Title

Reward-related neural activity and adolescent antisocial behavior in a community sample

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Abstract

Behavioral research has found evidence supporting reward dominance in adolescence with externalizing disorders, but findings from neuroimaging studies have been largely heterogeneous. We examined the Feedback-Related Negativity (FRN) and P3b in relation to self-reported externalizing behavior amongst seventy-eight adolescents (11-18 yrs.) during a monetary gambling task with concurrent high-density EEG. As expected, the P3b and the FRN demonstrated greater evoked activity to reward and punishment, respectively. Further, high externalizing behavior was associated with greater P3b difference and reduced FRN difference in response to reward and punishment, suggesting that externalizing behaviors may be associated with both reward dominance and reduced feedback-monitoring.

Adolescence is a key period in development characterized by major changes in youth’s social, emotional, and cognitive functioning, and concurrent alterations in underlying brain structure and function; it also coincides with well-documented increases in harmful risk-taking and antisocial behaviors (Steinberg, 2008). An important aim of neuroscience research is to understand the unfolding connections between developmental changes in antisocial behavior and underlying changes in brain function during this period. Increasingly, researchers have focused on learning and decision-making processes in an attempt to understand the mechanisms involved in adolescent risk-taking and antisocial behavior, and specifically the role of reward. Several authors suggest that the increases in antisocial behavior observed during the adolescence may be related to heightened reward sensitivity (e.g. Quay, 1993).

Several neural systems have been implicated in reward processing, particularly dopamine projections from midbrain structures to frontal striatal areas (Haber & Knutson, 2010). Meta analytic work has found activation in response to reward feedback cues in multiple brain regions (Liu, Hairston, Schrier, & Fan, 2011), including the bilateral nucleus accumbens (NAcc), medial orbitofrontal cortex (OFC), pregenual cingulate cortex, posterior cingulate cortex (PCC), anterior cingulate cortex (ACC). Furthermore, ventral striatum/NAcc BOLD responses, probably mediated by phasic dopamine activity, appear to act as an error signaling system involved in learning processes governed by reward-punishment (Pagnoni, Zink, Montague, & Berns, 2002).

Extensive behavioral research indicates that adolescents are prone to reward-driven behavior and choices, consistent with the idea of reward dominance in adolescence (Steinberg, 2008). For example, Smith, Xiao, and Bechara (2012) found that participants in early to mid-adolescence performed worse on the Iowa Gambling Task compared to adults. Whilst selecting cards from four decks, they favored those with a high reward/high punishment ratio, resulting in overall net loss on the task. Neuroimaging studies also find evidence for reward hypersensitivity in adolescents, with greater activation in the nucleus accumbens for adolescents relative to young adults during a passive slot machine task (e.g. van Leijenhorst et al., 2010). However, research findings concerning the role of reward-related neural systems in antisocial behavior are less clear. While several studies suggest heightened reward sensitivity in adults presenting with severe antisocial behavior (e.g. Brunelle, Douglas, Pihl, & Stewart, 2009), findings in adolescents characterised by high levels of externalizing behavior are less consistent. Previous work has yielded a heterogeneous set of findings. In existing research studies brain regions differentially activated by reward tasks in externalizing adolescents, relative to controls, include the caudate (Finger et al., 2008), the ACC (Bjork, Chen, Smith, & Hommer, 2010), the OFC (Rubia et al., 2009), the ventromedial prefrontal cortex (vmPFC; Finger et al., 2008), and the VS (Bjork et al., 2010). Moreover, the direction of reward responses (heightened or reduced BOLD signal in externalizing adolescents) is inconsistent across studies. This may reflect subtle differences in sample characteristics, varying between ‘pure’ Conduct Disorder, Conduct Disorder comorbid with ADHD or psychopathic/callous-unemotional traits, and Antisocial Substance Disorder. Mixed findings regarding the neural systems differentially engaged in reward tasks among antisocial adolescents may also reflect the diverse range of tasks employed to elicit reward-related neural activity.

The majority of neuroimaging work investigating the relationship between externalizing behavior and feedback processing in adolescence has relied on fMRI. Whilst ideal for spatial localisation, the low temporal resolution of fMRI cannot readily detect rapid, short-term neuronal responses to feedback cues, thus potentially blurring distinct phases of feedback processing, such as cue-processing, task-related contextual encoding, learning and outcome evaluation. Event-related potentials (ERPs), with their high temporal resolution, represent an attractive methodology for investigating neural activity related to the processing of feedback cues. A large literature identifying ERP components related to feedback response already exists (e.g. Crowley et al., 2009; Crowley et al., 2013).

Previous ERP studies have isolated two event-related components linked to the processing of feedback cues, the Feedback-Related Negativity (FRN) and the P3b. The FRN is a negative inflection in the ERP waveform occurring approximately 300ms after feedback presentation apparent in the medio-frontral electrode sites. The FRN is typically greater in amplitude (i.e., more negative) for cues signaling non-reward or punishment, rather than reward, and therefore the FRN may primarily reflect the activity of a reward-loss monitoring or classification system, similar to that indexed by the Error-Related Negativity (ERN; Holroyd & Cole, 2002). Notably, concurrent fMRI-EEG work by Hauser et al. (2014) suggests the FRN originates from the ACC, the source typically associated with the ERN (Gehring & Willoughby, 2002). Alternatively, it has been suggested that the FRN may index reward prediction error (Holroyd & Coles, 2002). However, the FRN is not influenced consistently by reward magnitude (e.g. Hajcak, Moser, Holroyd, & Simons, 2006; for an exception see Wu & Zhou, 2009), and Talmi, Fuentemilla, Litvak, Duzel, and Dolan (2012) found that FRN response does not conform to all axioms of reward prediction error signals. Therefore, while the FRN is a consistent neural signal related to reward processing, the precise neural processes or computations it reflects (outcome monitoring versus reward prediction error) remain to be fully resolved.

The feedback-P3b is a positive inflection located in centroparietal channels, typically occurring between 300 and 600 milliseconds after feedback. Previous work indicates that the P3b is larger (more positive) in amplitude for rewards than for punishments, and is sensitive to the magnitude of the feedback (Wu & Zhou, 2009). The P3b is thought to reflect evaluative processes related to the appraised motivational significance of the outcome (Wu & Zhou, 2009). Its greater amplitude for reward than loss feedback suggests a specific role in approach motivation or the appraisal of positive reward value (Wu & Zhou, 2009). Moreover, the P3b has been localized to dipoles in the posterior cingulate cortex (Luu, Shane, Pratt, & Tucker, 2009), an area associated with, among other things, subjective valuation of reward (Rushworth & Behrens, 2008).

Relatively few developmentally-focused studies have investigated reward-related ERPs in childhood and adolescence in general, or specifically in relation to externalizing behavior. However, existing evidence indicates that FRN amplitude decreases from childhood to adulthood (Hammerer, Li, Muller, & Lindenberger, 2011) and shows reduced (though still significant) differentiation between gains and losses in children compared to adolescents and adults (Hammerer et al., 2011). Crowley et al. (2013) examined the FRN in a monetary reward task in a sample of early (10-12 years), mid-(13-14 years) and late-(15-17 years) adolescents and found that FRN amplitudes decreased with age even within the adolescent period, although differences between win and lose conditions did not vary by age. Recent data also indirectly suggest that externalizing behavior in adolescence may be associated with differences in the FRN. Segalowitz et al. (2012) observed reduced FRN activity in adolescent boys self-rated as high on approach motivation (Surgency - sensation seeking, positive affect, and behavioral approach) when presented with negative feedback in a peer interaction task. However, this study did not include a reward condition, leaving open the question of whether the findings reflect reduced sensitivity to punishment versus reward or a more general insensitivity to feedback. Similarly, Crowley et al. (2009) measured FRN responses in a sample of 32 high risk adolescents (fetal cocaine and other drug exposure) who were screened for high or low risk taking behaviorusing an experimental task. They found that males who were characterised behaviorally as high risk-takers on the BART demonstrated smaller differences in FRN amplitudes to reward versus loss relative to males who were low risk takers, but only when feedback was presented after a short (1-second) delay and not after a longer (2-second) delay.

As Nieuwenhuis, Slagter, Alting von Geusau, Heslenfeld, and Holroyd (2005) have suggested that increasing feedback delay may diminish the motivational significant of feedback, Crowley et al's (2009) results indicate that motivational imbalance resulting in reward dominance is reduced with increasing feedback delay. Together, these studies suggest that approach motivation/risk-taking proclivity is associated with reduced FRN response, we might expect that individuals with externalizing problems, who also commonly show these traits, would also show reduced FRN responses to punishment (relative to rewards), and this effect will be increased in response to more immediate, motivationally significant feedback. Thus, while conceptual grounds for investigating the FRN as a candidate neural marker of risk for externalizing psychopathology in adolescence are strong, few studies have done so.

To date, only one study has addressed P3b response to reward cues in relation to externalizing behaviors in young adults. Bernat, Nelson, Stelle, Gehring, and Patrick (2011) found that externalizing behavior was associated with reduced P3b amplitudes to feedback cues in a gambling task, and also found a tendency for high externalizers to show reduced P3b response to reward compared to punishment. However, in this study feedback was presented 100ms after participant response, which is an unusually short period between choice and outcome. As previous work in other areas suggests that pre-stimulus EEG influences the P3 response through attentional mechanisms (Polich, 2007), and that activity in the anticipatory, pre-stimulus period affects P3b response (e.g.,van der Molan et al., 2013), this very brief pre-stimulus period may have affected these results.

The current study examined the FRN and P3b response in relation to normative individual differences in adolescent externalizing problems. Previous work suggests that adolescents with externalizing-relevant traits (approach motivation, risk-taking) demonstrate reduced responsivity to punishment when measured by the FRN (Crowley et al., 2009). Thus, we expected to observe reduced FRN amplitudes for cues signaling loss relative to those signaling reward among adolescents with higher self-reported externalizing behavior scores. Similarly, we tested the hypothesis that P3b amplitude would differ based on participants' externalizing scores, reflecting differences in the motivational significance ascribed to rewards and punishments. Further, as Crowley et al. (2009) found that adolescents with higher levels of externalizing related traits, such as approach motivation, demonstrated smaller differences between reward and punishment FRN response, we expected to see differences in FRN amplitude between high and low externalising participants, when feedback is presented after a short delay but not after a long delay. Finally, we examined the extent to which these components change developmentally across adolescence, and whether age differences in these ERP components mirror normative trends in adolescent externalizing behavior.

Methods

Participants

105 participants (52 female) recruited from local high schools participated in the Adolescent Thoughts and Feelings Project (ATFP). 82 participants provided sufficient ERP data for analysis, 78 of whom had data on externalizing behavior. Participants ranged in age from 11 to 18 years old (mean age = 14.5 years, S.D = 1.7). They were considered eligible to participate if they had normal, or corrected to normal, vision, English fluency, had no difficulty using their hands, had no latex or shampoo allergies, and they didn't have a hair style that would impede EEG measurement. Participants were excluded if they had a history of, or were currently being treated for, traumatic brain injury, epilepsy, seizures, alcohol/drug abuse, or hallucinations. Participants younger than 16 gave signed assent, whilst parents gave informed consent. This study was approved by the UCL Graduate School Ethics Committee (application number: 1908/001).

Procedure

The study session comprised of a series of neurocognitive and behavioral assessments, taking a total of 3 hours. Participants performed a battery of four tasks, the “Money Maker” being the second task the participants completed. They also completed a battery of online self-report questionnaires to ascertain clinical, personality, and demographic information.

Money Maker Task

This is a reward-feedback gambling task based upon the Balloon Context Task reported in Crowley et al. (2009). The task was displayed using E-prime v.2.0 software (PST, Inc.). Participants were presented with four differently colored balloon images randomly appearing in one of four positions along a row centred on the screen. The aim of the task was to select one balloon to win virtual monetary rewards that were later converted into performance-based remuneration in addition to £20 for participation. Participants selected the balloon that they thought would represent a reward via a 4-option response pad. At the end of each trial, participants either saw a green Pound sign (a 25 pence reward) or a red cross (a 25 pence loss). Prior to stimulus presentation, participants saw a fixation cross for 500ms followed by a blank for 500ms. Stimuli were then presented for up to 2000ms in which the participant could make their response. After participants made their response, feedback was delayed for either 1000ms for the short delay interval, or a 1400-2200ms delay period for the long delay interval, in which a blank screen was presented. Feedback was then displayed for 800ms. Participants waited 700ms before the next trial began. Every 50 trials the colours of the balloons changed.

Participants played a total of 140 trials evenly split between the four conditions (reward – short delay; reward – long delay; punishment – short delay; punishment – long delay), and outcomes were random so that no pattern between a specific balloon and an outcome could be established. As part of the instructions, participants were led to believe that for some people it was possible to “figure out a pattern some of the time”. Earnings were displayed at the bottom of the screen during the task, and were summarised at the end of each block. Overall, the task comprised four blocks of trials, each consisting of 35 trials. Each block started with 10 to 12 practice trials, 75% of which were wins to insure participants always had a winning balance.

Experimental Procedure

After obtaining informed consent, participants were seated 24 inches in front of a 17-inch LCD monitor. After measuring head circumference and determining the vertex (Cz) as a midway point between the nasion and inion, and the two preauricular notches, a Hydrocel high-density 128 Ag/AgCl electrode net (Geodesic Sensor Net, EGI Inc.) was soaked in a solution of potassium chloride (KCl; to act as an electrolyte) and baby shampoo (to break up grease on the scalp) and placed on the participant's head. ERP data was collected using the Netstation v.4.4.2 software package (EGI, Inc.) and EGI high impedance amplifiers, sampling at 250 Hz (EGI, Inc. Series 300 amplifier), and timings were adjusted to compensate for EGI online filters for this sampling rate-amplifier pairing. Data was recorded with online bandpass filters set at .1-100 Hz. Impedances for all electrodes remained below 70 KΩ as measured by the Netstation inbuilt impedance tool prior to and after the task.

Externalizing Questionnaire:

Participants completed a shortened version of the Externalizing Disorder Inventory (EDI, Krueger et al., 2002) comprising 46 items covering scales for physical, destructive, and interpersonal aggression, rebelliousness, theft, alcohol use, drug use, cannabis use, and honesty. Cronbach's alpha for the total scale was acceptable (α=.79). The total scale in the shortened version correlated r = 0.97 with the total from the original scale based on data provided by the EDI authors. Participants' externalizing score was calculated as the sum of all items. Participants were included in the final analysis if they answered at least 80% of all items. Final analyses were carried out on 78 participants.

ERP Pre-processing

Data filtering and epoching was performed in NetStation before being exported to EEGLAB (Delorme & Makeig, 2004). EEG data was filtered offline using a 0.3-40Hz band-pass filter. Data was then segmented around the feedback event using a 100 millisecond pre-stimulus and a 600 millisecond post-stimulus window. Channels were considered bad if their average variation in amplitude was greater than 3 standard deviations around the median of all electrodes, and were then interpolated using EEGLABs spherical interpolation method (Delorme & Makeig, 2004). All marked channels were visually inspected and verified before interpolation. Trials containing more than 10 marked channels were rejected. Blinks were identified using a template-based correlative method, in which a stereotyped blink was selected from each individual data case. Using a moving window of 80ms, any trial in which an eye channel demonstrated greater than a .97 correlation with the template led to the trial being marked as a blink, and following visual inspection, was rejected. Artifact rejection was performed by eye due to non-stereotypical noise in some data files, which was not adequately picked up by automated methods. To check for consistency of manual artifact detection, 20 cases were independently checked for artifact by another researcher, yielding a 79% concordance rate ($\kappa = 0.82$). Participants with greater than 15 trials in each condition were included in the statistical analysis ($n = 82$). After artifact rejection, the average number of trials per condition were: Win, short delay = 28 trials (S.D. = 5.0); Win, long delay = 27 trials (S.D. = 5.4); Lose, short delay = 25 trials (S.D. = 5.1); Lose, long delay = 27 trials (S.D. = 5.7). Epochs underwent baseline correction using the 100ms pre-stimulus period, then data was re-referenced from the vertex (Cz) to the average of all electrodes.

As past research has localised the FRN to frontal-midline regions, we chose a cluster of five electrodes positioned frontally around the midline (Luu et al., 2009). These were electrodes 11 (Fz), 15, 16 (FPz), 10 and 18 (see fig 1. inset). We defined the FRN as the most negative peak amplitude between 200 and 350 milliseconds, taking the mean of all values 16ms either side. Previous research has localised the P3b to parietal midline sites, so we chose a cluster of 8 electrodes centred on Pz. These electrodes were 62 (Pz), 61, 67, 78, 72, 77, 54 and 79 (see fig 1. inset). The P3b was considered to be the most positive amplitude occurring in the 220 to 370 milliseconds after stimulus presentation, and the amplitude value was the mean value from 16ms either side of the peak.

Statistical Analysis

Analysis were conducted using mixed-effects models via the STATA 13 statistical package (StataCorp, LP) xtmixed function. Valence (reward or punishment) and delay (short or long) were within subjects effects, with reward and short delay used a reference points for comparisons. Gender was a factor variable with males used as the reference group. However, as gender did not correlate with externalizing behavior, and demonstrated no significant main or interaction effects on either ERP amplitude, it was dropped from further analysis. Both age and externalizing behavior were centred and treated as continuous variables. Participant ID was treated as a random effect. For plotting purposes, age and externalizing groups were created using a median split. However, these were only used for ERP plots, and not for analysis.

For interaction terms including a continuous predictor, post-estimation tests of marginal effects were examined, taken at one standard deviation above and below the means of any continuous variables. Ten participants were 1 S.D. above the mean and 7 were 1 S.D. below the mean for externalising behaviour, and 16 were 1 S.D. above the mean and 12 were 1 S.D. below the mean for age. Post-estimation test produced chi-squared results, which were then rescaled to t-statistics to aid comparisons with past literature.

Results

The results are separated into three sections: associations between externalizing behavior, age and gender; FRN analysis (table 1); and P3b analysis (table 2).

Similar to previous work, topographical maps revealed activity over frontal sites around 200-250ms after feedback and activity over parietal sites 250-350ms after feedback, consistent with the FRN and P3b, respectively (fig. 1).

Externalizing behavior

Pearson correlations indicated that there were no significant associations between age and externalizing score ($r = 0.17$, $p > 0.05$) or gender and externalizing score ($r = -0.12$, $p > 0.05$).

Feedback-Related Negativity (FRN)

Within subjects effects: There was a significant effect of feedback valence on FRN amplitude ($b = -1.07$, S.E. $b = 0.34$, $z = -3.15$, $p = 0.002$; fig. 1), with a more negative FRN amplitude in response to punishment than reward (-6.01μV vs. -4.63μV). However, no other effects reached significance (*p*’s > 0.05).

Between subjects effects: There were no significant main effects of age ($b = 0.32$, S.E. $b = 0.24$, $z = 1.34$, $p = 0.18$) or externalizing behavior ($b = -0.02$, S.E. $b = 0.02$, $z = -1.20$, $p = 0.23$) on FRN amplitude.

Interaction effects: There was a significant interaction between valence and externalizing score ($b = -0.05$, S.E. $b = 0.14$, $z = 3.23$, $p = 0.001$; fig. 2). Post-estimation t-tests showed a significant difference in the FRN between reward and punishment in low (-1 S.D.) externalizers (t (73) = 5.35, $p < 0.001$, $d = 0.66$), with larger FRN amplitudes seen in response to punishment (-6.55μV, S.E = 0.49) compared to reward (-4.74μV, S.E = 0.49). However, high (+1 S.D.) externalizers did not demonstrate this difference (t (73) = 1.31, $p = 0.19$, $d = 0.18$), with similar amplitudes to punishment and reward (-5.52μV, S.E = 0.52 vs. -5.06μV, S.E = 0.52). Visual inspection of the ERP suggests that this is driven by an attenuated FRN response to punishment amongst the high externalizers compared to the low externalizers. Correlations between evoked FRN amplitudes and participant externalising score for reward and punishment stimuli indicate a trend-level relationship between externalising behaviour and FRN response to punishment ($r = 0.21$, $p = 0.07$), but not reward ($r = 0.02$, $p = 0.82$).

There was also a significant valence by age interaction ($b = -0.52$, S.E. $b = 0.21$, $z = -2.53$, $p = 0.01$). Older participants demonstrated a significant difference between valence conditions (t (73) = 5.20, $p < 0.001$, $d = 0.64$), with greater FRN response to punishment (-6.10μV, S.E = 0.49) than reward (-4.36μV, S.E = 0.49). Younger participants did not demonstrate this difference (punishment = -5.97μV, S.E = 0.54, reward = -5.50μV, S.E = 0.54; t (73) = 1.28, $p = 0.20$, $d = 0.18$).

Finally, there was a significant three-way interaction effect between valence, delay and externalizing behavior ($b = -0.04$, S.E. $b = 0.02$, $z = -1.95$, $p = 0.05$). Post estimation tests demonstrated that both low externalizers (punishment = -6.68μV, S.E = 0.54, reward = -5.34μV, S.E = 0.54; t (73) = 2.80, $p = 0.005$, $d = 0.49$) and high externalizers (punishment = -6.01μV, S.E = 0.58, reward = -5.03μV, S.E = 0.58; t (73) = 1.94, $p = 0.05$, $d = 0.36$) demonstrated a significant valence effect when feedback was presented after a long delay. After a short delay, the low externalizing participants showed a significant difference between valence conditions (punishment = -6.42μV, S.E = 0.54, reward = -4.15μV, S.E = 0.54; t (73) = 4.78, $p < 0.001$, $d = 0.83$), whereas the high externalizers did not (punishment = -5.05μV, S.E = 0.58, reward = -5.09μV, S.E = 0.58; t (73) = 0.1, $p = 0.94$ $d = 0.01$). All other interaction effects were non-significant (p values > 0.05).

P3b

Within subjects effects: There were significant main effects of valence ($b = -0.73$, S.E. $b = 0.30$, $z = -2.40$, $p = 0.02$; fig. 1) and delay ($b = 1.40$, S.E. $b = 0.30$, $z = 4.61$, $p < 0.001$) on

P3b amplitude. Larger P3b amplitudes were seen in response to reward (8.60μV) compared to punishment (7.96μV), and after long delays (8.96μV) compared to short delays (7.96μV).

Between subjects effects: Neither the main effect of age ($b = 0.02$, S.E. $b = 0.28$, $z = 0.08$, $p = 0.94$) nor externalizing behavior ($b = 0.01$, S.E. $b = 0.02$, $z = 0.62$, $p = 0.53$) reached significance.

Interaction effects: The interaction between valence and externalizing behavior was significant ($b = -0.03$, S.E. $b = 0.01$, $z = -2.23$, $p = 0.03$; fig. 2). Post-estimation comparisons of marginal means showed that high externalizers demonstrated a significant difference between reward and punishment (t (73) = 4.64, $p < 0.0001$, $d = 0.43$), whilst the low externalizers did not (t (73) = 0.56, $p = 0.58$, $d = 0.05$). High externalizers demonstrated a larger P3b response to reward (9.09μV, S.E = 0.63) than punishment (7.63μV, S.E = 0.63), an effect not seen in the low externalizers (reward: 8.56μV, S.E = 0.60, punishment: 8.40μV, S.E = 0.60). No other interaction terms reached significance (p values > 0.05).

Discussion

Adolescence is a period of development associated with maturation of reward circuitry in the brain, and significant increases in externalizing behavior. Despite the fact that several theories focus on reward sensitivity as a key mechanism in antisocial behavior (e.g. Quay, 1993), findings from previous neuroimaging studies investigating reward-related neural activity among adolescent externalizers have been mixed. In this study, adolescents from a community sample completed a monetary reward task with concurrent high-density EEG to assess two key ERP components related to reward processing, the FRN and the reward-related P3b. The relationship between these feedback evoked ERPs and self-reported externalizing scores was then investigated.

Consistent with previous ERP studies in adults (e.g. Wu & Zhou, 2009), both FRN and P3b amplitudes were influenced by feedback valence. As expected, greater amplitudes in the P3b and FRN were seen in response to reward and loss, respectively. The valence effects on these ERP components further reinforce their value as markers of reward processing in adolescence and therefore their potential as endophenotypes for externalizing problems at a pre-clinical level. While several studies have examined reward versus loss effects on the FRN in adolescence (Crowley et al., 2009; 2013), less work has done so in relation to the P3b. In that regard, our findings concerning the P3b were different to those observed by Crowley et al. (2009), who found larger P3b amplitudes for loss than reward, but were consistent with the majority of studies of reward and the P3b in adults (e.g., Wu & Zhou, 2009).

The primary aim of this study was to examine feedback-related neural responses linked to self-reported externalizing behavior problems in adolescence. Consistent with our expectations, both FRN and P3b amplitudes showed an interaction between externalizing behavior and feedback valence. In the FRN, adolescents scoring high on the externalizing measure demonstrated smaller differences in FRN amplitude between reward and punishment feedback. Visual inspection of the ERP data suggested that his was primarily due to reduced (more positive) FRN amplitudes to punishment feedback adolescents with high externalizing scores compared to those with low externalizing scores. The FRN is often considered to reflect error monitoring processes generated by the ACC. Thus, the reduced difference in FRN amplitude among those adolescents with relatively high externalizing behavior may indicate diminished error monitoring, particularly in response to punishment. An alternative interpretation of the FRN is that it reflects reward prediction errors generated by the ACC (Holroyd & Coles, 2002), though recent evidence suggests it may not display all the properties expected of a prediction error signal (Talmi et al., 2012). An alternative account suggested by the recent work of Talmi, Atkinson and El-Deredy (2013) is that the FRN reflects an unsigned prediction error, equivalent to expectation violation or surprise. The lack of differentiation between reward and punishment-evoked FRN response seen in our sample of high externalizing adolescents may therefore suggest that high externalizers fail to develop differential outcome expectations. Clearly, the precise mechanisms driving the FRN response and its role in externalizing behavior are important avenues for future research.

Notably, the interaction between valence and externalizing behavior in the FRN appeared only when feedback was presented after a short delay, with no interaction effect between valence and externalizing on FRN amplitude following a long delay. Past work investigating delay has been limited. Crowley et al. (2009) found that a 1-second delay period yielded greater FRN response than a 2 second delay regardless of feedback valence, consistent with Nieuwenhuis et al’s (2005) postulation of reduced motivational significance of feedback as time between action and feedback cue increases. Expanding on this, our results suggest that differences in error monitoring between the high and low externalizers exist, but are only apparent during a relatively brief window following a reward-related choice, with differences diminishing with increases in delay.

In contrast to the FRN, *larger* P3b amplitude differences between conditions were seen in participants with higher externalizing scores, with adolescents who scored highly on self-reported externalizing behavior showing larger P3b responses to reward than punishment, relative to those with low externalizing behavior scores. As the P3b is thought to reflect attentional effects associated with the motivational significance of stimuli during feedback tasks (Wu & Zhou, 2009), our results overall could be interpreted to suggest that the high externalizers demonstrated greater imbalance between the motivational significance of reward and punishment than their low externalizing counterparts, with greater significance attributed to reward.

Thus, our results seem to suggest that adolescents scoring highly on measures of externalizing behavior assign greater salience or motivational value to reward cues than their low-scoring counterparts (as evidenced by the P3b), consistent with reward dominance theories (Quay, 1993), but also show reduced outcome monitoring, particularly in relation to punishment. Our findings indicating that high externalizers produce less reliable error signals differentiating punishment and reward may have implications for how we understand the role of learning impairments in externalizing behavior. With that in mind, it is interesting to note that Cohen & Ranganath (2007) found that larger FRN amplitudes were associated with increased task-appropriate response switching during learning tasks; the reduced outcome monitoring we observed among high externalizing adolescents might thus lead us to expect these adolescents to show poorer reinforcement learning, similar to the weaker signal discrimination seen in those with higher externalizers scores compared to lower externalising scores observed by Endres, Rickert, Bogg, Lucas, and Finn (2011).

Two additional findings of interest emerged from our data. First, a valence by age interaction in the FRN indicated greater differences between punishment and reward ERP responses in older participants versus younger participants. As the FRN is generated in the ACC (Hauser et al., 2014), this difference between younger and older externalizers may reflect the development of frontal circuitry and related functional networks, that occur over adolescence. Developmental changes across adolescence may lead to more effective classification of reward and punishment feedback given the ACCs role in feedback processing (Holroyd et al., 2004) and error-driven learning (Brown & Braver, 2005).

Second, P3b amplitudes varied as a function of feedback delay. However, unlike previous FRN findings mentioned above, P3b amplitudes increased after long delays as opposed to short delays. As the P3b is thought to be generally related to attention and motivation (Polich, 2007), the greater response seen in our sample may be indicative of anticipatory or expectancy effects, where attention increases whilst waiting for feedback.

Limitations

This study should be considered in light of its limitations. First, while the shortened EDI demonstrated reasonable to good alpha values and correlations with its full-scale counterpart, it contains too few items per sub-scale to allow for meaningful statistical comparison at the sub-scale level. Given that presentation of externalizing behaviors differs between genders, sub-scale analysis would allow more precise investigation into gender differences in specific domains of externalizing problems and reward sensitivity. Future work using the full scale EDI could help elucidate differences between sub-samples. Additionally, the findings reported here concern externalizing behavior in a normative sample. Future work will need to examine feedback processing among youth with more severe antisocial behavior at clinical levels. Finally, whilst our results suggest that externalizers may demonstrate attenuated feedback monitoring processes, our findings only generalize to the type of chance-based task we used. Further work is needed investigating how externalizing youth may differ in FRN amplitude in a learning task.

Conclusions

In summary, our study supports theories of reward dominance in adolescents with high levels of externalizing behavior (e.g. Quay, 1993). Adolescent externalizers demonstrated greater motivational imbalance between reward and punishment, as measured by the P3b, than their low externalizing counterparts. Furthermore, high externalizers also demonstrated reduced differences between reward and punishment response in the FRN, indicative of a reduced prediction error response or reduced outcome monitoring, which may lead to poorer learning from feedback.

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Table 1. Results from the mixed effects model regressing FRN amplitude (μV) back on feedback valence, delay, participant age, and externalizing activity, as well as all higher-order interactions. Reward and short delay were used as the baseline conditions.

FRN **Wald $\chi^2(15) = 54.14$, $p<0.00001$**

Predictor	b	S.E. b	*z*	*p*
Valence	**-1.07**	**0.34**	**-3.15**	**0.002**
Delay	-0.57	0.34	-1.68	0.09
Age	0.32	0.24	1.34	0.18
Externalizing	-0.02	0.02	-1.20	0.23
Valence * Delay	-0.07	0.48	-0.14	0.89
Valence * Age	**-0.52**	**0.21**	**-2.53**	**0.01**
Delay * Age	0.0002	0.21	0.001	0.99
Valence * Externalizing	**0.05**	**0.14**	**3.23**	**0.001**
Delay * Externalizing	0.03	0.01	1.74	0.08
Age * Externalizing	0.02	0.01	1.62	0.11
Valence * Delay * Age	0.32	0.29	1.10	0.27
Valence * Delay * Externalizing	**-0.04**	**0.02**	**-1.95**	**0.05**
Valence * Age * Externalizing	0.002	0.01	0.20	0.84
Delay * Age * Externalizing	-0.001	0.01	-0.10	0.92
Valence * Delay * Age * Externalizing	0.004	0.01	0.37	0.71

Random Effects	Estimate	S.E.	95% Confidence Interval	
ID	2.72	0.25	2.27	3.26

Table 2. Results from the mixed effects model regressing P3b amplitude (µV) back on feedback valence, delay, participant age, and externalizing behavior, with all higher-order interaction terms. Reward and short delay were used as the baseline conditions.

P3b **Wald $\chi^2(15) = 70.29$, $p<0.00001$**

Predictor	b	S.E. b	*z*	*p*
Valence	**-0.73**	**0.30**	**-2.40**	**0.02**
Delay	**1.40**	**0.30**	**4.61**	**0.0001**
Age	0.02	0.28	0.08	0.94
Externalizing	0.01	0.02	0.62	0.53
Valence * Delay	-0.23	0.43	-0.55	0.58
Valence * Age	0.27	0.18	1.45	0.15
Delay * Age	-0.26	0.18	-1.14	0.16
Valence * Externalizing	**-0.03**	**0.01**	**-2.23**	**0.03**
Delay * Externalizing	-0.001	0.01	-0.10	0.92
Age * Externalizing	-0.01	0.01	-1.10	0.27
Valence * Delay * Age	0.21	0.26	0.79	0.43
Valence * Delay * Externalizing	0.003	0.02	0.17	0.87
Valence * Age * Externalizing	0.01	0.01	0.99	0.33
Delay * Age * Externalizing	0.002	0.01	0.27	0.79
Valence * Delay * Age * Externalizing	0.01	0.01	0.62	0.53

Random Effects	Estimate	S.E.	95% Confidence Interval	
ID	3.54	0.31	2.99	4.19

Figure 1. Grand-Average Event Related Potentials waveforms for the Feedback-Related Negativity (FRN) and the P3b in response to reward and punishment stimuli. Grey area indicates the window of measurement. Sensor net layouts are inset with relevent electrode clusters highlighted in black. Also inset are topographic maps demonstrating scalp distribution at the grand average peak for the FRN (310ms) and the P3b (350ms) .

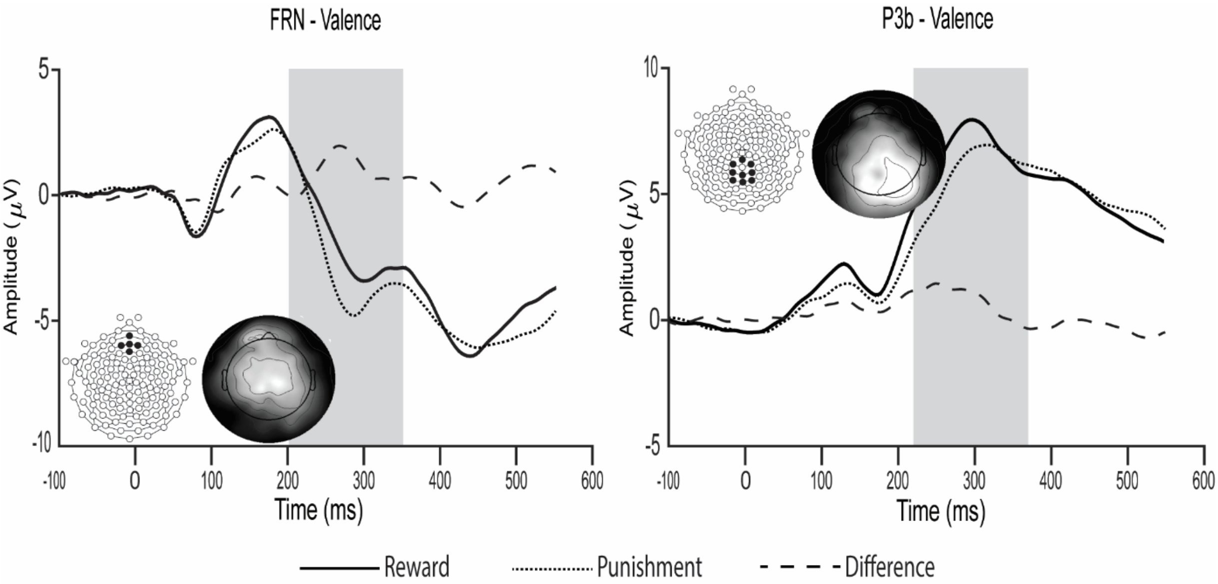

Figure 2. FRN (left) and P3b (right) in response to reward and punishment feedback, divided by externalizing group. Externalizing behavior was split based on the median. Grey area highlights the window of interest.