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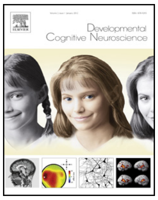

Social provocation modulates decision making and feedback processing: Examining the trajectory of development in adolescent participants

Hannah L. Pincham[a], Claire Wu[b], Clare Killikelly[c], Laura Vuillier[d], R.M. Pasco Fearon[a,e,*]

[a] Developmental Neuroscience Unit, Anna Freud Centre, UK
[b] Institute of Neurology, University College London, UK
[c] Institute of Psychiatry, Psychology and Neuroscience, King's College London, UK
[d] Department of Psychology, University of Cambridge, UK
[e] Research Department of Clinical, Educational and Health Psychology, University College London, UK

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ABSTRACT

Increasingly, research is turning to the ways in which social context impacts decision making and feedback processing in adolescents. The current study recorded electroencephalography to examine the trajectory of development across adolescence, with a focus on how social context impacts cognition and behaviour. To that end, younger (10–12 years) and older (14–16 years) adolescents played a modified Taylor Aggression Paradigm against two virtual opponents: a low-provoker and a high-provoker. During the task's decision phase (where participants select punishment for their opponent), we examined two event-related potentials: the N2 and the late positive potential (LPP). During the outcome phase (where participants experience win or loss feedback), we measured the feedback related negativity (FRN). Although N2 amplitudes did not vary with provocation, LPP amplitudes were enhanced under high provocation for the younger group, suggesting that emotional reactivity during the decision phase was heightened for early adolescents. During the outcome phase, the FRN was reduced following win outcomes under high provocation for both groups, suggesting that a highly provocative social opponent may influence the reward response. Collectively, the data argue that social context is an important factor modulating neural responses in adolescent behavioural and brain development.

1. Introduction

Adolescence is a period of major change, both behaviourally and emotionally (Blakemore and Mills, 2013; Blakemore and Robbins, 2012; Crone and Dahl, 2012). Although some aspects of cognitive and behavioural performance improve during adolescence, this period is also marked by impaired decision making and emotional dysregulation (Smith et al., 2012; Steinberg, 2008; Wahlstrom et al., 2010; Yurgelun-Todd, 2007). The apparent tension between the broad improvements observed for cognitive functioning and self-regulation from childhood to adolescence, and contrasting observations regarding affective control may be understood from several points of view. For example, adolescence may mark a period when cognitive functioning and emotional control are poorly integrated or out of step with each other developmentally (Casey et al., 2008; Steinberg, 2008). Alternatively, cognitive and affective performance during adolescence may be more contextually bound, particularly to the social context (Gardner and Steinberg, 2005). These two broad accounts are not mutually exclusive.

Recent research has begun to explore how social contexts shape adolescent decision making. In particular, the role of peer influence on cognitive and behavioural performance has been examined in a number of studies (Albert et al., 2013; Gardner and Steinberg, 2005). One domain that appears particularly prone to disruption by peer influence is feedback processing (Chein et al., 2011; Segalowitz et al., 2012). Despite a growing body of behavioural research, little is known about the neural processes that underpin socially-driven changes in cognition and behaviour throughout development, and in adolescence particularly. To that end, we employed electroencephalography (EEG) to examine the key neural processes associated with decision making and feedback processing during a competitive social task in younger (10–12 years) and older (14–16 years) adolescents. We aimed to reveal the trajectory of development across these two age groups.

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* Corresponding author.
E-mail address: p.fearon@ucl.ac.uk (R.M.P. Fearon).

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1.1. Feedback processing in adolescence

Feedback processing refers to the ability to evaluate, adapt and modify future behaviour based on certain outcomes (such as 'win' or 'loss' outcomes) (Ridderinkhof et al., 2004). Although feedback processing and feedback learning are vital for adaptive decision making (Banis et al., 2014), a number of studies indicate that adolescents make maladaptive decisions owing to deficient feedback processing. Specifically, adolescents are often reward dominant, and are biased towards reward-driven behaviour even when such behaviour is detrimental (Chein et al., 2011; Steinberg, 2008; Van Duijvenvoorde et al., 2008). Reward dominance refers to a motivational state characterized by increased approach behaviour, where individuals are hyper-responsive to personal rewards (see Gray, 1987; Quay, 1993). For example, Smith et al. (2012) report a U-shaped function between age and decision making performance on the Iowa Gambling Task. In that study, children (8 years old) and older adolescents (17 years old) performed well on the Iowa Gambling task but younger adolescents (11–13 years) performed poorly. Younger adolescents typically favoured card decks that produced high rewards but high punishments, resulting in the worst overall outcomes (large net losses). This suggests a potential developmental regression in decision making during early adolescence. This U-shaped developmental change has been previously linked to an increase in impulsivity, but remains an open area of research (Casey et al., 2008).

Interestingly, earlier work using the Iowa Gambling Task did not show an inverted U function. Using four groups of participants (aged 6–9 years, 10–12 years, 13–15 years and 18–25 years), Crone and van der Molen (2004) revealed an age-related increase in performance – or at least an increase in participant's sensitivity to consequences. Given the discrepancy between existing research studies, the younger adolescents' preference for the high reward/high punishment decks must be carefully interpreted. For example, is that preference due to an increased desire for rewards (so called 'reward dominance'), or a decreased sensitivity to losses, or an adolescent-specific processing style that leads to different expected values compared with those of children and adults, or another explanation altogether? These possibilities cannot be disentangled in the Iowa Gambling Task, suggesting that alternative tasks are needed to assess feedback processing in adolescents.

Unfortunately, most relevant developmental research has occurred within non-naturalistic contexts and has focused on neutral or 'cold' cognitive tasks, rather than examining how feedback processing is engaged by, or potentially impaired by, arousing social situations. This is problematic because it may well be the case that young adolescents are particularly vulnerable to impaired decision making in affectively laden social (especially peer) contexts. Furthermore, recent findings indicate that performance monitoring does not fully develop until late adolescence or adulthood (see Blakemore and Mills, 2013; Kar et al., 2012; Tamnes et al., 2013). Further, the neural activity associated with feedback processing (as measured using functional magnetic resonance imaging) differs over the course of development. Van den Bos and colleagues suggest that brain-based developmental differences to processing feedback are not driven by valence but by the informative value of stimuli (van Den Bos et al., 2009a), and are related to IQ levels in adolescents (van den Bos et al. 2012).

An examination of feedback processing in more naturalistic and emotionally arousing social contexts is therefore critical for understanding the neurodevelopmental changes involved in cognitive function, performance monitoring and decision making between younger (10–12 years) and older (14–16 years) adolescents. In line with recommendations that the selection of age groups be narrow and theory-driven (Crone and Ridderinkhof, 2011), we attempted to select two narrow age ranges that had the potential to capture neural changes associated with feedback processing. The selection of age ranges was based on a number of factors. First, we aimed to select participants who were all secondary school-aged. This is because social relationships change after adolescents leave secondary school (at the age of 16 in the UK) for college or further training pathways. By restricting the older adolescent group to a maximum age of 16 years, this factor should have been minimized. Second, given that the young adolescent group in Smith et al.'s (2012) recent work showed poorer choices (compared to those of children or adults), the early adolescent group in the current study was recruited to roughly overlap with that group. A slightly younger age range was recruited here compared with Smith et al. (10–12 years here compared with 11–13 years) in order to ensure a sufficient separation between our two recruited groups.

1.2. Using brain imaging to study feedback processing

Because adolescence is a period of dynamic neural change (Choudhury et al., 2008), neuroimaging techniques such as EEG can be employed to help unravel changes in decision making and feedback processing. For example, the feedback related negativity (FRN) is an event-related potential (ERP) that indexes important aspects of outcome evaluation. The FRN is a negative-going frontal component that usually peaks 300 ms after the presentation of feedback (for example, a win or loss outcome) (Gehring and Willoughby, 2002). The FRN is typically larger (that is, more negative) when the outcome is poor (a bad outcome). The FRN has an anterior topography and is attributed to activation of the anterior cingulate cortex (Gehring and Willoughby, 2002; Holroyd and Coles, 2002). In adults specifically, the FRN distinguishes between outcome valences (win vs. loss) and, in some studies, the magnitude of the outcome (Dunning and Hajcak, 2007; Goyer et al., 2008). This component is thought to reflect emotional appraisal of the feedback (Hajcak et al., 2006), or violations of feedback expectancy (Bellebaum et al., 2010; Oliveira et al., 2007; Potts et al., 2006), as the FRN is larger (more negative) for worse outcomes (e.g., a loss rather than a win) and is larger (more negative) when the outcome violates the participant's expectation. Interestingly, there is evidence for an asymmetry between neural responses to wins and losses (Cohen et al., 2007). Cohen et al. demonstrated that the FRN was sensitive to the probability of reward on win trials, but not on loss trials. Specifically, FRN amplitudes were shown to be more positive when outcomes were better than expected (e.g., on win trials when the probability of a win was low). Huang and Yu recently demonstrated that a larger (more negative) FRN is associated with feedback that is 'more' than expected, rather than 'worse' than expected (Huang and Yu, 2014).

In adults, an increasing body of work reveals that the FRN is sensitive to social context. For example, the FRN has been shown to distinguish positive and negative feedback, but only when participants compete against another player, and not when playing alone (Van Meel and Van Heijningen, 2010). In other words, the FRN is increased in social contexts for adult participants. Furthermore, FRN amplitude is correlated with feelings of subjective happiness when participants compare their task winnings with another player, or compete for winnings against that player (Rigoni et al., 2010). The FRN is also influenced by factors such as social status (for example based on performance on a cognitive task) (Boksem et al., 2012). In that study, participants allocated to the low status group were more likely to evaluate and attend more to their own performance. Existing research therefore suggests that an arousing social context increases the FRN, and this increase may be linked to the heightened emotional significance of outcomes in social situations. Such modulation of feedback monitoring to take account of the social significance of one's decision-making is likely to be an important neurodevelopmental achievement; however little research has examined how social processing and reward/outcome processing become integrated during development.

1.3. Social context and feedback processing

One interesting demonstration of the interaction between social context and feedback processing employed a modified version of the Taylor Aggression Paradigm (TAP; Taylor, 1967) in combination with EEG (Krämer et al., 2008). The TAP separates each trial into a decision making phase (where participants set a punishment for their opponent) and an outcome phase (where participants receive win or loss feedback). Between the two phases, participants compete with opponents on a simple task. The opponents can differ in terms of how harshly they provoke (punish) the participant. Krämer et al. (2008) reported an increased frontal negativity (N2) during the decision phase for trait-aggressive adult participants under high provocation, suggesting that aggressive participants recruit greater cognitive resources when provoked. In a related study, non-violent men showed an increased N2 and were less harsh in their punishment selections than violent men during the decision phase (Wiswede et al., 2011). During the outcome phase, the FRN differentiated win and loss outcomes. Although provocation did not impact FRN amplitude, the difference between win and loss outcomes was larger in aggressive participants (Krämer et al., 2008). FRN amplitudes were also increased when participants were passive recipients of punishment, who were prevented from punishing their opponents (Wiswede et al., 2011). Collectively, these data suggest that a competitive or socially provocative context alters the neural systems underlying decision making and feedback processing – at least in adult participants.

To the best of our knowledge, only one study has employed EEG to investigate the relationship between feedback processing and social context in adolescents. Segalowitz et al. (2012) asked 15 year old boys to play a driving video game under two conditions: alone or in the presence of two friends who verbally encouraged and advised the participant during the game. FRN amplitudes decreased when the participants played in the presence of peers compared to when alone, suggesting that peer presence may interfere with feedback processing. Segalowitz et al.'s work confirms that the FRN is useful for investigating whether, and how, social context impacts an adolescent's ability to evaluate feedback. Interestingly, however, Segalowitz et al.'s findings of reduced FRN magnitude conflict with adult research, where social context increased FRN magnitude (see Van Meel and Van Heijningen, 2010). The discrepancy between adult and adolescent findings may reflect an important developmental effect: adults might engage in outcome monitoring more during social contexts (increased FRN), whereas adolescents may engage less in outcome monitoring in social situations (decreased FRN). Alternatively, the adolescent participants in Segalowitz et al.'s study may have been distracted in the presence of their peers, such that the experience of 'win' or 'loss' outcomes was less emotionally salient (although distraction in this sense should have also impacted other ERP components by increasing latency jitter, which was not the case). Another possibility is 'social distraction': Participants may have devalued the loss outcome when playing in a social context, because the outcome of crashing a virtual car may be less salient in the presence of peers. Finally, it is useful to note that the design of the tasks differed across the aforementioned adult and adolescent research studies, as adult participants directly competed against peers (Van Meel and Van Heijningen, 2010), whereas adolescents were merely observed by their peers (Segalowitz et al., 2012). It may be the direct competitive aspect of the social situation that works to enhance the FRN.

1.4. The current study

Given the need to better understand how social context impacts the trajectory of decision making and feedback processing in adolescence, the current study recorded EEG while younger (aged 10–12 years) and older (aged 14–16 years) adolescents played a modified TAP against two virtual opponents: a low-provoker and a high-provoker. The modified TAP attempts to balance the need for an appropriately controlled, scientifically tractable experiment with the need for an ecologically valid task that captures the emotional and cognitive dynamics of real world adolescent interactions. Following Krämer et al. (2008), this paradigm allowed us to separately examine the neural correlates of punishment selection (using the N2) and feedback processing (using the FRN) and varying conditions of social provocation. We also aimed to investigate participants' emotional evaluation of their punishment selection decisions. To that end, the late positive potential (LPP) component was also measured during the decision phase.

We hypothesized that younger and older adolescents would react to the opponents' provocation and punish high-provoking opponents more than low-provoking opponents. Given the developmental trajectories discussed above, it was predicted that younger adolescents would be more reactive to the social context than older adolescents and select harsher punishments for their opponents. We suspected that the group differences in behaviour would be paralleled by group differences in brain activity, such that N2 amplitudes would also be increased in younger adolescents, as the N2 has been shown to be enhanced in participants who select higher behavioural punishments (see Krämer et al., 2008). It was also expected that the decision phase LPP would be larger during high provocation vs. low provocation, because high provocation is, presumably, a more arousing emotional context.

2. Materials and methods

2.1. Participants

Participants were 60 adolescents recruited from North London secondary schools. 30 participants (15 female) made up the young adolescent group (mean age: 11.87 years, range: 10.48–12.99 years) and 30 participants (15 female) made up the older adolescent group (mean age: 15.65 years, range: 14.05–16.76 years). All participants and their parents provided written, informed consent. Participants had normal or corrected-to-normal vision. The study was approved by the Psychology Research Ethics Committee at the University of Cambridge, UK.

2.2. Stimuli and apparatus

All stimuli were presented on a light grey background on a Dell 17-inch monitor, refreshing at 60 Hz. In the Decision Phase, the stimulus of interest was the words 'Think about punishment', which appeared in the centre of the screen in black text (Arial font, occupying an area of 8 cm × 2 cm). In the Outcome Phase, the stimuli of interest were images of a green tick (indicating a win outcome) or a red cross (indicating a loss outcome). The feedback stimuli appeared in the centre of the screen and occupied an area of 5.5 cm × 5.5 cm. Punishment outcomes screens were followed by an aversive auditory stimulus (white noise). This noise increased in amplitude with increasing punishment level. The experiment was programmed and presented using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

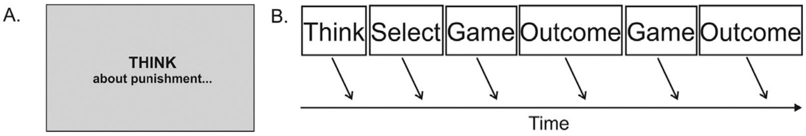

Fig. 1. (A) shows the Think screen, where participants were instructed to consider the level of punishment for their opponent. (B) shows the outline of one experimental trial. Participants were initially asked to think about the potential punishment that they would like to select for their opponent. Participants then selected the level of punishment (between 10p and 60p) for their opponent. Participants then played a Go/No-go game followed by a win or loss outcome and then played another Go/No-go game followed by another win or loss outcome.

2.3. Procedure

The experiment was a modified version of the Taylor Aggression Paradigm (Taylor, 1967). Participants were informed that they would be taking part in an online, multi-player game, competing in turn against two different opponents. The game that participants played against their opponents was a simple Go/No-go game. In reality, however, no other players existed and participants were effectively playing against a pre-programmed set of responses by the two (virtual) opponents. To enhance the believability of the social interaction, participants were introduced to their opponents via a fictional web-camera. Participants were able to see their opponents waving at them before the onset of the block (these were pre-recorded videos). The opponents were adolescents wearing a similar EEG net, and were approximately the same age and gender as the participants (we had a total of 8 fictional opponents to choose from, to match with the participants). This aspect of the experiment appeared to solidify the believability of the task, and no participants indicated disbelief in the opponents' existence.

The experiment consisted of four blocks of 14 trials/block. As shown in Fig. 1, a single trial comprised the following sequence of events: Think screen, Punishment Selection, a Go/No-go game, Feedback (win or loss outcome), a Go/No-go game, Feedback (win or loss outcome). Punishment selection occurred at the beginning of each trial. During this time, a screen with the word 'Think' appeared in the centre of the monitor for 1500 ms, and participants were instructed to use this time to consider the level of punishment that they would like to select for their opponent (as per Krämer et al., 2008). The Think screen was replaced by a display that enabled participants to select a potential punishment for their opponent, with punishment options ranging from 10p to 60p, increasing in 10p intervals. Participants were informed that the level of punishment they selected would be administered to their opponent if the opponent lost either of the two games during that trial. Within a given trial, participants could win both games, lose both games, or win one game but not the other (in either order). However, the programme ensured that, for each participant, the distribution of win/loss outcomes was 50% win and 50% loss (overall, not per trial). The task was designed in this manner to equate the number of win vs. loss outcomes for the ERP analyses (unfortunately, however, the loss trials were subject to greater movement artifacts, as explained below).

Because we were primarily interested in feedback processing, we do not present data concerning performance on the Go/No-go game. The Go/No-go game was included so that participants could compete against their opponents in an engaging task, and could therefore be shown win or loss outcomes, which were supposedly based on their Go/No-go performance.

Feedback occurred after every Go/No-go game. During feedback, a green tick or red cross appeared in a circle (diameter = 5 cm) in the centre of the screen for 2000 ms to respectively indicate a win or loss outcome on the immediately preceding Go/No-go game. Participants were then informed about the level of punishment that their opponent had chosen to inflict on them. Participants were informed about the level of punishment selected by their opponent regardless of whether they had won or lost that game.

Participants competed for a financial reward. Every win outcome was credited with 40p and a loss resulted in financial punishment ranging between 10p and 60p, according to the opponent's punishment 'selection'. As indicated above, however, the opponents did not exist and therefore the opponents did not 'select' punishments. Instead, the punishments administered by the two opponents were predetermined: one opponent was programmed as a 'low provoker' (administering punishments of 10p, 20p or 30p, mean punishment = 20p) and the other was programmed as a 'high provoker' (administering punishments of 40p, 50p and 60p, mean punishment = 50p). The type of opponent (low provoker vs. high provoker) alternated between blocks and the type of opponent first encountered (low provoker vs. high provoker) was counterbalanced across participants. There were four blocks in total, such that each participant played against the low provoking opponent twice, and against the high provoking opponent twice. Participants were paid in cash the amount of money that they won during the game. Due to the fact that wins, losses and opponent punishment selections were predetermined, payments ranged from £3.50 to £6.50 (a range was necessary to ensure that all participants did not win the exact same amount, which would have detracted from the believability of the task).

The game was thoroughly explained to participants, and the data collection did not begin until the experimenter was confident that the participant fully understood the nature of the task. The experimenter was present while participants played at least five practice trials against the computer. Additional practice trials could be played before the experiment proper, if required.

As participants were recruited from local schools in the area, debriefing occurred after all participants had taken part in the study (rather than at the end of each individual participant's session). This decision was made to ensure that participants could not inform future participants about the true nature of the task. The task appeared to be highly realistic, believable and engaging for participants. The pre-recorded videos of the other 'online players' were particularly useful in maintaining the coverstory.

2.4. EEG acquisition and preprocessing

EEG was recorded using the Electrical Geodesics Inc. 128-channel hydrocel geodesic sensor net system at a sampling rate of 250 Hz. An anti-aliasing low-pass filter of 70 Hz was applied during data acquisition. Offline, the data were band-pass filtered between 0.1 and 30 Hz and recomputed to an average reference. The continuous EEG was segmented into epochs between −200 and 700 ms relative to the epoching stimulus. Spline interpolation was carried out on individual channels if required. The mean percentage and range of interpolated channels was 6.07% (range: 0–9.3%). Independent component analysis was run using FASTER to remove stereotyped artifacts (Nolan et al., 2010). Epochs were excluded from analysis if they met any of the following artifact rejection criteria: voltage deviations exceeded 150 μV relative to baseline or the peak to peak moving amplitude exceeded 150 μV in a 200 ms moving window.

2.5. Data analysis

2.5.1. Behavioural data

The punishment level selected by participants in the first trial of the experiment (before participants had interacted with the opponents) was used as an index of unprovoked aggression, and compared across the two groups using an independent-samples *t*-test. In order to investigate how participants' punishment selections were influenced by provocation and age, we calculated average punishment selections under low and high provocation, and subjected these data to a two-way ANOVA with provocation (low vs. high) and group (younger vs. older) as factors. To explore how participants' decision making was impacted by their opponent's behaviour, we calculated the magnitude of difference between the punishment level selected by the participant and the punishment level 'selected' by their opponent on the immediately preceding trial. A positive score indicates that the participant selected a larger punishment than was selected by their opponent on the previous trial. Punishment difference scores were subjected to an ANOVA with provocation (low vs. high) as within-subjects factors and group (younger vs. older) as a between-subjects factor.

2.5.2. ERP data

EEG data from both the decision phase and the outcome phase were analysed. To achieve these analyses, ERPs were separately locked to two different events: the onset of the Think screen and the onset of the Outcome screen.

2.5.2.1. Decision phase. Following Krämer et al. (2008) we examined the N2 evoked during the decision phase by segmenting the continuous EEG data into epochs between −200 and 700 ms relative to the Think screen. The N2 component was defined as the most negative deflection occurring at Fz (electrode 11 in the hydrocel geodesic sensor net) in the period 200–400 ms after stimulus onset. Peak N2 latency was calculated in this window and subjected to an ANOVA with provocation (low vs. high) as a within-subjects factor and group (younger vs. older) as a between-subjects factor. Because the temporal latency of the N2 differed between the two groups, the grand average peak latency (averaged across participants) was calculated for each group and mean amplitudes were extracted in a window extending 50 ms before and 50 ms after the peak latency for each age group. Therefore, for younger adolescents, mean amplitudes were calculated 280–380 ms after stimulus onset and for older adolescents, 220–320 ms after stimulus onset.

The LPP was examined in the epochs locked to the Think screen. The LPP was defined at a centro-parieto-occipital scalp location around POz (electrodes 62, 66, 67, 71, 76, 77 and 84 in the hydrocel geodesic sensor net). As per Cuthbert et al. (2000) we examined the LPP in the period 400–700 ms after stimulus onset. A single extended time window was used to investigate this effect because there was no clear-cut peak that could be used to determine separate group windows. Mean activity in this period was analysed using an ANOVA with provocation and age as factors.

2.5.2.2. Outcome phase. Data were epoched relative to the onset of the Win and Loss outcome screens (−200 to 700 ms). Following previous research (Yeung and Sanfey, 2004; Zottoli and Grose-Fifer, 2012), activity at FCz (electrode 6 in the hydrocel geodesic sensor net) was used to calculate the FRN. Movement artifacts following the loss outcome screen prevented an examination of the electrophysiological activity evoked by negative outcomes. Consequently, the FRN analysis was restricted to the ERPs evoked by the win outcome. A peak latency analysis in the period 200–400 ms after outcome presentation revealed significant latency shifts between the two groups. As a result, mean amplitudes were extracted in a window extending 50 ms before and 50 ms after the peak latency identified in each group. This corresponded to 280–380 ms for younger adolescents and 232–332 ms for older adolescents. Mean amplitudes were analysed using an ANOVA with provocation (low vs. high) and group (younger vs. older) as factors. For all behavioural, physiological and ERP data, Sidak corrected post hoc contrasts were used to probe significant interaction effects, where required.

2.5.3. Relationship between behavioural and ERP data

To uncover the way in which punishment selection was associated with neural indices of decision making and feedback processing, we calculated correlations between behavioural measures of punishment selection and ERP difference scores. The two behavioural variables of interest were participants' first punishment selection and mean punishment selection differences (mean punishment selection under high provocation minus mean punishment selection under low provocation). ERP difference scores were defined as mean amplitude under high provocation minus mean amplitude under low provocation. Difference scores were calculated separately for the N2, the LPP and the FRN (on win trials). These correlational analyses were conducted because they have the potential to reveal which neural correlates are linked with punishment selection on this competitive task.

3. Results

3.1. Behavioural data

Although initial punishment selection was statistically equivalent across the two groups ($F < 1$), average punishment selections (across the entire experiment) were higher in younger adolescents ($F(1,58) = 4.7$, $p = .035$, $\eta^2 = .074$). For both groups, punishment selections were larger under high provocation compared with low provocation ($F(1,58) = 49.2$, $p < .001$, $\eta^2 = .459$). No interaction between age group and provocation was detected, indicating that high provocation enhanced punishment selections for both groups of participants ($F < 1$). The analysis investigating participant/opponent punishment differences indicated that younger adolescents were more reactive to the social context because their punishment difference scores were larger than older adolescents' punishment difference scores ($F(1,58) = 4.4$, $p = .041$, $\eta^2 = .070$). These data are shown in Table 1.

3.2. ERP data

3.2.1. Decision phase

The Think N2 peaked 60 ms later for younger adolescents than for older adolescents ($F(1,58) = 9.9$, $p = .003$, $\eta^2 = .146$) and was significantly larger (more negative) for younger adolescents ($F(1,58) = 6.3$, $p = .015$, $\eta^2 = .098$). For both N2 amplitude and latency measures, no main or interaction effects involving provocation were statistically significant (largest $F = 3.3$). These data are shown in Fig. 2.

With respect to the LPP, there were no main effects of age group ($F < 1$) or provocation ($F(1,58) = 2.4$, $p = .127$, $\eta^2 = .040$). However, a significant provocation × group interaction revealed that provocation impacted the LPP more strongly for younger adolescents than older adolescents ($F(1,58) = 4.1$, $p = .049$, $\eta^2 = .065$). Sidak-corrected post hoc comparisons confirmed that mean LPP amplitude was more positive under high provocation for younger adolescents ($p = .015$), but did not differ across provocation levels for older adolescents ($p = .742$). These data are shown in Fig. 3.

3.2.2. Outcome phase

As shown in Fig. 4, the FRN evoked by Win outcomes was significantly delayed for younger adolescents ($F(1,58) = 13.3$, $p = .001$,

Table 1
Mean behavioural data from the TAP for the younger and older adolescent groups. Participants' punishment selections could range from 1 (10p punishment) to 6 (60p punishment). Initial punishment selection refers to the punishment level selected by the participant on the first trial of the experiment, before receiving any outcome information. Average punishments refer to mean punishment levels selected by participants across all trials with the 'low provocation' opponent, and all trials with the 'high provocation' opponent. Higher values are indicative of larger punishments. Punishment difference scores refer to the magnitude of difference between the punishment selected by the opponent on trial *X*, and the punishment selected by the participant on trial *X* + 1. A more positive score indicates that the participant selected a larger punishment than was selected by their opponent on the previous trial. Standard deviations are shown in brackets.

	Initial punishment selection	Average punishment		Punishment difference scores
		Low provocation opponent	High provocation opponent	
Younger	3.37 (1.75)	4.04 (1.53)	5.10 (0.73)	1.034 (0.17)
Older	3.27 (1.57)	3.52 (1.25)	4.45 (1.08)	0.447 (0.20)

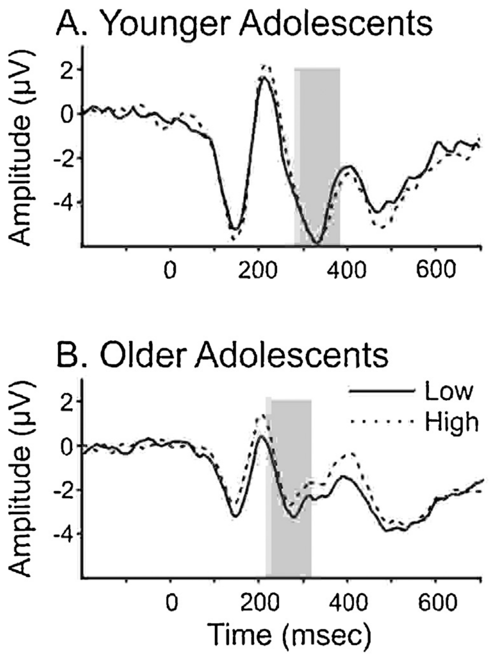

Fig. 2. ERPs as a function of age and provocation level (low or high), time-locked to the onset of the 'Think' screen. ERPs are shown at Fz (electrode 11 in the hydrocel geodesic sensor net). Grey boxes show the time windows used to calculate mean amplitudes.

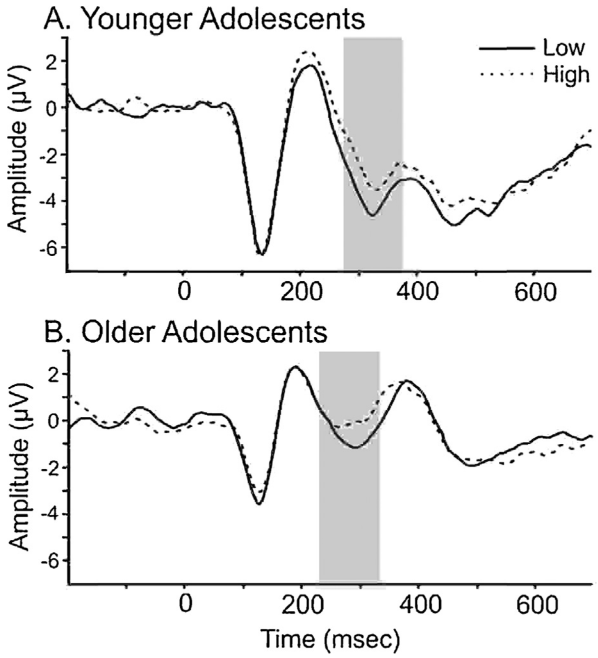

Fig. 4. ERPs as a function of age and provocation level (low or high), time-locked to the onset of the outcome screen. ERPs are shown at FCz (electrode 6 in the hydrocel geodesic sensor net). Grey boxes show the time windows used to calculate mean amplitudes.

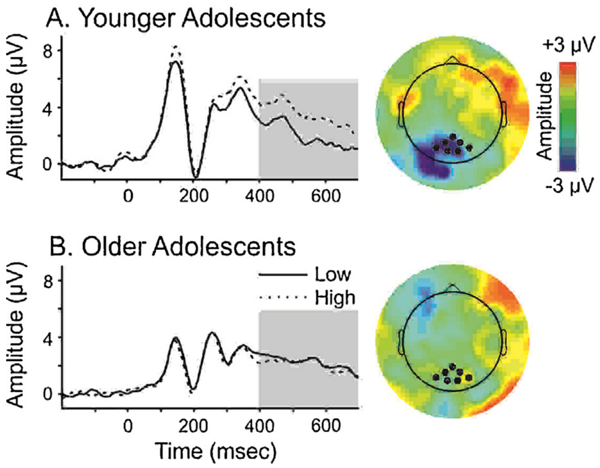

Fig. 3. ERPs as a function of age and provocation level (low or high), time-locked to the onset of the 'Think' screen. Grey boxes show the time windows used to calculate mean amplitudes. Difference topographies (low provocation minus high provocation) are also shown. Difference topographies are shown for the time window 400–700 ms after the onset of the 'Think' screen. Small black circles on the topographies highlight the electrodes used in the ERP analysis.

$\eta^2 = .186$). For both groups, the amplitude of this component was more negative under low provocation than under high provocation ($F(1,58) = 4.1$, $p = .047$, $\eta^2 = .066$), and was more negative in younger adolescents than older adolescents ($F(1,58) = 5.2$, $p = .026$, $\eta^2 = .082$). The group × provocation interaction effect was not statistically robust ($F < 1$), suggesting that the impact of provocation on the FRN was equivalent across the two groups. Note that the same results were obtained when a single time window (250–350 ms) was used for both groups (provocation: $F(1,58) = 5.6$, $p = .021$, $\eta^2 = .088$; age: $F(1,58) = 3.1$, $p = .082$, $\eta^2 = .051$).

3.3. Relationships between behavioural and ERP data

None of the ERP measures (N2, LPP or FRN) significantly correlated with participants' first punishment selections (N2: $r = .122$, $p = .354$; LPP: $r = -.232$, $p = .074$; FRN: $r = .019$, $p = .885$). Further, the N2 and FRN were not related to average punishment selection difference scores (N2: $r = -.027$, $p = .839$; FRN: $r = .000$, $p = .998$). However, LPP difference scores correlated positively with the magnitude of punishment selection differences ($r = .263$, $p = .042$). In other words, a larger LPP amplitude difference between high and low provoking opponents corresponded to a larger punishment selection difference between high and low provoking opponents.

4. Discussion

The current study examined the effect of social provocation on neural indices of decision making and feedback processing. Specifically, the trajectory of development between early and late adolescence was mapped by comparing 10–12 year olds and 14–16 year olds. Moving beyond traditional 'cold' decision making tasks such as the Stroop or Wisconsin card sorting tasks, we used a socially arousing version of the TAP. This task aims to enhance ecological validity by engaging participants in a competitive social environment that requires reaction to low or high provocation by a peer. By examining neural markers of punishment selection (N2, LPP) and feedback processing (FRN) under conditions of high and low peer provocation, we were able to examine neurodevelopmental differences across two groups of adolescents. The results are discussed below.

4.1. Punishment selection: decision phase

Perhaps unsurprisingly, social provocation impacted decision making in both younger and older adolescents. For both groups, the magnitude of average punishment selection was larger under high provocation than low provocation. Although both groups were affected by provocation, punishment selection responses differed across the two groups. As hypothesized, average punishment selection scores were larger for the younger adolescent group than the older adolescent group. High punishment selections by younger adolescents appeared to reflect a reactive (rather than pro-active) response to the social context. This is because initial punishment selections were equivalent across the two groups, yet the magnitude of difference between the participant's punishment selection score and their opponent's previous punishment selection score was larger in younger adolescents. These results are consistent with the observation that the regulation of reactive control develops from childhood through adolescence (Barker et al., 2006; Killikelly and Szűcs, 2013; Tremblay, 2000).

We observed two ERP components during the decision phase of this task (N2 and LPP), time-locked to the onset of the 'Think' screen. Unlike Krämer et al. (2008), the decision phase N2 was not modulated by provocation. However, in Krämer et al.'s study, N2 differences were only observed when high trait aggressive participants exhibited low levels of aggression. Therefore, we might not necessarily expect N2 differences here (as we did not recruit high trait aggressive adolescents).

Examination of the LPP helped to reveal participants' emotional evaluation during the decision phase of the task. Critically we found evidence that LPP amplitudes in this task were significantly larger under high provocation vs. low provocation for younger adolescents but not older adolescents. The LPP is typically elicited in response to emotional stimuli, is larger (more positive) following arousing stimuli (such as unpleasant images) (Bradley et al., 2007; Cuthbert et al., 2000; Naumann et al., 1992), and reflects sustained processing of arousing stimuli, and is largely unaffected by early attention (Codispoti et al., 2007). The LPP is argued to index an obligatory motivational system (Lang et al., 1997). This explanation is consistent with evidence suggesting that the neural generators of the LPP comprise emotional and motivational brain circuits including the amygdala, insula and cingulate cortex (Liu et al., 2012). Our findings therefore suggests that, during the decision phase, emotional reactivity is heightened for younger adolescents which may in turn explain their high punishment selections. This notion is supported by the fact that LPP difference scores correlated with punishment selection difference scores, suggesting that the LPP is a useful neural marker of decision making in the modified TAP task.

4.2. Feedback processing: outcome phase

In addition to impacting decision making, social provocation influenced a neural measure of feedback processing: the FRN. Due to artifacts on loss trials, we were only able to examine the FRN evoked by win outcomes. The inability to examine loss trials constitutes a major limitation of the current work, because FRN amplitudes are typically larger for worse outcomes. Therefore, we would have expected greater variance in FRN amplitudes during the loss trials, and arguably, the loss trials would have been more likely to reveal important age × provocation interaction effects. The fact that the analyses were restricted to win trials means that the current study was unable to fully examine the impact of outcome (win vs. loss) on the FRN. Participants were asked to try and avoid expressing their feelings (e.g., outrage, disappointment, pleasure) until the end of the outcome screen. Despite the instructions to try and remain still during feedback, we speculate that the loss trials were lost to movement artifacts due to the affective nature of the task. Indeed, if one assumes that the degree of movement artifacts is reflective of a participants' emotional reaction to the feedback, then it could be inferred that participants regarded the loss trials as more emotionally engaging, such that their physical response to those trials could not be adequately suppressed.

For both groups of participants, the FRN was reduced (i.e. more positive) following a win outcome under high provocation compared with a win outcome under low provocation. The FRN is typically reduced following more positive or pleasing outcomes, consistent with the notion that the FRN reflects the emotional or value-appraisal of the outcome (Gehring and Willoughby, 2002; Goyer et al., 2008; Hajcak et al., 2006). In this study, a win under high provocation was more rewarding than a win under low provocation, which is arguably why the FRN was more positive under high provocation. Wins under high provocation may have been more emotionally pleasing for participants, as they felt satisfied in having beaten a highly provocative opponent. Additionally, the size of the FRN could reflect the magnitude of the expected outcome. Specifically, the potential loss under high provocation (average loss 50p) was larger than the potential loss under low provocation (average loss 20p). Because all wins were associated with a 40p gain (regardless of provocation condition), wins under high provocation were also associated with a larger prediction error (and a more positive FRN) than wins under low provocation.

The impact of provocation on FRN amplitude observed here is in contrast to data presented by Krämer et al. (2008) where FRN amplitudes in adult participants were not modulated by provocation. It might be the case that, in the context of the TAP task, adolescent participants are more emotionally invested in the task so that their neural responses to feedback (especially during the win trials) were heightened. This makes sense given that adolescents tend to be reward dominant and are therefore more likely to focus attention on feedback stimuli, particularly in a socially-competitive context (Chein et al., 2011; Steinberg, 2008; Van Duijvenvoorde et al., 2008).

To the best of our knowledge, only one other study has examined the impact of social context on the FRN in male adolescent participants (Segalowitz et al., 2012). Our study extends those findings by showing that the nature of a social context (high vs. low provocation) and not simply the presence or absence of a social context, impacts FRN amplitude. We also demonstrate that a social context impacts FRN amplitude in a mixed gender sample, and that the impact of social context on FRN amplitude is apparent in adolescents as young as 11 years. Segalowitz et al. (2012) argued that peer influence invoked a decrease in activation of the medial prefrontal cortex (indexed by FRN activity), and our findings may be understood in similar terms. Contrary to our expectations, provocation impacted FRN amplitude in the same manner for both age groups. Because all of our participants were adolescents, and adolescents across this age range have been previously documented as reward dominant (see Steinberg, 2005; Van Leijenhorst et al., 2010), it is possible that differences would emerge if a wider range of ages (both older and younger than those included here) were considered, or if adolescents were compared directly with adults.

4.3. Conclusion

The current study responds to the contemporary literature's focus on integrative examinations of social/cognitive/emotional development. Recently, Blakemore and Mills (2013) argued that changes in the adolescent's social environment interact with normal cognitive development, such that social contexts must be considered when examining adolescent behaviour and cognition. Evidence from neuroimaging also highlights the importance of social context in neurocognitive development throughout adolescence. For example, in their review of developmental neuroimaging studies, Crone and Dahl (2012) suggest that theories attributing adolescent behaviour to immature frontal lobes are overly simplistic. Instead, adolescent behaviour is driven by complex interactions between cognitive, social and affective contexts (see Segalowitz et al., 2012; van den Bos et al., 2009b; Van Duijvenvoorde et al., 2008). By combining the modified TAP with EEG recordings, we were able to reveal that social provocation influences decision making and feedback processing, and that these processes may change over adolescence.

Despite its contribution to understanding the complex interactions involved in adolescent development, this study has some limitations that require acknowledgement. First, we were unable to examine the FRN on loss trials due to artifacts on those trials. Second, we only examined normative developmental samples across two narrow age ranges. This constitutes both a strength and a limitation because, on the one hand, we were able to validate this task in a developmental sample, and provide normative data. On the other hand, the same results may not hold for different age groups or clinical populations. Further, it is important to note that this study does not include young children or adults. It is therefore not possible to reveal whether the current results are specific to adolescent development or development more generally. Future research using engaging tasks that are appropriate for use across a wide age range will help to uncover whether the current results are adolescent specific. Future research should also consider including additional non-social control conditions that would help to delineate whether the obtained results are purely expectation based or socially driven.

In summary, the current findings provide further support for the view that social context, and in this case social provocation, impacts on behavioural and neural aspects of decision making and feedback processing. The relationships between provocation, decision making and feedback processing showed a developmental trajectory, as they were not stable across early and later adolescent groups. Young adolescents appear to be harsher in their punishment selection and more emotionally responsive during this decision phase of the modified TAP. Feedback processing, as indicated by the FRN, also appears to be impacted by social provocation in both younger and older adolescents. Collectively, these data suggest that decision making improves from early to late adolescence whereas feedback processing remains relatively stable. Overall, the current results highlight the importance of viewing adolescent neurocognitive development as a complex interplay of social and cognitive change, where social context may act as a key a modulator of behaviour and neural processing.

Conflict of interest

No conflicts of interest are declared.

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