, so that participants had a chance to get to know each other. Throughout the school year, participants were invited for laboratory visits at McGill University for EEG data collection. All procedures were approved by McGill University's Research Ethics Board, and all participants and their guardian provided written informed consent and/or assent.

2.2 | Peer stress measures

2.2.1 | Self-reported revised peer experiences questionnaire

The revised peer experiences questionnaire (RPEQ; Prinstein et al., 2001) was administered to obtain adolescents' self-reported levels of peer victimization in the school context. The measure contains 13 items assessing overt (direct physical or verbal), relational (interpersonal), and reputational forms of victimization, as well as five items assessing adolescents' receipt of prosocial behavior from peers. Participants were asked to rate how often a behavior was directed toward them over the past year on a 5-point Likert scale ranging from never (1) to a few times a week (5). Peer victimization scores were obtained by summing the items for the 13 items assessing victimization, with higher scores indicating greater levels of victimization (Cronbach's $\alpha = .87$).

2.2.2 | Peer difficulties scale from the parent-reported strengths and difficulties questionnaire

The strengths and difficulties questionnaire—parent form (SDQ-P; Goodman et al., 1998) was administered to assess parent-rated peer stress of participants. It consists of 25 items describing positive and negative attributes of children and adolescents that are allocated to five scales of five items each. This study focused on the peer difficulties scale, for which each item is scored on a 3-point Likert scale: not true (0), somewhat true (1), and certainly true (2), such that higher scores reflect greater peer difficulties for the target child (Cronbach's $\alpha = .69$). Items in this scale assess, for instance, peer victimization, the child's popularity, whether they have at least one good friend, and whether they get along better with adults than other children. Although the internal consistency of this scale is on the lower end, this is largely due to the low number of items in the scale, and is consistent with other studies that have also used the SDQ (e.g., Bettge et al., 2002; Goodman, 2001; Stadler et al., 2010).

2.2.3 | Peer-nominated victimization

Participants' reputation for peer victimization was assessed with peer nominations. To collect peer nominations, participants read five descriptions of victimization, including physical (i.e., hit, pushed, or kicked by other kids), verbal (i.e., teased, called names, or made fun of by other kids), and relational (e.g., other kids gossip about or say bad things about him/her behind his back). All participants attended one school, in which students rotate through classes with all other students in their grade. Thus, each description was paired with a randomized subset of 60 classmates participating in the study. The specific participants were different for each item, and each participant appeared on approximately the same number of rosters. Note that previous work has shown that the use of random subsets yields comparable data to complete lists (Bellmore et al., 2010). Participants were asked to circle the name of every person who fit the behavioral description, and to rate whether the behavior occurred "sometimes" or "a lot" (Kochenderfer-Ladd & Ladd, 2004). After completing their nominations, participants were given a list of the names of all participating students and asked to cross out the name of anyone they did not know (Bellmore et al., 2010). When people's names were crossed off, they were not counted as having been on that roster. The average number of raters per item was 43. Scores for each item were calculated by adding up the number of nominations a participant received (1 for "sometimes" and 2 for "a lot") and dividing by the number of raters. These scores were then standardized. Peer-nominated victimization was computed by calculating the mean score across all five items (Cronbach's $\alpha = .86$).

2.3 | Social feedback task

In the laboratory, we recorded EEG data from participants while they completed the Island Getaway task (Ethridge et al., 2017, 2018; Kujawa et al., 2014) to elicit ERPs to peer acceptance and rejection feedback. Participants were told that they would be playing a game against 11 other coplayers of a similar age range (coplayers were actually part of the computer program). Participants were asked to create a profile with their photograph and demographic information. They would then review each coplayer's profile and vote whether they wanted each coplayer to continue on with them in the game, with options being to "keep" or "kick out" the coplayer. Participants were told they were voting simultaneously with that coplayer on that trial. After the participant voted, they saw the coplayers' vote, indicating whether the coplayer accepted or rejected them, represented by images of a green "thumbs up" or a red "thumbs down," respectively. Each voting trial began with a coplayer profile presented until the participant's vote. This was followed by a fixation cross presented for 1000 ms, feedback displayed for

2000 ms, and a blank screen presented for 1500 ms. To simulate variation in coplayer response speed, a message saying "Waiting for [coplayer's name] to vote … " was shown before the fixation cross if participants voted faster than the stimulated voting time for that coplayer. The assigned voting pattern of the coplayers was such that two would reject the participant on four or five out of six rounds, two would accept the participant on most rounds, and the rest were equally likely to accept or reject the participant. Thus, there was a slight variation in the proportion of rejection and acceptance feedback in each round across participants. For added realism, participants were also told that if they received the greatest number of "kick-out" votes, the task would be terminated regardless of which round they were in. In actuality, after each of the first five rounds of voting, participants were told that one of the coplayers had been sent home, and after completing the sixth, participants were informed that they had won the game. There were 51 feedback trials split evenly between acceptance and rejection, with one trial type determined randomly. Acceptance and rejection feedback were respectively interpreted as social reward and nonreward.

2.4 | Electroencephalographic recording and data processing

Continuous 32-channel EEG was recorded with a BrainVision actiCHamp system (Brain Products, Munich, Germany) based on the standard 10/20 layout with the ground electrode at Fpz. The electrooculogram was collected using facial electrodes placed approximately 1 cm above and below the left eye (VEO) and 1 cm to the outside of both eyes (HEO). Data was recorded using a sampling rate of 1000 Hz. No online filter was used.

Offline analysis was conducted with BrainVision Analyzer software (Brain Products). Unsegmented data were band-pass filtered with low and high cutoffs of 0.01 and 30 Hz (24 db/oct slopes). Data were then referenced offline to the left and right mastoids (TP9 and TP10) and segmented 200 ms before and 1000 ms after feedback onset. Eye-blink and ocular corrections were conducted using HEO and VEO per modification of the original algorithm published in Gratton et al. (1983) . A semi-automatic artifact rejection procedure was then conducted. Artifacts were automatically detected and rejected from channels within a trial when any of the following occurred: a voltage step of more than 50.0 μV between sample points, a maximum voltage difference of 175.0 μV within 400 ms intervals, or a minimum voltage difference of 0.50 μV within 100 ms intervals. Visual inspection of the data was then conducted to manually detect and reject remaining artifacts for channels within a trial. Channels with fewer than five trials following artifact rejection were interpolated from four surrounding channels, with the exception of channels on the outer edge of the cap (e.g., Fp1, Fp2), in which case three surrounding channels were used for interpolation. Following artifact rejection procedures, participants included in these analyses had on average 26.76 (SD = 1.06; range: 24–29) trials for the accept condition and 23.89 (SD = 1.04; range: 21–26) trials for the reject condition. ERPs were then averaged across trials separately for acceptance and rejection conditions, then baseline corrected from −200 to 0 ms.

2.5 | Analysis

In order to decompose the observed waveform into distinct components, a temporospatial PCA was conducted, using the ERP PCA Toolkit (Dien, 2010a). Two grand averages (accept/reject) containing information at all time points and channels were entered into a data matrix for each participant. We performed a temporal PCA, followed by a spatial ICA (Dien, 2010b; Dien et al., 2005; Dien et al., 2007). For the temporal PCA, a Promax rotation was used to rotate to simple structure (Dien, 2010b; Dien et al., 2007). Following the first rotation, a parallel test was conducted on the resulting Scree plot (Cattell, 1966), in which the Scree of the actual dataset was compared to a Scree plot derived from a fully random dataset. The number of temporal factors retained was based on the largest number of factors that account for a greater proportion of variance than the fully random dataset (see Dien, 2010a for more information). Based on this criterion, 19 temporal factors were extracted for rotation. The covariance matrix and Kaiser normalization were used (Dien et al., 2005). For each factor, scores were derived for every combination of electrode, participant, and trial type. Each temporal factor score represents the percentage of activity in the original data captured by that particular factor.

A spatial ICA was then conducted on each temporal factor in order to identify the spatial distribution of these factor scores. Variables consisted of all recording sites, and observations consisted of all participants, trial types, and temporal factor scores. Infomax was used to rotate the spatial factors to independence (Dien, 2010b; Dien et al., 2007). Based on the results of the parallel test, three spatial factors were extracted from each temporal factor. This temporospatial PCA resulted in 57 factor combinations that accounted for 74.5% of total variance in the data.

Data exported for each participant represent the loadings of that participant's data onto the factor combination at the peak channel and time point. In order to directly assess timing and spatial voltage distributions, these factor loadings are translated back into voltages. Four factor combinations were temporally and spatially similar to known ERP components. These components are depicted in Figure 1 and described in Table 1.

2.6 | Statistics

Sensitivity analysis using G*Power (Faul et al., 2007) indicate that with a sample size of 46, α error probability of 0.05, power of 0.8, and three[1] peer victimization predictors in a multiple regression, the smallest detectable effect size was $f^2 = 0.26$ or $\eta_p{}^2 = 0.21$, a medium-to-large effect. All statistical analyses were conducted in R with the {stats} package (R Core Team, 2017). To operationalize the neural response unique to peer acceptance, we computed a standardized residual as it is a more specific and interpretable measure with higher internal consis-

[1] Participant sex was originally included as a predictor, but there were no effects of sex nor differences in the significance and direction of other predictor effects. For greater statistical power, sex was removed from the model.

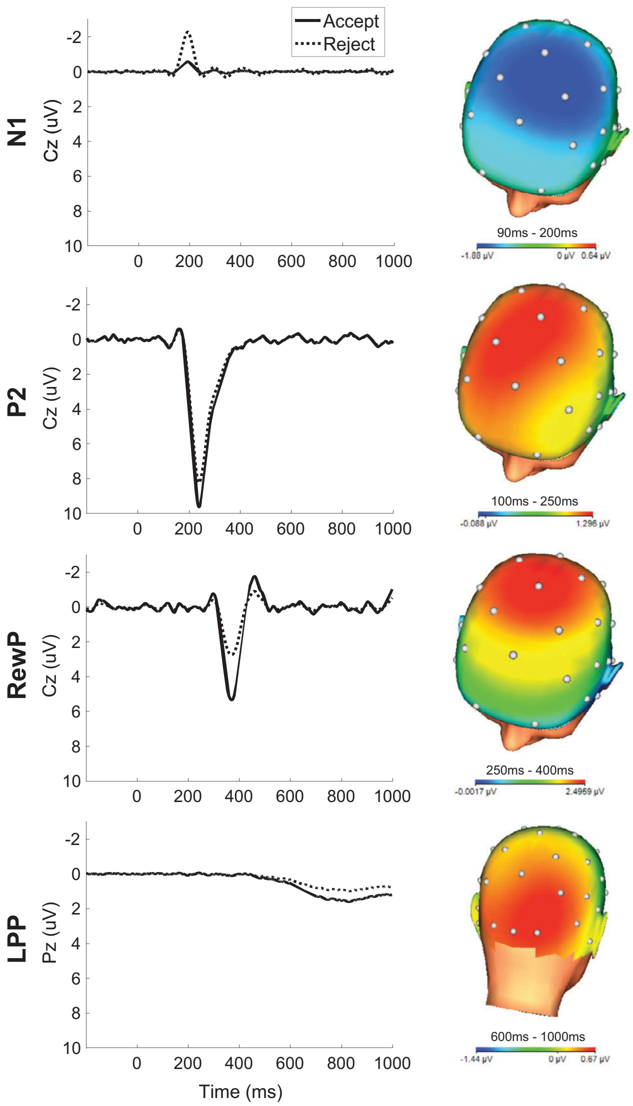

FIGURE 1 Waveforms and scalp topographies depicting temporospatial factor combinations corresponding to each of the 4 ERP components. Components are labeled in the top left corner

tency as opposed to difference scores (e.g., Ethridge & Weinberg, 2018; Meyer et al., 2017). We regressed the neural response to acceptance on rejection for the three acceptance-sensitive components: P2, RewP, and LPP, and saved the residuals. To capture variance unique to rejection, we regressed the neural response to rejection on acceptance for N1, the rejection-sensitive component. Following this, we computed Pearson product–moment correlations to describe bivariate associations amongst our variables (the three peer victimization measures and four ERP_{Resids}) before conducting four regression models. In each model, parent-report, self-report, and peer-report of peer difficulties were entered as predictors. Each of the four ERP_{Resids} was a DV.

3 | RESULTS

Figure 1 shows the PCA-derived grand-averaged ERPs at Cz for N1, P2, and RewP, and Pz for LPP for acceptance and rejection task conditions. Topographic maps depict voltage differences (mean amplitude of acceptance feedback condition minus rejection feedback condition) across the scalp in the time window of each ERP.

Correlations between peer stress variables and ERP_{Resids} are reported in Table 2. Results indicate that parent, self, and peer sources of peer stress were positively correlated. We also observed a significant correlation between parent-reported peer difficulties and $RewP_{Resid}$, such that those adolescents whose parents reported greater peer difficulties had a smaller RewP to acceptance.

The results of the regression models (presented in Table 3) revealed that peer stress showed different patterns of associations with the four ERP variables. The VIF scores for parent, self, and peer sources of peer stress were 1.49, 1.14, and 1.47, respectively, suggesting a low multicollinearity and thus a stable solution of the regression models. Greater parent-reported peer difficulties were significantly associated with a smaller RewP following peer acceptance, but were not significantly associated with the P2, whereas greater self-reported peer victimization was associated with a smaller P2, but was not significantly associated with the RewP. In contrast, and contrary to our predictions, greater peer-nominated peer victimization was associated with *larger* P2, RewP, and LPP following acceptance feedback (see Figure 2). The

TABLE 1 Temporospatial factor combinations corresponding to each of the 4 ERP components for the Island Getaway Task

ERP component	Temporospatial factor combination	Variance explained (%)	Temporal loading peak (ms)	Spatial distribution	Accept vs. reject $T_{WJt}/c(1.0,42.0)$
N1	TF9/SF1	0.94	192	Frontocentral negativity	6.37*
P2	TF3/SF1	4.1	239	Frontocentral positivity	2.64
RewP	TF10/SF1	1.04	370	Central positivity	21.47***
LPP	TF2SF2	5.49	829	Occipital positivity	3.26

Note. *t*-Values were calculated using a robust ANOVA.
*$p < .05$.
**$p < .01$.
***$p < .001$.

TABLE 2 Summary of means, standard deviations, ranges, and Pearson correlations of peer stress variables and ERP_{Resids}

Variable	*M* (SD)	Range	1	2	3	4	5	6
1. Parent-reported peer difficulties	1.28 (1.72)	0, 8						
2. Self-reported peer victimization	20.55 (6.85)	13, 43	.31*					
			[.04, .56]					
3. Peer-nominated peer victimization	−0.06 (0.74)	−0.6, 3.4	.55***	.30*				
			[.31, .72]	[.02, .54]				
4. $N1_{Resid}$	0.03 (0.98)	−2.5, 2.0	.03	.13	−.07			
			[−.26, .32]	[−.16, .40]	[−.35, .22]			
5. $P2_{Resid}$	0.00 (1.00)	−1.8, 2.7	.04	-.27	.24	−.26		
			[−.25, .33]	[−.52, .01]	[−.05, .50]	[−.51, .03]		
6. $RewP_{Resid}$	0.00 (1.00)	−2.4, 2.5	−.47**	−.08	.003	.04	.22	
			[−.67, −.21]	[−.36, .22]	[−.28, .29]	[−.25, .32]	[−.07, .48]	
7. LPP_{Resid}	0.00 (0.99)	−1.9, 3.0	.07	−.18	.25	−.03	.31*	−.06
			[−.23, .35]	[−.44, .12]	[−.04, .50]	[−.32, .26]	[.03, .55]	[−.34, .23]

Note. *M* and SD are used to represent mean and standard deviation respectively. The 95% confidence interval is listed under each correlation.
*$p < .05$.
**$p < .01$.
***$p < .001$.

TABLE 3 Summary of each regression analysis ($N = 46$)

	B	SE *B*	*β*	*t*	*p*	ηp^2
$N1_{Resid}$						
$R^2 = .04$, Adjusted $R^2 = -.03$, $F(3, 42) = 0.51$, $p = .677$						
SDQ	0.05	0.11	0.08	0.46	.650	.005
RPEQ	0.02	0.02	0.14	0.88	.383	.02
Peer nominated	−0.23	0.24	−0.18	−0.97	.340	.02
$P2_{Resid}$						
$R^2 = .20$, Adjusted $R^2 = .14$, $F(3, 42) = 3.41$, $p = .026$						
SDQ	−0.03	0.10	−0.05	−0.31	.762	.002
RPEQ	−0.05	0.02	−0.37	−2.52	.016*	.13
Peer nominated	0.52	0.22	0.39	2.31	.027*	.13
$RewP_{Resid}$						
$R^2 = .32$, Adjusted $R^2 = .27$, $F(3, 42) = 6.67$, $p < .001$						
SDQ	−0.40	0.09	−0.69	−4.43	<.001***	.32
RPEQ	0.005	0.02	0.03	0.25	.807	.001
Peer nominated	0.49	0.21	0.37	2.40	.021*	.12
LPP_{Resid}						
$R^2 = .14$, Adjusted $R^2 = .08$, $F(3, 42) = 2.25$, $p = .096$						
SDQ	−0.03	0.10	−0.05	−0.29	.772	.002
RPEQ	−0.04	0.02	−0.26	−1.72	.094	.07
Peer nominated	0.49	0.23	0.37	2.14	.039*	.10

Note. SDQ refers to the parent-reported peer difficulties measure, and RPEQ refers to the self-reported peer victimization measure.
*$p < .05$.
**$p < .01$.
***$p < .001$.

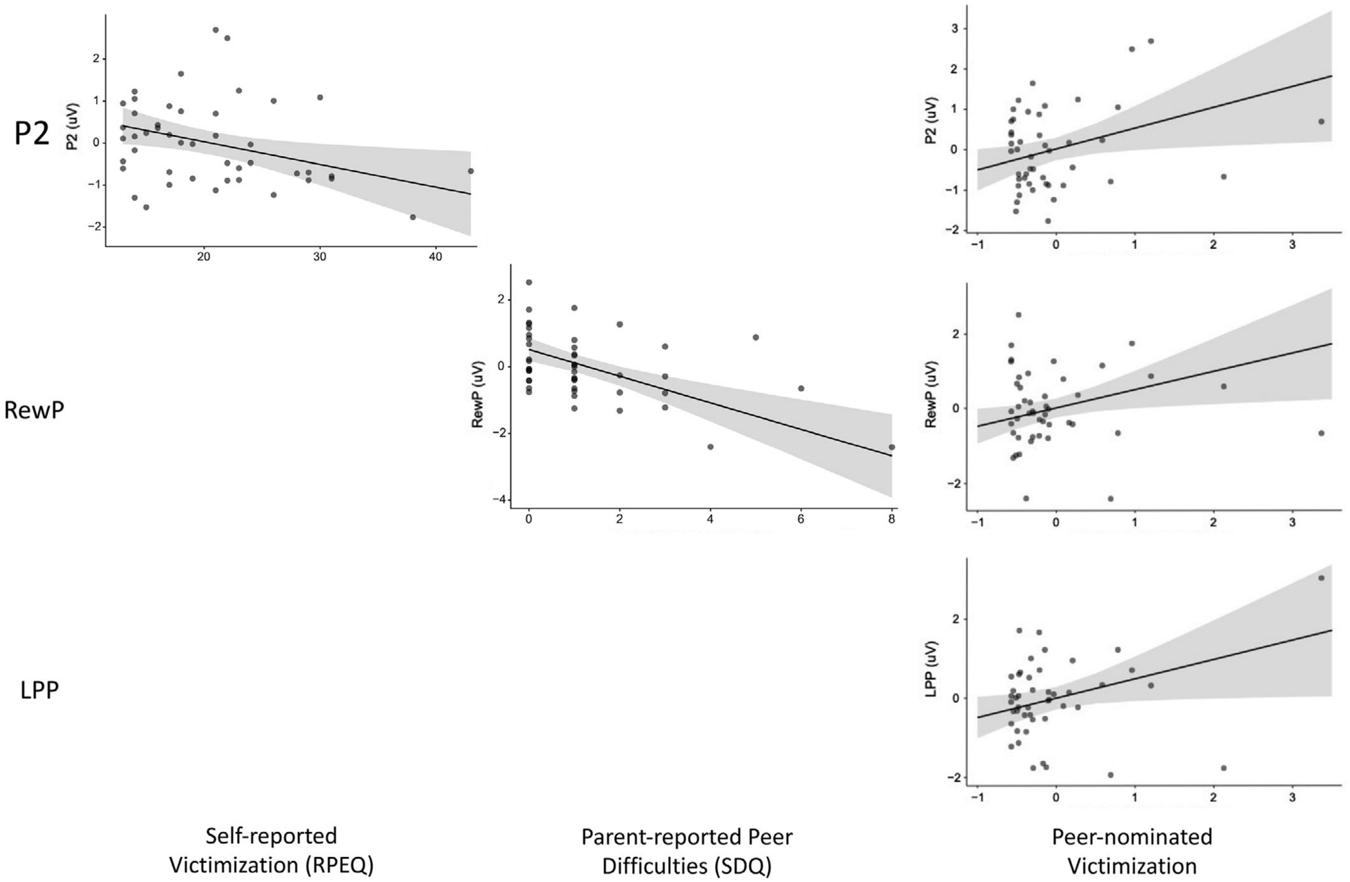

FIGURE 2 Predicted values (black line with gray confidence interval) of ERPs from the regression models, overlaid on actual values. Only significant regression effects from Table 3 are plotted. Note: All variables were screened for statistical outliers, and none were identified

rejection-sensitive N1 was not significantly associated with any measure of peer stress.

4 | DISCUSSION

The goal of this study was to identify associations between neural responses reflecting distinct stages of social information processing, namely the N1, P2, RewP, and LPP, and multiple measures of peer stress in early adolescents. Although different informant reports of peer stress were positively associated with one another, we did not observe strong correlations between the ERP measures. This is consistent with the social information processing network model, which argues that processing social stimuli involves sequential, and interactive, but separate steps (Nelson et al., 2005), which can be linked temporally to different ERPs. Moreover, in these data, we observed associations between peer victimization and the magnitudes of the P2, RewP, and LPP, ERP components that reflect distinct steps of social information processing. Our data therefore suggest that experiences of social stress or negative experiences with peers are associated with variation in multiple social processing steps—each with potentially different functional outcomes for these adolescents.

4.1 | RewP and peer stress

Regarding the RewP, consistent with previous investigations (e.g., Rappaport et al., 2019), a blunted RewP to positive feedback from peers was associated with greater peer difficulties as reported by parents. In previous research, a blunted RewP to social reward in the Island Getaway task has also been found in early adolescents with greater depressive symptoms (Kujawa et al., 2017), as well as in adolescents at increased *risk* for depression (Freeman et al., 2022). Future work might therefore explore whether this blunted RewP mediates between experiences of interpersonal stress with peers and subsequent risk for depression, and if social support might be a protective buffer against the effects of peer victimization on the development of depression.

However, this causal association cannot be assumed in these cross-sectional data. It is also possible that adolescents with a blunted RewP engage in more maladaptive behaviors and elicit more negative responses from others. For instance, the RewP has been linked to behavior in the Island Getaway task, such that a smaller RewP is associated with a decreased tendency to make behavioral adjustments following feedback from peers (Weinberg et al., 2020). This suggests that neural responses to social feedback can guide social behaviors. Mackin et al. (2019) also found that a blunted RewP prospectively predicted increased life stress, and particularly increased *dependent* life stress, or life stress to which the individual contributes. It is possible that individuals with a blunted RewP have greater difficulties in adapting social behavior in real-world interactions, resulting in greater conflict with others, or more negative perceptions from peers. Our measure of parent-reported peer difficulties might have tapped into this aspect of social stress, as this SDQ scale captures not just experiences of victimization and/or exclusion, as our other measures do, but also elements of behavior and interactions with others, such as getting along with adults better than peers. Future studies will be necessary to fully explore these questions.

4.2 | P2, N1, and LPP associations with peer stress

As with the RewP, greater self-reported peer victimization was associated with a smaller P2 to acceptance. As the P2 is also a reward-sensitive component, these data suggest that peer stress may have blunting effects on multiple indices of social reward sensitivity. It may therefore be the case that the stress of these negative peer interactions has broader and more potent effects on processing aspects of peer feedback related to reward than other elements of social information processing. The P2 and RewP were also only modestly, and not significantly, correlated with one another in this sample, suggesting that they capture distinct aspects of social reward processing. If this is the case, future studies might fruitfully examine the RewP and P2 together as potential mediators on a pathway from stress to affective disturbance (e.g., Ethridge et al., 2020), or behaviors that result in social dysfunction (e.g., Mackin et al., 2019; Weinberg et al., 2020). However, it is important to note that although the P2 association with peer stress was significant, the effect size was smaller than we were powered to detect, and we should cautiously interpret this finding. That said, this early-stage discovery may still be useful in examining developmental pathways from peer stress to later adverse outcomes.

N1 amplitudes following rejection feedback were not significantly associated with the degree of peer stress participants reported, suggesting that a history of heightened interpersonal stress is not strongly related with the increase in very early allocation of attentional resources to rejection cues, at least at this developmental stage. One possibility, therefore, is that peer stress may have relatively specific effects on later, but not very early, indices of attention to peer feedback. However, our sample was still relatively young, and future prospective studies might examine whether the associations between peer stress and the ERP components studied here might change over time. In particular, given evidence that there is substantial continuity in peer stress over time and across development (Brendgen et al., 2016; De Los Reyes & Prinstein, 2004), it is possible that ongoing experiences of peer stress might result in heightened N1 amplitudes in adulthood (e.g., Qi, Gao & Liu, 2018; Shackman et al., 2011). It is also possible that the brain networks that generate the N1 are more susceptible to the effects of early life stress (e.g., Kujawa et al., 2020), and not stress in adolescence, again indicating the need for careful developmental and prospective studies to understand the effects of peer stress on brain functioning.

Contrary to our expectations, not all measures of peer stress predicted the RewP and together did not account for more overall variance in the RewP, suggesting that the different measures of stress captured different constructs. Additionally, we found that peer-nominated peer victimization, unlike parent- or self-report, exhibited *positive* associations with the P2, RewP, and LPP. These latter effects were in the opposite direction of what we might have expected, and were smaller than we were powered to detect with confidence, and so again should be interpreted with caution. However, one possible explanation for the differences that we observed was that self-reported victimization captures personal, dyadic interactions (Card & Hodges, 2008; De Los Reyes & Prinstein, 2004), whereas peer-reported victimization captures public victimization. Thus, those with higher peer-nominated victimization scores might find peer acceptance in a group setting more novel, and therefore more salient. The larger ERPs we observe in this sample in response to virtual peer acceptance might then be related to these individuals having experienced less social acceptance than their peers. However, we did not measure the frequency with which our participants experienced positive overtures from peers, and so future studies will have to examine this possibility further.

4.3 | Comparison between different informants

This unexpected finding further suggests that peer stress as reported by different informants captures unique aspects of social interaction. Differences in informants were borne out in our data as well, in that the correlations between peer stress measures were positive but modest in magnitude, similar to previous findings (Branson & Cornell, 2009; Pouwels et al., 2016). As mentioned above, the parent-reported measure of peer difficulties assessed a broader construct than the self-reported and peer-nominated measures of peer stress, which focused only on peer victimization, and this may explain some of the difference between informants. That said, we also propose two additional possible explanations: first, the difference between reports might be dependent on the access to information that different informants have. Peer-nominated peer victimization might differ from the other measures in the salience of the forms of victimization it captures. For instance, more subtle experiences of victimization such as exclusion or cyberbullying might be more likely to go unnoticed by peers and are less likely to be factored into the peer-nominated reports (Card & Hodges, 2008; Crick & Bigbee, 1998), whereas self- and parent-report would be more likely to capture this. Peer-reports are typically more strongly associated with visible problematic social adjustment (Bouman et al., 2012), which may include aggressive experiences such as teasing, name-calling, or hitting, whereas self-reports are strongly associated with internalizing symptoms that may be easier to hide (Brendgan et al., 2016).

Second, differences between reports also appear to be dependent on the interpretation of social information. Peer-nominated peer victimization can provide another insight into an individual's social networks as peers become more prominent in these networks (Steinberg

& Morris, 2001). For example, adolescents with impoverished networks may be less adept at perceiving social processes and regulating behavior in social contexts (Nelson et al., 2005). This aspect of social functioning might be absent in an adolescent's self-report if the adolescent is not cognizant of their victimized status. That is, some adolescents consider victimization experiences humorous and self-report low victimization scores, whereas others may perceive bullying from ambiguous peer interactions, consequently self-reporting higher victimization scores (e.g., Card & Hodges, 2008; Juvonen et al., 2001). Peer-report thus reflects a unique interpretation of social interactions that can differ from self- and parent-reports.

Thus, although it is possible that the findings reported here regarding peer-nominated peer victimization and effects on ERPs are an anomaly, it is also possible that this measure is instead capturing a particular aspect of adolescent social connections. There is utility in analyzing measures from multiple informants that target distinct constructs, especially in adolescent samples looking at social interaction. Further studies should investigate how individual differences in interpretation of peer experience can affect neural responses to social information, which then shape the risk for internalizing disorders.

4.4 | Limitations

Limitations of the present study suggest avenues for future studies. For instance, our majority white sample likely does not fully represent real-world social acceptance and rejection experiences of racial and ethnic minorities (Paulus & Wentura, 2014, 2018). Coupled with our relatively small sample size, we should therefore be careful in generalizing these results. Additionally, our operationalization of the ERP measures involved isolating variance unique to neural responses to acceptance, controlling for neural response to rejection (or vice-versa). Our results show some blunted ERPs in response to acceptance, but conceptually this refers to the difference in acceptance and rejection conditions, not a change from a neutral baseline. A no-feedback condition might be a useful comparison for the acceptance and rejection conditions, as both acceptance and rejection feedback can elicit an active neural response (Guyer et al., 2016; Masten et al., 2012; Somerville et al., 2013). However, results of previous research using the Island Getaway task with a neutral condition suggest that ambiguous social feedback can be interpreted as rejection, and that the RewP and the LPP are also sensitive to this "neutral" feedback (Funkhouser et al., 2019). Thus, future studies should focus efforts on identifying a true "neutral" social feedback condition in order to better understand the processes at play.

4.5 | Conclusion

Our findings indicate that the experience of peer stressors such as victimization in early adolescence is associated most strongly with reward-related processes, but also shows potential associations with multiple stages of processing. This emphasizes the need to look beyond just reward-related processes and instead look more broadly at how neural markers of multiple steps of social information processing might be altered by social stress in adolescence. More importantly, our work highlights the importance of obtaining information from *multiple* sources to examine relationships between social functioning and social information processing. Thus, our research supports further investigation of how social stress might get "under the skin" to influence future social functioning and affective outcomes.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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