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# The influence of reward anticipation on conflict control in children and adolescents: Evidences from hierarchical drift-diffusion model and event-related potentials

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## ABSTRACT

Reward is deemed a performance reinforcer. The current study investigated how social and monetary reward anticipation affected cognitive control in 39 children, 40 adolescents, and 40 adults. We found that cognitive control performance improved with age in a Simon task, and the reaction time (RT) was modulated by the reward magnitude. The conflict monitoring process (target N2 amplitudes) of adolescents and the attentional control processes (target P3 amplitudes) of adolescents and adults could be adjusted by reward magnitude, suggesting that adolescents were more sensitive to rewards compared to children. Reward magnitudes influenced the neural process of attentional control with larger P3 in congruent trials than that in incongruent trials only in low reward condition. The result of hierarchical drift-diffusion model indicated that children had slower drift rates, higher decision threshold, and longer non-decision time than adolescents and adults. Adolescents had faster drift rates in monetary task than in social task under the high reward condition, and they had faster drift rates under high reward condition than no reward condition only in the monetary task. The correlation analysis further showed that adults' non-decision time and decision threshold correlated with conflict monitoring process (N2 responses) and attentional control process on conflicts (P3 responses). Adolescents' drift rates associated with neural process of attentional control. The current study reveals that reward magnitude and reward type can modulate cognitive control process, especially in adolescents.

## 1. Introduction

Rewards are essential incentives to strengthen individuals' motivation and excite positive emotional states, and a proper amount of reward stimulation can optimise individuals' allocation of attention to the task and promote their behaviours to maximise benefits (Beck et al., 2010; Delgado, 2007; Helfinstein et al., 2011; Kujawa et al., 2015). Both social (such as happy faces) and monetary rewards have been widely adopted as important reinforcers to motivate individuals' performance (Anderson, 2016; Broyd et al., 2012; Cao et al., 2018; Chan et al., 2016; Flores et al., 2015; Foti et al., 2015; Knutson et al., 2000; Kohls et al., 2009; Lamm et al., 2006; Oldham et al., 2018; Spreckelmeyer et al., 2009; Stavropoulos and Carver, 2013; Vohs et al., 2006; Wei et al., 2015; Weinberg et al., 2014). The development of reward system is closely

related to the neural activity in the prefrontal cortex (PFC), striatum, and nucleus accumbens (Delgado, 2007; Fareri et al., 2008; Galvan, 2013; Van Leijenhorst et al., 2009, 2010). During childhood, the reciprocal projections between the striatum and prefrontal lobe are immature; therefore, it is difficult for children to control their behaviour after receiving rewards. Adolescence is a specific period with remarkable changes in physical and hormonal levels as well as brain structures, and these changes might influence adolescents' neural responsiveness in their reward system (Blakemore and Choudhury, 2006; Casey et al., 2008; Fareri et al., 2008; Galvan, 2013; Steinberg et al., 2017; van Duijvenvoorde et al., 2016). The ventral striatum of adolescents has been reported to be hypersensitive to the expectation of both intrinsic and extrinsic rewards (Demurie et al., 2011, 2012; Galvan, 2013; Kohls et al., 2009). Therefore, the development of the reward system is

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regarded as nonlinear development (Bjork et al., 2010; Ernst et al., 2005; Ethridge et al., 2017; Kujawa et al., 2018; Lamm et al., 2014; Somerville and Casey, 2010).

Electrophysiological studies can record human activities with high temporal resolution, and reward processes are associated with the following event-related potential (ERP) components: the centroparietal cue-P3 is related to the cue detection and neural activation of the motivational system (Broyd et al., 2012; Flores et al., 2015; Goldstein et al., 2006; Oumeziane et al., 2017; Spreckelmeyer et al., 2009; Wei et al., 2015), with higher reward magnitude and more desirable rewards inducing greater cue P3 amplitudes (Broyd et al., 2012; Flores et al., 2015; Pfabigan et al., 2014, 2015; Wei et al., 2015). In addition, the feedback-related negativity (FRN) that is induced over frontal-central brain areas relates to the neural process on the feedback information (Crowley et al., 2013; Hämmerer et al., 2011; Kujawa et al., 2014). Some studies found FRN responses were similar from childhood to early adulthood (Lukie et al., 2014; Luking et al., 2017), while others reported that the magnitudes of FRN were significantly changed with age in both social and monetary reward tasks (Ethridge and Weinberg, 2018; Hämmerer et al., 2011; Zottoli and Grose-Fifer, 2012).

Several studies have compared the neural responses to social and monetary rewards (Demurie et al., 2011, 2012; Ethridge et al., 2017; Ethridge and Weinberg, 2018; Izuma et al., 2008; Lin et al., 2012; Rademacher et al., 2010; Saxe and Haushofer, 2008; Wang et al., 2017, 2020). We previously investigated how social and monetary rewards affected a simple two-choice process (a triangle with left hand response, a square with right hand response) in children, adolescents, and adults (Wang et al., 2017, 2020). We found that both monetary and social rewards could speed up participants' responses, and their reaction time (RT) decreased with the enhancement of the reward magnitude. Compared to adults, children and adolescents had larger cue-P3 amplitudes for motivational process, and they showed larger target P3 to complete the simple two-choice task (Wang et al., 2017, 2020). Moreover, all participants showed higher accuracy rates and larger target P3 in the monetary task than that in the social task (Wang et al., 2017, 2020). These findings suggested that reward could promote low level of cognitive function in children and adolescents. However, whether children's and adolescents' advanced cognitive function, such as cognitive control process, could be enhanced by rewards is unknown.

Cognitive control refers to the top-down control processes of detecting and suppressing inappropriate behaviour and solving conflicts in favour of goal-directed behaviours. Individuals experience rapid growth in cognitive control from childhood to late adolescence (Anderson, 2002; Hsu and Jaeggi, 2013; Luna et al., 2015). Children and adolescents are not as effective as adults in cognitive control process due to their immature prefrontal and parietal cortices (see for reviews Bunge and Wright, 2007; Casey et al., 2008). ERP studies have found that frontal N2 with the anterior cingulate cortex (ACC) and PFC as its neural generators (Botvinick et al., 2004; Kerns et al., 2004) is related to the detection of conflicts (Larson et al., 2014; Tillman and Wiens, 2011; van Veen and Carter, 2002; West, 2003), and parietal P3 is related to attentional control and conflict resolution (Liotti et al., 2000; Mansouri et al., 2009; West, 2003).

Furthermore, interactions between reward process and cognitive control have been proposed, such as the dual-system theory (McKewen et al., 2019; Shulman et al., 2016; Steinberg et al., 2017) and the neurobiological model of cognitive control (Hare and Casey, 2005). It is found that rewards can promote cognitive control processes, such as selective attention [with Posner-type tasks] (Anderson et al., 2016; Engemann et al., 2009; Libera and Chelazzi, 2006; Small et al., 2005), inhibition control [with Go-Nogo tasks and antisaccade tasks] (Diao et al., 2016; Dixon and Christoff, 2012; Freeman and Aron, 2016; Geier et al., 2010; Kohls et al., 2009), proactive control [with AX-CPT tasks] (Chaillou et al., 2017; Fröber and Dreisbach, 2014, 2016; Locke and Braver, 2008), cognitive flexibility [with task switch paradigms and set-shifting tasks] (Aarts et al., 2010; Dixon and Christoff, 2012; Müller

et al., 2007), conflict control [with Stroop tasks] (Dixon and Christoff, 2012; Padmala and Pessoa, 2011), and decision making [with gambling tasks] (Satterthwaite et al., 2007). These studies found that greater cognitive control was engaged when larger amounts or higher values of reward outcome were expected or anticipated, and rewards can modulate the recruitment of prefrontal and parietal function and further allocate selective attention and cognitive resources to execute the cognitive control (Vassena et al., 2014; Watanabe, 2007). For instance, Padmala and Pessoa (2011) investigated how rewards affected conflict control processes in adults. At the beginning of each trial, a cue was presented to indicate motivational condition (\$20 reward condition or no reward condition). Then, images of houses/buildings with overlaying words of "HOUSE"/"BLDNG" were adopted to create congruent and incongruent conditions, meanwhile, the images of houses/buildings with a "XXXXX" string were regarded as the neutral condition. Participants were required to indicate whether they saw a house image or a building image. The authors reported that rewards decreased both interference (the differences between incongruent condition and neutral condition) and facilitation effects (the differences between congruent condition and neutral condition), which suggested that rewards enhanced attentional filtering process and reduced the influence of task-irrelevant information. They also found the fronto-parietal responses during cue-related processing could predict neural responses in the medial PFC (mPFC) and ACC during cognitive control process on conflicts. Furthermore, a path analysis revealed that the relationship between cue-related reward process (neural activity in the right intra-parietal sulcus) and interference control process (neural activity in mPFC) was mediated by the distractor process. This study suggested that rewards can modulate the top-down attentional control process and result in a more efficient conflict control. However, how conflict control processes can be affected by various reward motivations from the perspective of developmental psychopathology is unknown. Therefore, further research on social and monetary rewards modulation of conflict control process in children and adolescents is needed.

Drift diffusion model (DDM) is considered a standard for the two-alternative choice tasks, and the DDM has been adopted to decompose trial-by-trial choices into dynamic decision, in which the parameter of drift rate relates to the speed of evidence accumulation process and the ability to extract effective evidence from perceived input information (Ratcliff and McKoon, 2008). Moreover, a Bayesian hierarchical version of DDM, named HDDM has been used to enhance statistical power and to estimate latent dynamic decision parameters (Wiecki, Sofer and Frank, 2013). HDDM allows to simultaneously estimate parameters at both group and individual levels, which is appropriate for comparison of group discrepancy in dynamic decision making (Wiecki et al., 2013). Therefore, the current study compares the age group differences in the reward influence on cognitive control based on the HDDM analyses.

The aim of the current study was to explore how reward anticipation processes affected the neural processes of conflict control in children, adolescents, and adults. We conducted the HDDM and ERP analyses to present the influence of reward anticipation to cognitive control processes from computational model and electrophysiological perspectives. Children of 7–10 years old gradually understand the concept of money but their cognitive control abilities are still immature (Abundis-Gutiérrez et al., 2014; Berti and Bombi, 1981; Erb et al., 2017; Grunberg and Anthony, 1980; Larson et al., 2012). Rewards might influence their general performance, while rewards might not modulate their conflict control process due to their immature frontal function. Individuals aged 12–15 years are in the early and middle periods of adolescence, and they show strong emotional reactivity and hyper-sensitivity to rewards (Crone and Dahl, 2012). Based on previous studies, it is hypothesized that both monetary and social rewards could promote adolescents' conflict control process by shortening their RT, and their behavioural and neural responses will be modulated by reward magnitudes. Adults would show more mature frontal and parietal function for cognitive control process than children and adolescents, and they would show

closer relationship between neural responses and behavioural performance.

## 2. Methods

### 2.1. Ethical statement

This study was conducted in accordance with the Declaration of Helsinki and approved by the local Review Board.

### 2.2. Participants

Three age groups were enrolled in the study including 39 children (17 boys, 7.8–9.1 years, mean age of 8.4 years), 40 adolescents (17 boys, 12.4–14.7 years, mean age of 13.4 years), and 40 adults (20 men, 20.3–32.6 years, mean age of 24.1 years). Children and adolescents were from a primary school and a secondary school in the same community, respectively. Adult participants were undergraduate students from a local university. All participants were right-handed, with normal or corrected-to-normal visual acuity. None of them or their family had a history of neurological and mental disorders. Prior to the experiment, parents of the children and adolescent participants provided written informed consent, and adult participants signed the written informed consent themselves.

### 2.3. Materials and procedure

The E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA, United States) was adopted to display the experimental stimuli and record participants' reaction time (RT) and accuracy. Participants completed the study in a dimly lit and sound-attenuated room. The main task was revised according to the Simon paradigm (Hommel, 1993). For the baseline measurement, participants were not informed that the experiment was about rewards at this stage. For each trial, a white fixation point ( $0.48^\circ \times 0.48^\circ$ ) was presented for 600–1000 ms at the centre of a screen with black background. Then, the target (a white  $2.12^\circ \times 2.12^\circ$  square or a white  $3.22^\circ \times 2.79^\circ$  triangle) was displayed for 800 ms on the left or right side of the screen, and participants were required to press the left or right buttons in accordance with the target. For half of the trials, the responding hand was on the ipsilateral side of the target, and for the other half on the contralateral side of the target. After the participant's response, the feedback was presented for 500 ms (the feedback for correct responses: " $\sqrt{\phantom{x}}$ " [ $3.99^\circ \times 2.64^\circ$ ]; the feedback for incorrect responses: " $\times$ " [ $2.64^\circ \times 2.64^\circ$ ]). Forty trials were performed, and the mean RT of correct responses was adopted as the baseline RT for each participant in the formal measurement.

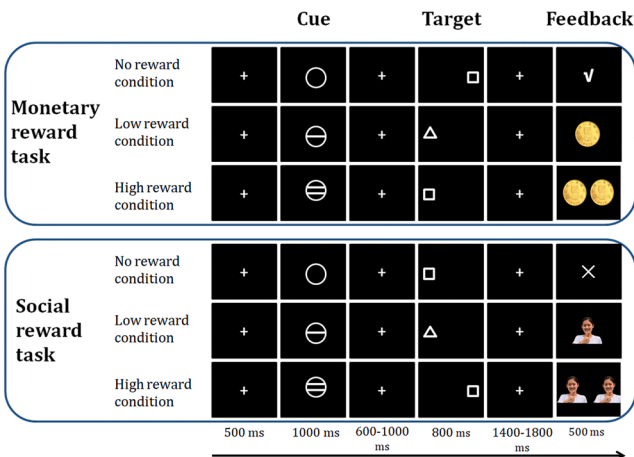
In the formal task, each participant was explicitly told that the tasks were about reward process, and they were instructed to accomplish a social reward task and a monetary reward task. Participants were told that if they outperformed their average RT in the baseline stage, they would get the reward in that trial. For the social reward task, the reward feedback was a praise from an image of a real experimenter at the end of each trial, and a papery certificate with their scores and ranking (first to fifth prize) would be given to each participant after they completed the social task. For the monetary reward task, the reward feedback was an image of coins indicating their good performance at the end of each trial, and 9–45 Chinese Yuan would be given to each participant based on their performance after they accomplished the monetary task. All participants clearly understood the relation between their performance and the final reward. Both social and monetary reward tasks contained three blocks with 180 trials. In each task, three types of reward magnitudes were set—high reward magnitude, low reward magnitude, and non-reward magnitude, with one-third of the trials for each type of magnitude in each block. The order of different reward magnitudes was counterbalanced among participants. The presentation sequence of the monetary and social reward tasks was also counterbalanced among

participants.

Each trial in the formal tasks started with a white fixation (500 ms), and then a cue picture was presented (1000 ms), which indicated the reward magnitude in the trial by the number of horizontal lines: the high reward magnitude with two lines, the low reward magnitude with one line, and the non-reward magnitude with no lines. The blank interval between the cue and target was 600–1000 ms. The target (a white triangle or square) was displayed on the left or right side of the screen for 800 ms. Participants were required to react to the target as accurately and quickly as possible. In each block, half of the trials were congruent trials with the responding hand ipsilateral to the location of the target, and the other half were incongruent trials with the responding hand contralateral to the location of the target. The assignments of the response hand for the target were counterbalanced across the participants. After the target, the feedback picture was displayed for 500 ms. If the participants performed accurately and their response speed was faster than their baseline RT, the images of two coins or two happy faces were displayed as the monetary or social feedback for the high reward trials, and the image of one coin or one happy face was presented for the low reward trials. Incorrect responses resulted in a " $\times$ " image as the feedback. For the no reward trials, a " $\sqrt{\phantom{x}}$ " or " $\times$ " symbol was the feedback indicating whether the participant's performance was correct or not. After the completion of the ERP tasks, participants were instructed to rate their motivation for social and monetary rewards with a 7-point Likert scale ranging from 1-point (do not want it at all) to 7-point (want it very much). The sample procedure for the social and monetary reward tasks is presented in Fig. 1.

### 2.4. Electroencephalogram data collection and analyses

Electroencephalogram (EEG) data were recorded with a 40-channel cap (Neuroscan; Compumedics, EI Paso, TX, United States) with an on-line bandwidth of 0.05–100 Hz, and the sample rate was 1000 Hz. Horizontal and vertical electrooculograms (EOGs) were recorded by the electrodes placed at the outer canthi of each eye and above and below the left eye, using the left mastoid as an online reference. The average signal from the right and left mastoids was re-referenced for offline analysis. The electrode impedance was maintained below 5 k $\Omega$ . The EEG signal was epoched with 100 ms before and 1000 ms after the stimulus onset, and the pre-stimulus 100 ms interval was used for baseline correction. The epochs contaminated by body movements and eye blinks were detected and corrected by the independent component analysis



**Fig. 1.** Sample procedures for both social and monetary reward tasks. Both social and monetary tasks contained the no reward condition, the low reward condition, and the high reward condition indicated by the cues. The monetary feedback of coin images or the social feedback of happy faces was presented at the end of each trial.



(ICA) algorithm (Delorme and Makeig, 2004). The epochs that contained artifacts exceeding  $\pm 90 \mu\text{V}$  were excluded. The signals were offline filtered with bandpass at 0.10–30 Hz for further analysis. Topographic maps were produced by FieldTrip (Oostenveld et al., 2011).

Based on the visual inspection of current grand average waveforms and previous ERP studies on reward process (Broyd et al., 2012; Flores et al., 2015; Oumeziane et al., 2017; Wei et al., 2015; Wang et al., 2020) and conflict control process (Abundis-Gutiérrez et al., 2014; Brydges et al., 2014; Clayson and Larson, 2011a; b; Tillman and Wiens, 2011; Liu et al., 2016, 2018, 2019), the following ERP components were analysed to investigate how reward anticipation affects conflict control processes. For the cue presentation stage, cue-P3 relating to reward induced motivational process was analysed over the central-parietal areas (on the electrodes of C3, Cz, C4, CP3, CPz, CP4, P3, Pz, and P4) during 430–570 ms after cue onset. For the conflict control processes, N2 was analysed during 230–360 ms over the frontal areas (F3, Fz, F4) for conflict monitoring, and P3 was analysed at 300–400 ms over the parietal areas (the electrodes of CP3, CPz, CP4, P3, Pz, and P4) for the attentional control process. During the feedback phase, the FRN was analysed over the fronto-central areas (the electrodes of FC3, FCz, and FC4) after the presentation of feedback between 200 and 400 ms (Ethridge and Weinberg, 2018). FRN<sub>residual</sub> was also analysed by calculating unstandardized residual FRN to high rewards and low rewards adjusting for FRN to no rewards (Ethridge and Weinberg, 2018; Meyer et al., 2017).

## 2.5. Data analysis

In addition to classic RTs and accuracy, HDDM analysis was also conducted on trial-by-trial RTs (Wiecki et al., 2013) and three parameters were extracted from the best-fitting model—(1) the drift rate parameter ( $v$ ), which relates to information accumulation; (2) the decision threshold parameter ( $a$ ), which represents the boundary separation referring to the amount of information required to trigger the response; (3) the non-decision time parameter ( $t$ ), which is a non-decision related factor and refers to the time for the initial sensory encoding of the information and the time for executing the motor response (Ratcliff and McKoon, 2008). These parameters were compared among different age groups under varied experimental conditions.

To eliminate the influence of subjective ratings to the social and monetary rewards on participant's behavioural and neural responses, ANCOVA analysis was conducted with the subjective ratings to social and monetary rewards as covariates. The between-subject independent

variable was the age group (children, adolescents, adults), and the within-subject independent variables were the reward type (the social task vs. the monetary task), reward amount (high reward condition vs. low reward condition vs. non reward condition), and congruency (the congruent trial vs. the incongruent trial).

The correlation between ERP responses (cue P3, N2, P3, and FRN) and HDDM parameters (drift rate, non-decision time, decision threshold) was further calculated in each age group, and the Bonferroni correction was used with  $p < 0.05/10 = 0.005$ .

## 3. Results

### 3.1. Behavioural data

The accuracy rates and RTs are presented in Fig. 2. For accuracy, the main effect of the age group was significant ( $F(2, 114) = 29.21$ ,  $p < 0.001$ ,  $\eta^2 = 0.34$ ). Children had lower accuracy than adolescents ( $t = 2.71$ ,  $p = 0.015$ ) and adults ( $t = 7.29$ ,  $p < 0.001$ ), and adolescents had lower accuracy than adults ( $t = 4.57$ ,  $p < 0.001$ ). The main effect of congruency was significant ( $F(1, 114) = 6.73$ ,  $p = 0.01$ ,  $\eta^2 = 0.06$ ), and accuracy rates were higher in congruent trials than in incongruent trials. A significant interaction between congruency and the age group was also detected ( $F(2, 114) = 9.11$ ,  $p < 0.001$ ,  $\eta^2 = 0.14$ ). In congruent trials, adults showed higher accuracy than children ( $t = 3.71$ ,  $p < 0.001$ ) and adolescents ( $t = 2.86$ ,  $p = 0.015$ ), while no differences were observed between children and adolescents ( $p > 0.05$ ). In incongruent trials, adults had higher accuracy than children ( $t = 6.82$ ,  $p < 0.001$ ) and adolescents ( $t = 4$ ,  $p < 0.001$ ), and adolescents had higher accuracy than children ( $t = 2.82$ ,  $p < 0.001$ ). Moreover, children and adolescents had higher accuracy in congruent trials than incongruent trials (children:  $t = 8$ ,  $p < 0.001$ ; adolescents:  $t = 4.88$ ,  $p < 0.001$ ), but adults had comparable accuracy in congruent and incongruent trials ( $t = 1.88$ ,  $p > 0.05$ ). The interaction among reward type, reward magnitude and age group was significant on accuracy,  $F(4, 228) = 2.68$ ,  $p = 0.03$ ,  $\eta^2 = 0.05$ . In the social task, adults had larger accuracy than children and adolescents ( $ps < 0.005$ ); adolescents had larger accuracy than children in no reward condition ( $t = 2.89$ ,  $p = 0.013$ ). In the monetary task, adults had larger accuracy than children and adolescents in no reward and low reward conditions ( $ps < 0.005$ ); children had smaller accuracy than adolescents and adults in high condition ( $ps < 0.005$ ). For children, they had higher accuracy in social task than that in monetary task for high rewards ( $t = 2.43$ ,  $p = 0.017$ ). There were no other significant main or interaction effects.

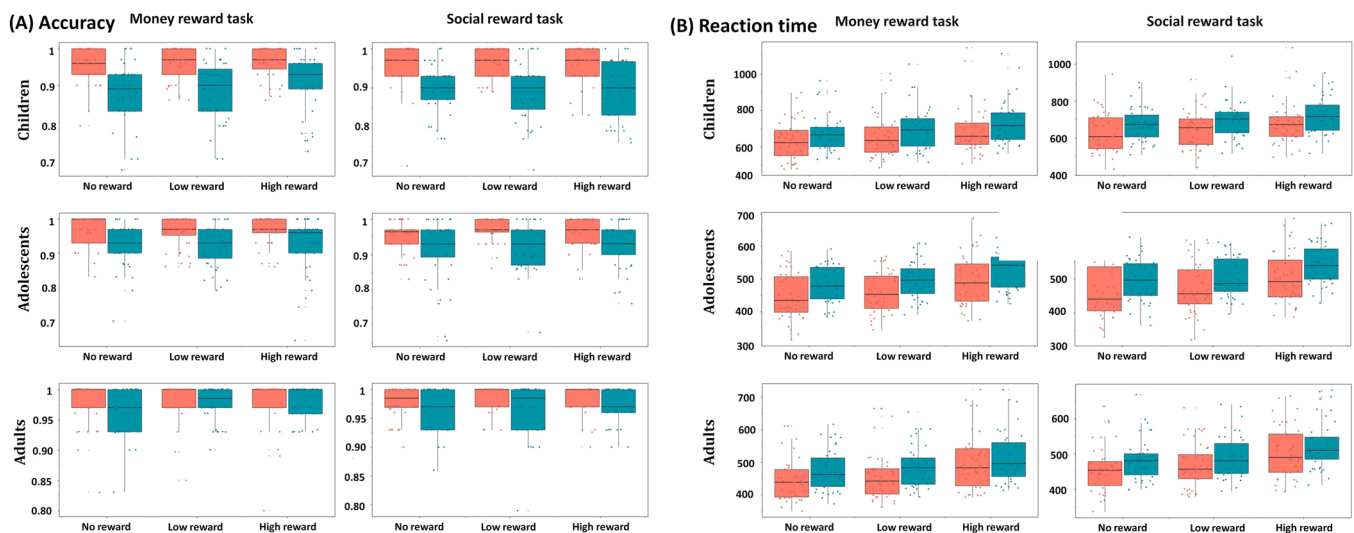


Fig. 2. Reaction time (ms) and accuracy for each age group in social and monetary tasks. Red boxes were for congruent trails and green boxes were for incongruent trials.

For RT, the main effect of age group was significant,  $F(2, 114) = 82.03, p < 0.001, \eta^2 = 0.59$ , children had longer RT than adolescents and adults (children vs. adolescents:  $t = 10.44, p < 0.001$ ; children vs. adults:  $t = 11.25, p < 0.001$ ). The main effect of reward magnitude was significant ( $F(2, 114) = 3.19, p = 0.04, \eta^2 = 0.03$ ), and RT was shorter under high reward condition than that under no and low reward conditions (high vs. no:  $t = 14.31, p < 0.001$ ; high vs. low:  $t = 9.29, p < 0.001$ ), and RT was shorter in low reward condition than that in no reward condition ( $t = 11.58, p < 0.001$ ). The main effect of congruency was significant ( $F(1, 114) = 8.13, p = 0.005, \eta^2 = 0.07$ ), and participant had faster response in congruent trials than in incongruent trials. The interaction between reward type and age group was significant,  $F(2, 114) = 3.47, p = 0.035, \eta^2 = 0.06$ , and adolescents showed faster RT in monetary task than that in social task ( $t = 2.65, p = 0.009$ ).

The HDDM parameters for each age group in social and monetary tasks are given in Fig. 3. For the drift rates, the main effect of age group was significant,  $F(2, 114) = 84.46, p < 0.001$ , and the drift rates of children were smaller than those of adolescents and adults (children vs. adolescents:  $t = 7.42, p < 0.001$ ; children vs. adults:  $t = 12.86, p < 0.001$ ), and the drift rates of adolescents were smaller than those of adults ( $t = 5.22, p < 0.001$ ), which suggested that the rates of evidence accumulation became faster with age development. The main effect of congruency was significant ( $F(1, 114) = 6.53, p = 0.01 < 0.03, \eta^2 = 0.05$ ), and the drift rates in congruent trials were larger than those in

incongruent trials. The interaction effect between congruency and age group was significant,  $F(2, 114) = 4.76, p < 0.01, \eta^2 = 0.08$ , and for children and adolescents, the drift rates in congruent trials were larger than those in incongruent trials (children:  $t = 6.39, p < 0.001$ ; adolescents:  $t = 4.48, p < 0.001$ ), which suggested that the rates of accumulation was faster in congruent trials than that in incongruent trials; there were no differences in drift rates between congruent and incongruent conditions for adults ( $t = 1.85, p > 0.05$ ), which might indicate that adults had comparable rates of accumulation in congruent and incongruent trials. The interaction among reward type, reward magnitude and age group was significant ( $F(4, 228) = 2.47, p = 0.046, \eta^2 = 0.04$ ). For adults, they had larger drift rates in high and low reward conditions than that in no reward condition under both monetary and social tasks ( $ps < 0.001$ ), and they had larger drift rates in monetary task than in social task under no reward condition ( $t = 2.11, p = 0.036$ ), low reward condition ( $t = 3.50, p < 0.001$ ) and high reward condition ( $t = 3.39, p < 0.001$ ). For adolescents, they had larger drift rates in high reward condition than that in no reward condition under the monetary task ( $t = 3.35, p = 0.003$ ), and they had larger drift rates in money task than in social task under the high reward condition ( $t = 3.59, p < 0.001$ ). The implication of these results was that adolescents had faster rates of evidence accumulation in high reward condition than in no reward condition for monetary rewards, and faster rates of accumulation for monetary rewards than social rewards under high reward condition.

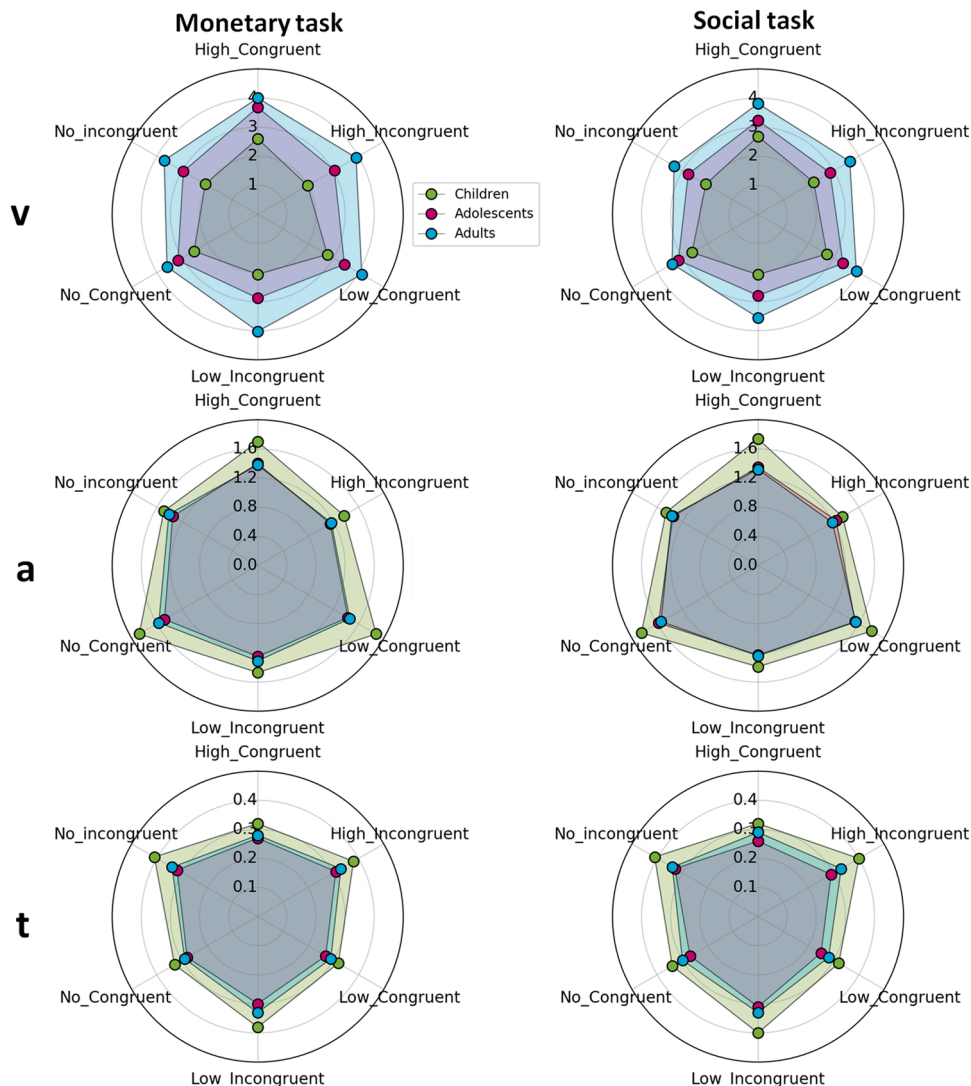


Fig. 3. The HDDM parameters for each age group. "v" stands for drift rates, "a" for decision thresholds, and "t" for non-decision time.

However, children did not show such differences.

With regard to the decision threshold parameter ( $a$ ), the main effect of age group was significant,  $F(2, 114) = 35.37, p < 0.001, \eta^2 = 0.38$ , and children had larger  $a$  value than adolescents ( $t = 7.09, p < 0.001$ ) and adults ( $t = 7.23, p < 0.001$ ), which suggested that larger amount of information was required for children to trigger the corresponding response compared to adolescents and adults. The main effect of congruency was significant,  $F(1, 114) = 7.9, p = 0.006, \eta^2 = 0.07$ , and incongruent trials had smaller  $a$  value than congruent trials, which indicated that smaller amount of information was required to make a response in incongruent trials than that in congruent trials.

For the non-decision time parameter ( $t$ ), the main effect of age group was significant ( $F(2, 114) = 34.72, p < 0.001, \eta^2 = 0.38$ ), and children had larger  $t$  value than adolescents ( $t = 8.8, p < 0.001$ ) and adults ( $t = 6.3, p < 0.001$ ), which suggested that it took children more time for sensory encoding of the information coupled with executing the motor response than adolescents and adults. The main effect of congruency was significant,  $F(1, 114) = 400.06, p < 0.001, \eta^2 = 0.78$ , and  $t$  value was smaller in congruent trials than that in incongruent trials, which indicated that less time was taken by the sensory encoding of the information coupled with executing the motor response in the congruent trials than in incongruent trials.

### 3.2. ERP data

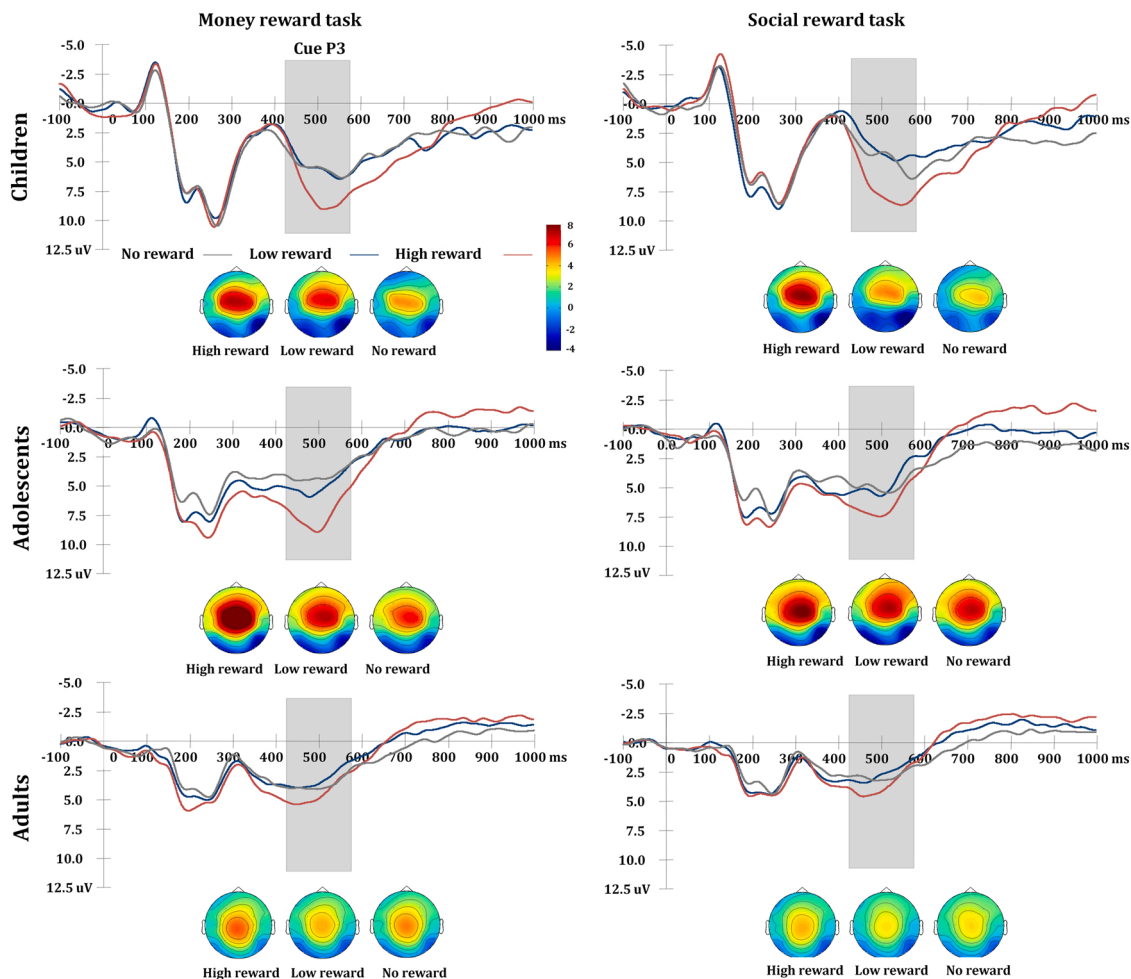
#### 3.2.1. Cue P3

The average waveforms and topographic maps of the cue P3

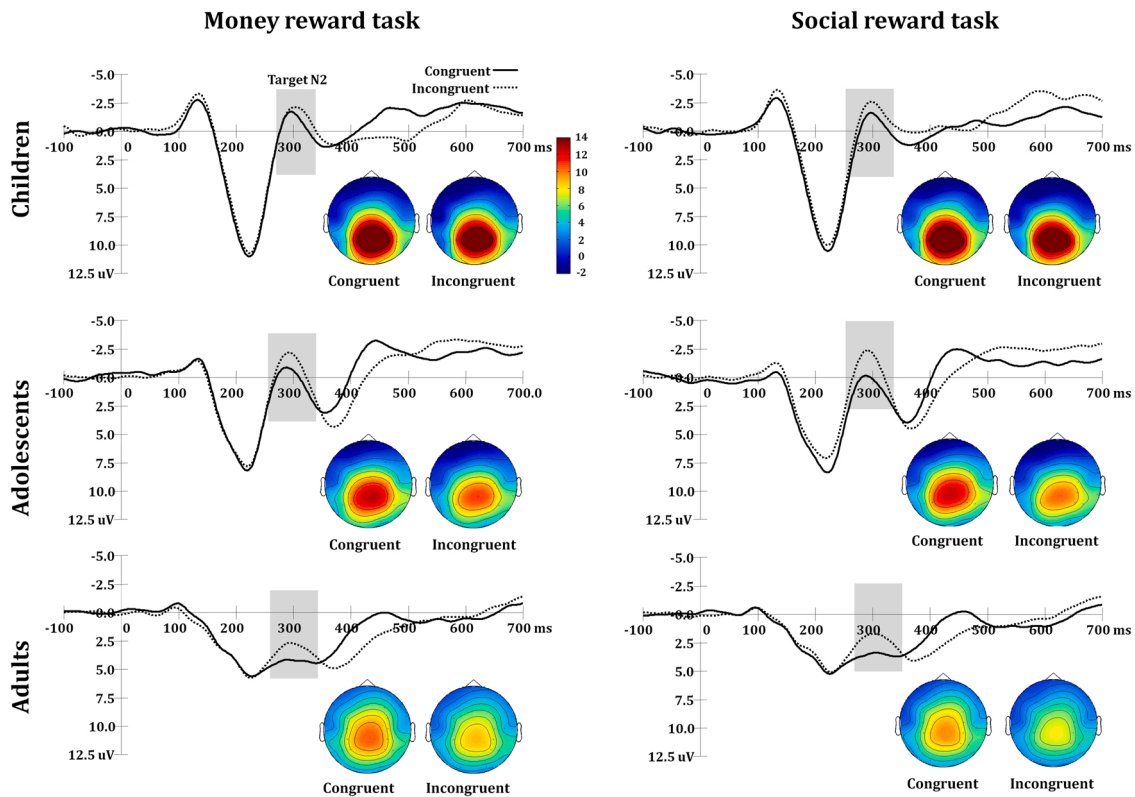
component are shown in Fig. 4. For cue P3 latency, a significant main effect of the age group was detected ( $F(2, 114) = 21.76, p < 0.001$ ); children showed longer cue P3 latencies than adolescents and adults (children vs. adolescents:  $t = 4.34, p < 0.001$ ; children vs. adults:  $t = 6.37, p < 0.001$ ). The main effect of the reward amount was significant ( $F(2, 228) = 4.16, p = 0.017, \eta^2 = 0.04$ ), and the latency of cue-P3 was shorter in the low reward condition than in no reward condition ( $t = 4.42, p < 0.001$ ). For cue P3 amplitude, the main effect of the age group was significant ( $F(2, 114) = 9.03, p < 0.001, \eta^2 = 0.14$ ); children and adolescents had greater cue P3 than adults (children vs. adults:  $t = 3.65, p < 0.001$ ; adolescents vs. adults:  $t = 3.79, p < 0.001$ ). The interaction between the age group and reward magnitude was significant ( $F(4, 228) = 2.63, p = 0.035, \eta^2 = 0.044$ ), and cue P3 amplitudes in high reward conditions were significantly larger than in the no reward and low reward conditions for all the age groups (children: non vs. high:  $t = 3.78, p < 0.001$ ; low vs. high:  $t = 5.87, p < 0.001$ ; adolescents: non vs. high:  $t = 5.45, p < 0.001$ ; low vs. high:  $t = 3.53, p = 0.002$ ; adults: non vs. high:  $t = 2.69, p = 0.025$ ; low vs. high:  $t = 2.8, p = 0.018$ ).

#### 3.2.2. Target N2

The average waveforms and topographic maps of the target N2 components are given in Fig. 5. For target N2 latency, a significant main effect of the age group was detected,  $F(2, 114) = 6, p = 0.003$ , and adolescents showed shorter N2 latencies compared to children ( $t = 3.31, p = 0.004$ ). For target N2 amplitude, a significant main effect of the age group was observed ( $F(2, 114) = 19.79, p < 0.001, \eta^2 = 0.26$ ); children and adolescents showed more negative N2 responses than adults



**Fig. 4.** The grand average waveforms and the topographic maps of cue P3 component for each age group. Children and adolescents had greater cue P3 than adults, and cue P3 amplitudes in high reward condition were larger than in no and low reward conditions.



**Fig. 5.** The grand average waveforms and the topographic maps of target N2 for conflict monitoring processes. Children and adolescents showed more negative N2 responses than adults, and N2 amplitudes were more negative in incongruent trials than in congruent trials.

(children vs. adults:  $t = 6.12$ ,  $p < 0.001$ ; adolescents vs. adults:  $t = 4.46$ ,  $p < 0.001$ ). The main effect of congruency was significant ( $F(1, 114) = 5.40$ ,  $p = 0.022$ ,  $\eta^2 = 0.05$ ), and the target N2 amplitudes were more negative in incongruent trials than in congruent trials. The interaction between reward magnitude and age group was significant,  $F(4, 228) = 4.52$ ,  $p = 0.002$ , and adolescents had more negative target N2 amplitude in no reward condition than that in low and high reward conditions (no vs. low:  $t = 2.94$ ,  $p = 0.012$ ; no vs. high:  $t = 3.67$ ,  $p < 0.001$ ), while the other two groups did not show these differences.

### 3.2.3. Target P3

For target P3 latency, the interaction between the age group and congruency was significant ( $F(2, 114) = 4.64$ ,  $p = 0.012$ ), and adolescents and adults had shorter P3 responses in congruent trials than in incongruent trials (adolescents:  $t = 4.67$ ,  $p < 0.001$ ; adults:  $t = 5.85$ ,  $p < 0.001$ ), and children did not show such differences between congruent and incongruent trials ( $p > 0.05$ ). For target P3 amplitude, a significant main effect of the age group was found ( $F(2, 114) = 29.28$ ,  $p < 0.001$ ); children showed greater P3 responses than adolescents and adults (children vs. adolescents:  $t = 4.69$ ,  $p < 0.001$ ; children vs. adults:  $t = 7.49$ ,  $p < 0.001$ ), and adolescents had larger P3 responses than adults ( $t = 2.69$ ,  $p = 0.024$ ). A significant interaction between the age group and reward magnitude was observed ( $F(4, 228) = 7.55$ ,  $p < 0.001$ ). Adolescents had larger P3 in high reward condition than no and low conditions, and larger P3 in low condition than no reward condition (high vs. no:  $t = 4.72$ ,  $p < 0.001$ ; high vs. low:  $t = 3.26$ ,  $p = 0.004$ ; low vs. no:  $t = 2.44$ ,  $p = 0.048$ ). Adults had larger P3 in low and high reward conditions than no reward condition (low vs. no:  $t = 3.14$ ,  $p = 0.006$ ; high vs. no:  $t = 3.46$ ,  $p = 0.002$ ). The interaction between the reward magnitude and congruency was significant ( $F(2, 228) = 6.86$ ,  $p < 0.001$ ). In low reward condition, participants had larger P3 in congruent trials than that in incongruent trials ( $t = 4.29$ ,  $p < 0.001$ ) and there were no such differences in other reward

conditions ( $ps > 0.05$ ). For congruent trials, P3 was larger in low and high reward conditions than that in no reward condition (no vs. low:  $t = 2.53$ ,  $p = 0.039$ ; no vs. high:  $t = 3.68$ ,  $p < 0.001$ ). For incongruent trials, P3 was larger in high reward condition than that in no and low reward conditions (high vs. no:  $t = 3.81$ ,  $p < 0.001$ ; high vs. low:  $t = 4.58$ ,  $p < 0.001$ ). The average waveforms and topographic maps of target P3 are presented in Fig. 6.

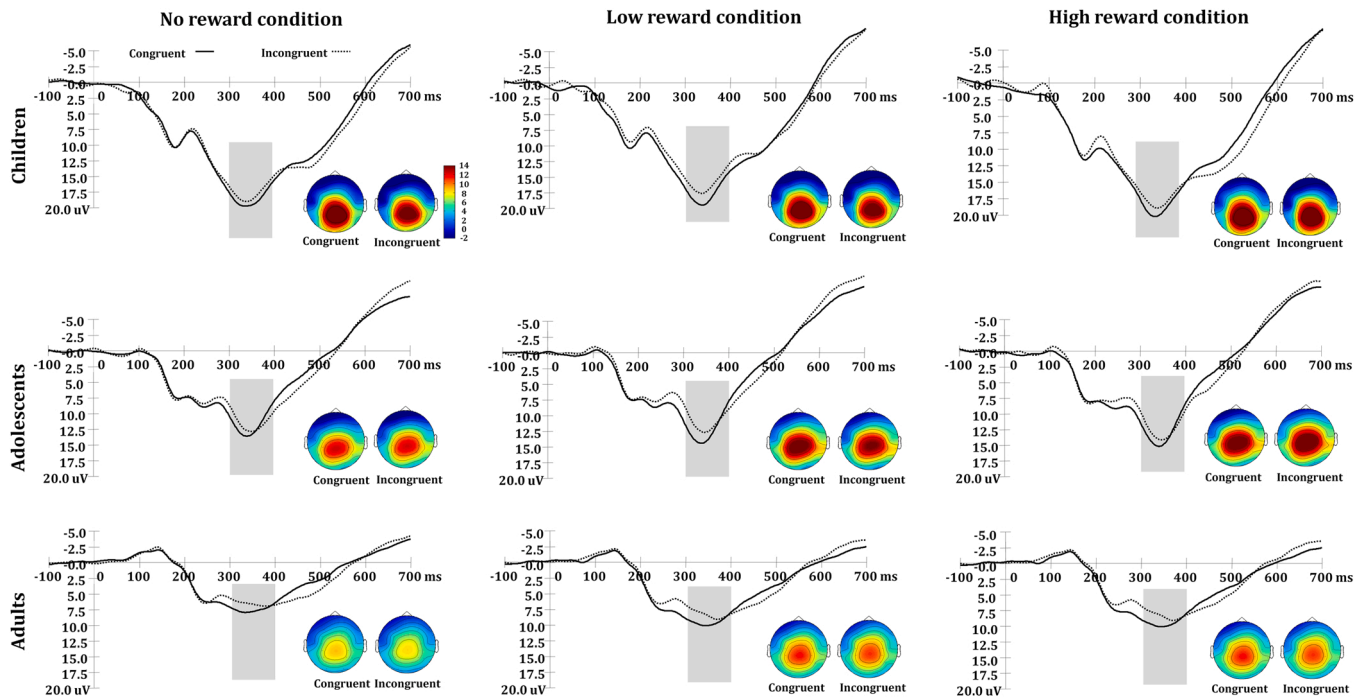
### 3.2.4. Feedback-related negativity (FRN) and $FRN_{residual}$

The waveforms and topographic maps of the FRN are shown in Fig. 7. For FRN amplitude, the main effect of age group was significant,  $F(2, 114) = 70.64$ ,  $p < 0.001$ ,  $\eta^2 = 0.55$ , and children had more negative FRN than adolescents ( $t = -7.53$ ,  $p < 0.001$ ) and adults ( $t = -11.57$ ,  $p < 0.001$ ), and adolescents had more negative FRN than adults ( $t = -3.89$ ,  $p < 0.001$ ). The interaction between reward magnitude and age group was significant ( $F(4, 228) = 15.28$ ,  $p < 0.001$ ,  $\eta^2 = 0.21$ ), and children had less negative FRN in no reward condition than that in low reward condition ( $t = 10.86$ ,  $p < 0.001$ ) and high reward condition ( $t = 9.2$ ,  $p < 0.001$ ). Adults had less negative FRN in no reward condition than in low reward condition ( $t = 2.51$ ,  $p = 0.04$ ). For  $FRN_{residual}$  amplitude, the main effect of age group was significant,  $F(2, 114) = 35.98$ ,  $p < 0.001$ ,  $\eta^2 = 0.39$ , and children had more negative  $FRN_{residual}$  than adolescents ( $t = 7.17$ ,  $p < 0.001$ ) and adults ( $t = 7.17$ ,  $p < 0.001$ ).

### 3.3. The correlation between HDDM parameters and ERP data

For the correlation between N2 responses and HDDM parameters, adults' non-decision time correlated with their N2 latencies in congruent trials under both high and low social reward conditions ( $r = 0.443$ ,  $p = 0.004$ ). Adults' decision threshold correlated with N2 amplitudes in congruent trials under no social reward condition ( $r = -0.513$ ,  $p = 0.001$ ). There were no significant correlations between HDDM





**Fig. 6.** The grand average waveforms and the topographic maps of target P3 for attentional control processes. P3 amplitudes significantly increased with age, and adolescents' P3 responses enhanced with the increasing reward magnitudes. Cognitive control on conflicts were modulated by reward magnitudes, and P3 amplitudes were larger in congruent trials than in incongruent trials only under low reward condition.

parameters and N2 responses in children and adolescents ( $ps > 0.005$ ).

For the correlation between P3 responses and HDDM parameters, adolescents' drift rates significantly correlated with P3 amplitudes in congruent trials under high social and low monetary reward conditions (high social reward condition:  $r = 0.447$ ,  $p = 0.004$ ; low monetary reward condition:  $r = 0.509$ ,  $p = 0.001$ ). Adults' non-decision time correlated with P3 amplitudes ( $r = -0.458$ ,  $p = 0.003$ ) and latencies ( $r = 0.535$ ,  $p < 0.001$ ) in congruent trials under high social and monetary reward conditions, respectively. Adults' non-decision time correlated with P3 amplitudes in incongruent trials under low social ( $r = -0.53$ ,  $p < 0.001$ ) and no social conditions ( $r = -0.531$ ,  $p < 0.001$ ) as well as high monetary ( $r = -0.603$ ,  $p < 0.001$ ) and no monetary conditions ( $r = -0.547$ ,  $p < 0.001$ ). Adults' decision threshold significantly correlated with P3 amplitudes in incongruent trial under low monetary reward condition ( $r = -0.475$ ,  $p = 0.002$ ) and in congruent trials under no monetary reward condition ( $r = -0.442$ ,  $p = 0.004$ ).

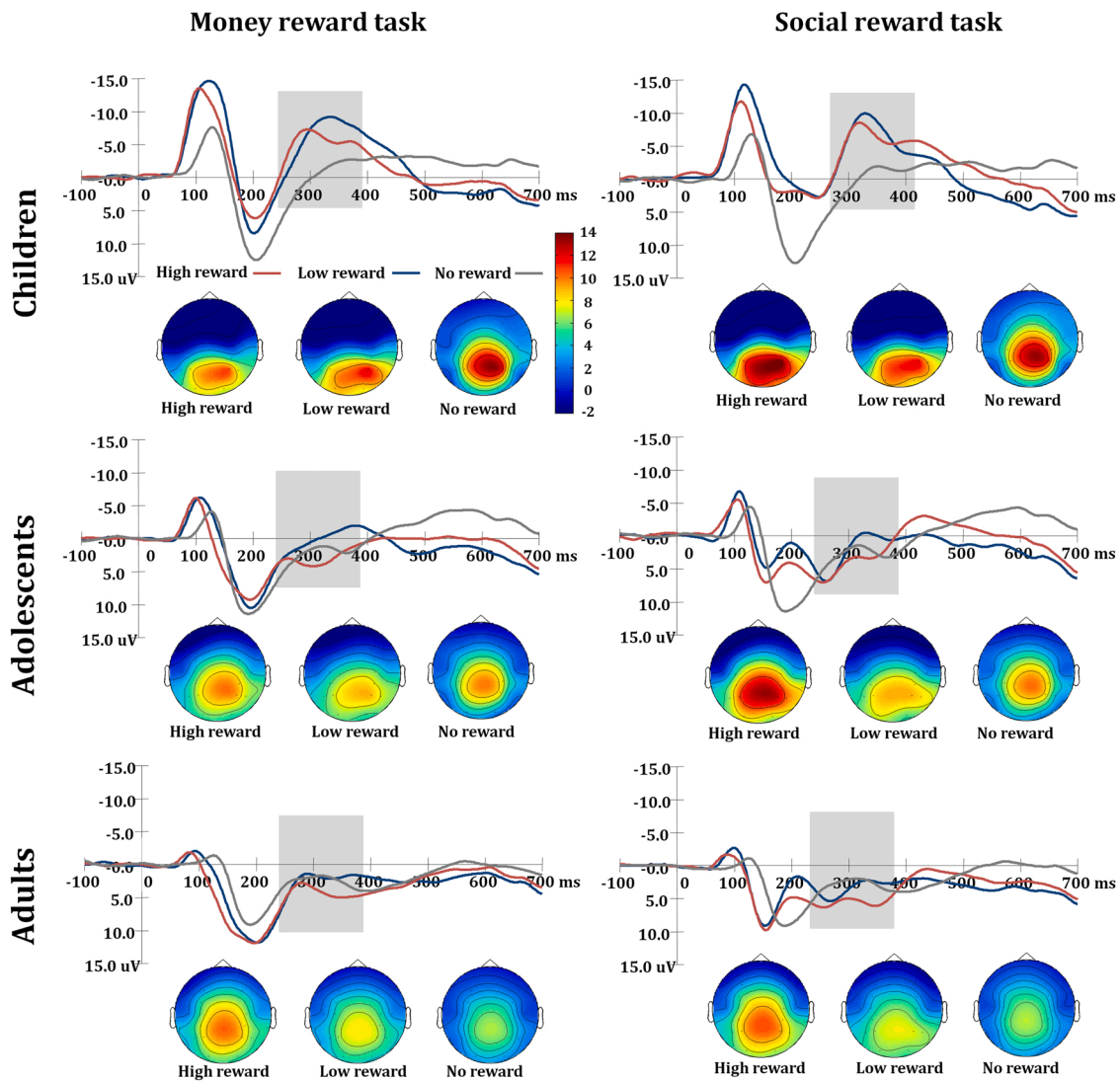
#### 4. Discussion

The current study investigated how the neurodevelopment of the reward process affects cognitive control processes in children, adolescents, and adults. Participants showed enhanced cognitive control performances with increase in age, and children had lower accuracy, longer RT, slower drift rates, higher decision threshold, and longer non-decision time than adolescents and adults, and adolescent had lower accuracy and slower drift rates than adults. More importantly, participants' response speed accelerated with the increase in reward magnitudes. Congruent trials had larger drift rates, lower decision threshold, and smaller non-decision time than incongruent trials. Cognitive control on conflicts could be modulated by reward magnitudes during neural process of attentional control, and P3 was larger in congruent trials than that in incongruent trials only in low reward condition.

##### 4.1. The development of reward process and reward-related cognitive control

It has been proposed that the influence of motivation on control function is presented in two aspects—(1) basic ability to process controlled information, (2) sensitivity to reward (Padmala and Pessoa, 2011). According to the dual-system theory (McKewen et al., 2019; Shulman et al., 2016; Steinberg et al., 2017), it is essential to investigate how reward anticipation affects conflict control from a developmental perspective. Our findings showed that children show lower accuracy and slower response speed than adolescents and adults, and adolescents have poorer performance than adults in the Simon task. In addition, according to the results of HDDM, the drift rates of adults were higher than adolescents and children, and the drift rates of adolescents were higher than children, which suggested that the rates of evidence accumulation became faster with child development. For the parameter of decision threshold, children had higher decision thresholds than adolescents and adults, that is, children need to accumulate more information to trigger the corresponding response in the face of competing alternatives (Voss et al., 2004). Iuculano et al. (2020) reported that children with autism showed higher decision threshold compared to their normal peers. These findings might demonstrate that individuals with poorer decision-making abilities would show higher decision thresholds. With regard to the parameter of non-decision time, children had longer non-decision time than adolescents and adults, which indicated that children spent more time for sensory information encoding plus executing the motor response and their conflict control process was less efficient compared to adolescents and adults. Taken together, these findings support that children have immature cognitive control abilities compared to adolescents and adults (Liu et al., 2018), and adolescents may have reached comparatively mature levels in decision thresholds and non-decision time as adults, but their rates of evidence accumulation still develops (Wilk and Morton, 2012).

Significant congruency effects were observed for both behavioural performance and neural responses, and individuals were faster in congruent trials than in incongruent trials, which was in the same vein



**Fig. 7.** The grand average waveforms and the topographic maps of feedback FRN for each age group. The FRN responses decreased with age. Children and adults' FRN responses were affected by the varied reward magnitudes, but adolescents did not show such affection.

with existing studies (Botvinick et al., 2004; Kerns et al., 2004; Mansouri et al., 2009; Tillman and Wiens, 2011; van Veen and Carter, 2002). Children and adolescents showed significant congruency effects for the accuracy and drift rates, and their accuracy and drift rates were higher in congruent trials than in incongruent trials. However, adults did not show the congruency effects and they had comparable accuracy and drift rates in both congruent and incongruent trials. These findings indicated that children and adolescents' rates of information accumulation was faster in congruent trials than that in incongruent trials, while adults had comparable rates of information accumulation in congruent and incongruent trials. A possible reason might be that in the reward context, adults take advantage of their more mature brain function to devote stronger cognitive control to both conflict and non-conflict stimuli, which leads to adults' comparable response accuracy and rates of information accumulation in incongruent and congruent trials (Liu et al., 2018). Moreover, the computational parameters of decision thresholds and non-decision time were also modulated by the congruency of the stimuli, and participants showed lower decision thresholds and longer non-decision time in incongruent trials than that in congruent trials, which indicated that smaller amount of information was required to trigger the corresponding response and more time was taken by the sensory information encoding coupled with executing the motor response in incongruent trials than in congruent trials.

The neural structures of the ACC, PFC, and parietal cortex play essential roles in the cognitive control of conflicts (Botvinick et al., 2004; Kerns et al., 2004; Kerns, 2006; van Veen and Carter, 2002). These regions are regarded as neural generators of N2 and P3 components (Polich, 2007). In the conflict detection process, it was found that adolescents had faster target N2 response than children, which indicates that adolescents have a more mature frontal function with faster neural response speed to detect the conflicts more quickly than children. Moreover, both children and adolescents were found to show greater target N2 responses than adults, which further suggests that children and adolescents have to devote more effort to detect conflicts compared with adults (Larson et al., 2012; Liu et al., 2018). These findings further support that the frontal function for conflict detection matures gradually with individual development, reaching a mature level of neural activity and brain connectivity for stable cognitive control in adulthood (Abundis-Gutiérrez et al., 2014; Erb et al., 2017; Friedman et al., 2009; Liu et al., 2018; Wilk and Morton, 2012). Here, it was found that N2 was stronger in incongruent trials than in congruent trials, and it suggests that individuals had to devote more resources to detect conflicts under both social and monetary reward conditions (Chan et al., 2016; Demurie et al., 2011, 2012; Flores et al., 2015; Rademacher et al., 2010; Spreckelmeyer et al., 2009; Wang et al., 2017).

Furthermore, target P3 amplitudes decreased with age, which

indicates that children and adolescents may have less mature parietal function. This is consistent with previous studies showing brain efficiency is enhanced with age during the neurodevelopment of cognitive control (Wilk and Morton, 2012), especially for the cognitive control of conflicts (Abundis-Gutiérrez et al., 2014). These findings suggest that children and adolescents have lower neural efficiency and need to devote more parietal effort to complete the attentional control process and to achieve the similar levels of adults during conflict control process (Larson et al., 2012; Liu et al., 2018). More importantly, reward magnitudes exerted a remarkable influence on attentional control process, and participants showed greater target P3 in congruent trials than in incongruent trials only under low reward condition. These findings suggest that median level of motivation could induce congruency effects and provide further evidence that rewards could have effect on cognitive control from a human development perspective (Diao et al., 2016; Dixon and Christoff, 2012; Engelmann et al., 2009; Freeman and Aron, 2016; Locke and Braver, 2008; Padmala and Pessoa, 2011).

Regarding the neurodevelopment of reward motivation, children and adolescents had stronger cue P3 responses than adults, which further indicated that children and adolescents are more sensitive to reward-related cues and induce stronger neural activity than adults (Wang et al., 2020). For the feedback processing, we found that the magnitude of FRN amplitudes decreased with age, which was in the same vein with several existing studies and demonstrated that children are more sensitive to external feedback compared to adolescents and adults (Crowley et al., 2013; Hämmerer et al., 2011; Wang et al., 2020). Compared to adolescents and adults, children's stronger neural responses to external feedback might be related to their immature ability to execute internal motor control (Luna and Sweeney, 2004).

The results of correlation analysis between neural responses and HDDM parameters showed that adults' non-decision time correlated with their conflict monitoring process (N2 latency) and attentional control process (P3 amplitude and latency), and their decision threshold correlated with their conflict monitoring process (N2 amplitude) and attentional control process (P3 amplitude). These findings might further indicate that adults' mature frontal and parietal brain function was essential for efficient sensory encoding of the information and motor response speed as well as the amount of information required to trigger the response. Consistently, several studies have revealed that decision threshold is modulated by the conflict-related process and relies on the neural activity in the frontal cortex (Cavanagh et al., 2011; Cavanagh and Frank, 2014; Frank et al., 2015). Our current study further demonstrated that decision threshold not only correlated with neural activity in frontal cortex but also in parietal cortex during cognitive control on response conflicts. More importantly, adolescents' drift rates were found to be significantly correlated with attentional control process (P3 amplitudes), which suggests that adolescents might have developed comparatively mature parietal function to bridge the association between neural activity during attentional control and the rates of evidence accumulation. However, children did not show any correlation between neural responses and HDDM parameters during conflict control process, which might be due to their immature brain function.

#### 4.2. The influence of reward magnitude and reward types on cognitive control processes

Consistent with previous studies, we also observed that participant's performance speed increases with the enhancement of reward magnitude, which demonstrates that rewards make an essential role in promoting individuals' performances (Demurie et al., 2012; Kohls et al., 2009; Spreckelmeyer et al., 2009; Stavropoulos and Carver, 2013; Wang et al., 2017; Wei et al., 2015). The current findings of computational model revealed that adolescents had higher drift rates under high reward condition than no reward condition in the monetary reward task. While, adults showed higher drift rates under high and low reward conditions than that under no reward condition in both monetary and

social tasks. Similarly, a previous study also found that drift rates could be modulated by reward magnitudes (Yankouskaya, Bührle, Lugt, Stolte, and Sui, 2020). These observed behavioural phenomena can be further explained by the present electrophysiological findings. First, from the aspect of motivation responses, the current neural activities of cue perception showed that cue P3 was greater under the high reward condition than under the low and no reward conditions, and cue P3 latency was shorter in low reward condition than in no reward condition. These findings suggest that higher magnitude of rewards might induce stronger and faster neural responses compared with the lower magnitude of rewards. Second, from the conflict monitoring and attention control aspect, adolescents had more negative target N2 amplitude in no reward condition than that in low and high reward conditions, and their target P3 response was larger under higher reward condition than under lower and no reward conditions, which might indicate that more attention and control resources were allocated and devoted under the high reward situation. Adults showed larger P3 under reward (both high and low reward) conditions than under the no reward condition. Taken together, these findings shed more light on how different magnitudes of rewards lead to varied cognitive control performance (Libera and Chelazzi, 2006; Small et al., 2005; Watanabe, 2007; Wei et al., 2015).

The current study also found that reward types could modulate children's cognitive control performance, with higher accuracy in social task than that in monetary task under high reward condition. Adolescents had shorter RT in monetary task than in social task. Adults had higher drift rates in monetary task than in social task. These findings suggest that these two types of rewards play different roles and rely on different brain networks during varied child development stages (Chan et al., 2016; Rademacher et al., 2010; Spreckelmeyer et al., 2009). Furthermore, adolescents had higher drift rates in monetary task than in social task under high reward condition, and they showed higher drift rates under high reward condition than under no reward condition in the monetary task. These HDDM findings indicated that reward type and reward magnitude interplayed to modulate adolescents' cognitive control behaviours, and adolescents can be strongly motivated by monetary rewards compared to social rewards (Demurie et al., 2011, 2012; Flores et al., 2015; Spreckelmeyer et al., 2009; Wang et al., 2017). They further supported that adolescents are hypersensitive to rewards, especially high magnitude of rewards (Bjork et al., 2004; Casey et al., 2008; Ernst et al., 2005; Foulkes and Blakemore, 2016; Geier et al., 2010; Hoogendam et al., 2013; Lamm et al., 2014; Nees et al., 2012; Richards et al., 2013; Shulman et al., 2016; Silverman et al., 2015; Steinberg et al., 2017; Urošević et al., 2012; Van Leijenhorst et al., 2010; Wahlstrom et al., 2010).

## 5. Conclusion

This study found that cognitive control processes develop with age, and all age groups show significant congruency effects at both behavioural and neural levels. Rewards can modulate attentional control process with significant congruency effects under low reward condition. Adolescents' neural processes of conflict monitoring and attentional control could be adjusted by reward magnitude. Different age groups showed varied correlations between neural activity during cognitive control and HDDM parameters. In summary, the present study suggests that reward anticipation affects the development of cognitive control processes based on computational models and electrophysiological findings.

#### CRedit authorship contribution statement

**Tongran Liu:** Supervision; Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Methodology, Software, Visualization, Writing – review & editing, Funding acquisition. **Di Wang:** Data curation; Methodology, Writing – original draf. **Chenglong Wang:** Data curation, Formal analysis, Methodology, Software,



Visualization. **Tong Xiao**: Data curation, Formal analysis, Methodology, Software, Visualization. **Jiannong Shi**: Supervision; Conceptualization; Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Readers can access to the data by directly connecting the corresponding author, liutr@psych.ac.cn. Data will be available after the completion of a data transfer agreement.

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