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RESEARCH ARTICLE

Midfrontal theta oscillations and conflict monitoring in children and adults

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Abstract

Conflict monitoring is central in cognitive control, as detection of conflict serves as a signal for the need to engage control. This study examined whether (1) midfrontal theta oscillations similarly support conflict monitoring in children and adults, and (2) performance monitoring difficulty influences conflict monitoring and resolution. Children ($n = 25$) and adults ($n = 24$) completed a flanker task with fair or rigged response feedback. Relative to adults, children showed a smaller congruency effect on midfrontal theta power, overall lower midfrontal theta power and coherence, and (unlike adults) no correlation between midfrontal theta power and N2 amplitude, suggesting that reduced neural communication efficiency contributes to less efficient conflict monitoring in children than adults. In both age groups, response feedback fairness affected response times and the P3, but neither midfrontal theta oscillations nor the N2, indicating that performance monitoring difficulty influenced conflict resolution but not conflict monitoring.

KEYWORDS
children, cognitive control, conflict monitoring, EEG, midfrontal theta oscillations

1 | INTRODUCTION

As children grow older, they control their attention and actions with increasing efficiency, which in turn supports growing behavioral complexity, flexibility, and autonomy. Such cognitive control critically hinges on monitoring of conflict (or interference) between goal-relevant and irrelevant information (e.g., different interpretations of the same word) or responses (e.g., different possible sequences of notes while learning a musical piece). Detection of conflict serves as a signal for the need to engage greater cognitive control (to resolve this conflict) through top-down biasing of sensory information processing and response selection (e.g., Botvinick et al., 2001; Shenhav et al., 2013). Performance in situations that require conflict monitoring and resolution improves during childhood (Ambrosi et al., 2019; Ambrosi et al., 2020; Cragg, 2016; Erb & Marcovitch, 2018, 2019; Iani et al., 2014; McDermott et al., 2007). However, it is not clear whether and how conflict monitoring may change and contribute to behavioral improvement with age.

Conflict monitoring and resolution are supported by the interplay between the cingulo-opercular and frontoparietal networks underlying cognitive control (e.g., Shenhav et al., 2013; Wu et al., 2020). Slow neural oscillations in the theta frequency band (4–8 Hz) provide a medium for neural communication within and across these functional networks (Cavanagh & Frank, 2014). Specifically, greater midfrontal (frontomedial) theta oscillations originating in the anterior cingulate cortex (ACC) when conflict is detected may serve as a signal for the need for more top-down control over sensory information processing. To recruit more control, this signal may be communicated from the ACC to the lateral prefrontal cortex (PFC) through enhanced functional connectivity within the theta band. Meanwhile, control implementation to resolve conflict, including goal maintenance and biasing of sensory information processing and response selection, likely involves cross-frequency coupling between slow oscillations (<20 Hz) in lateral PFC and high-frequency oscillations in sensory and motor cortices (Cavanagh & Frank, 2014; Eschmann et al., 2018; Helfrich & Knight, 2016). The role of theta oscillations in conflict monitoring

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can be observed in the flanker task (Eriksen & Eriksen, 1974). In this task, participants must respond to the orientation of a central target while ignoring flanking distractors. The flankers can have the opposite orientation, hence generating conflict that needs to be detected and resolved. Midfrontal theta oscillations show greater power (i.e., amplitude squared, which reflects the strength of theta activity), temporal coherence (i.e., phase angle synchrony across trials within the same channel), and connectivity with lateral frontal channels (i.e., phase angle synchrony across different channels) in incongruent (i.e., flankers and target conflict) than congruent (i.e., no conflict between the target and flankers) trials in adolescents and adults (Buzzell et al., 2019; Gyurkovics & Levita, 2021).

It is unclear whether midfrontal theta power supports conflict monitoring in children the way that it does later in development. However, it relates to cognitive performance more generally (in contexts other than the flanker task) from infancy on (e.g., Braithwaite et al., 2020; Canen & Brooker, 2017; Uhlhaas et al., 2009). As functional connectivity both between the cingulo-opercular (including ACC) and frontoparietal (including lateral PFC) networks, and within each network, increases during childhood and adolescence (Baum et al., 2017; Fair et al., 2008; Luna et al., 2015), it is possible that more mature patterns of theta oscillations support growing efficiency in conflict monitoring and better signal the need for more control over sensory information processing. This increase in maturity seems to occur during later childhood, as studies using the Simon and Go/No-Go tasks have reported little variation in midfrontal theta power as a function of conflict in 4- to 8-year-olds (Adam et al., 2020), but have shown an increase in midfrontal theta power and coherence from middle childhood to adulthood (Liu et al., 2014; Papenberg et al., 2013). Increase in midfrontal theta oscillations directly relates to cognitive control performance. In particular, greater midfrontal theta coherence is associated with less response time (RT) variability (Papenberg et al., 2013), suggesting that conflict monitoring may become more temporally reliable with age.

Besides midfrontal theta power, conflict monitoring has been probed through event-related potentials, especially the N2. This component corresponds to a frontocentral negative deflection that is generated in the ACC and shows larger amplitudes on incongruent than congruent trials in the flanker task in both adolescents and adults (e.g., Erb & Cavanagh, 2019; Groom & Cragg, 2015; Overbye et al., 2021). In children, however, N2 findings are much less clear. Some studies have reported a pronounced N2 congruency effect in children (Grützmann et al., 2021; Hadley et al., 2020; Johnstone & Galletta, 2013; Overbye et al., 2021), but others have shown no effect or a much-reduced effect before preadolescence (Abundis-Gutiérrez et al., 2014; Checa et al., 2014; Reuter et al., 2019; Rueda et al., 2004), making it difficult to draw firm conclusions about conflict monitoring efficiency at that age. In contrast, a congruency effect is consistently observed for the P3 across development (e.g., Johnstone & Galletta, 2013; Overbye et al., 2021; Rueda et al., 2004). The P3 is a later-occurring centroparietal positivity, which is associated with the frontoparietal network and reflects effortful/attentional processing of the target, that is, how much top-down control is implemented to resolve conflict (e.g., Erb & Cavanagh, 2019; Groom & Cragg, 2015; Johnstone & Galletta, 2013).

Finally, midfrontal theta oscillations also support performance monitoring, including feedback processing, across development (Albrecht et al., 2009; Bowers et al., 2018; Crowley et al., 2014). However, an open question is whether and how performance monitoring and conflict monitoring, which are both supported by midfrontal theta oscillations, relate to each other. Facilitation of performance monitoring and control adjustment through response feedback, which conveys information about goal attainment, yields better behavioral performance in children, especially in incongruent trials (Oeri et al., 2019). However, it is unknown whether response feedback benefits performance via better conflict monitoring, better conflict resolution, or both. Response feedback may affect conflict resolution to a greater extent than conflict monitoring because (1) conflict monitoring may correspond to a more implicit or automatic form of cognitive control than conflict resolution (see Erb & Cavanagh, 2019; Gonthier et al., 2021), and (2) information about how well one is doing may help to ramp up or release top-down control over information processing regardless of conflict. Alternatively, response feedback may increase vigilance and benefit both conflict monitoring and resolution. Importantly, this effect may differ with age. Children may rely on response feedback to a greater extent than adults, who are more likely to monitor performance internally. Indeed, the beneficial effect of response feedback is greater in younger than older children (Oeri et al., 2019) and adolescents and adults show more mature online performance monitoring than children (Crone et al., 2006; Hadley et al., 2020).

This study examined whether conflict monitoring is (1) similarly supported by midfrontal theta oscillations in children and adults, and (2) influenced by performance monitoring difficulty. To this end, EEG data were recorded while children and adults performed a flanker task with fair or partly rigged feedback. Target duration was adjusted online as a function of prior responses so that task difficulty would be equally challenging for all participants and to ensure frequent sampling of all feedback options (correct, incorrect, too late; Canen & Brooker, 2017; Checa et al., 2014; Hadley et al., 2020). Conflict monitoring was measured via midfrontal theta power and coherence and N2 amplitudes, while conflict resolution was indexed by P3 amplitudes. Less efficient conflict monitoring in children should yield smaller midfrontal theta power and coherence as well as less pronounced congruency effects on power, coherence and N2 in children than adults. Less efficient conflict resolution should be evidenced by a less pronounced congruency effect on P3 in children than adults. Although predictions were open as whether the manipulation of performance monitoring difficulty through response feedback fairness would affect conflict monitoring, conflict resolution, or both, we expected greater effects in children than adults.

2 | METHODS

2.1 | Participants

Study participants included 25 children (M age = 7.4 years, SD = 1.4 years, range = 5–10, 9 females) and 24 adults (M age = 23.1 years,

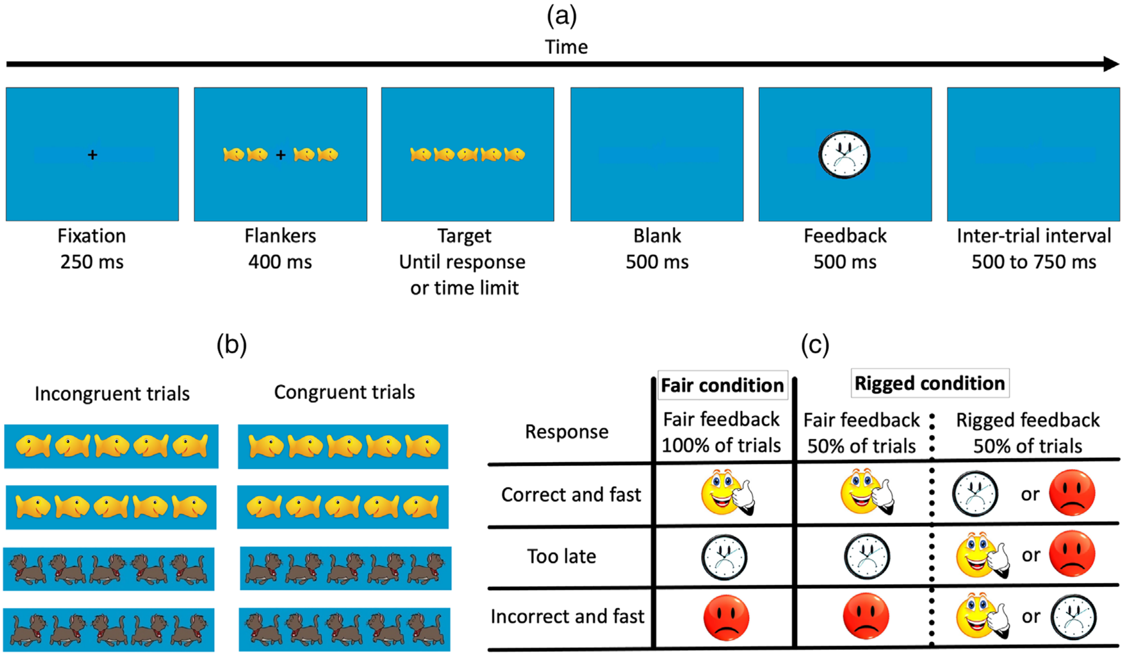

FIGURE 1 Illustration of the flanker task. Participants had to respond to the centrally presented target while ignoring the flanker distractors, by pressing the response button on the side the target was facing. (a) Example of a trial. (b) Stimuli presented in incongruent and congruent trials. (c) Feedback contingency in the Fair and Rigged conditions

SD = 3.5 years, range = 19–31, 16 females). An additional 11 children and five adults were recruited but later excluded because of failure to complete the session (one child), technical issues (two children, five adults) or EEG data being too noisy (i.e., fewer than 10 good segments per experimental cell: eight children). We recruited about 20% more children than adults, as we anticipated a greater exclusion rate for children. Children were recruited from the local community and were mostly from middle to high socioeconomic backgrounds, although family demographic information was not systematically collected. They received a small, age-appropriate prize at the end of the session while accompanying caregivers were compensated £10. Adults were university students and received £10 compensation. Adult participants and caregivers provided written, informed consent. Child participants provided verbal assent as well as written assent if they were at least 7 years old.

2.2 | Materials and procedure

Trained experimenters tested each participant individually in a 90-min session. After EEG cap application, participants completed the flanker task (Figure 1) in which they had to attend and respond to a central target while ignoring four flanker distractors (two on each side of the target). They were instructed to keep their index fingers over the two response buttons constantly during the task and to press the button that matched the orientation (left or right) of the target as quickly and accurately as possible. In congruent trials, the flankers had the same orientation as the central target (no conflict between the target and flankers), but in incongruent trials, their orientation was opposite to the central target, hence generating conflict. They were as many congruent as incongruent trials and the two trial types were randomly interleaved.

Each participant completed two conditions (order counterbalanced across participants) with different response feedback contingencies in order to manipulate the difficulty of performance monitoring. In the Fair condition (low performance monitoring difficulty), response feedback consisted of a smiley face if the response was correct and fast, a clock if the participant did not respond in time, or a frowning face if an error was made. In the Rigged condition (high performance monitoring difficulty), response feedback matched the participant's actual response (i.e., same contingencies as in the Fair condition) in half of the trials, but it was rigged in the other half of the trials. Specifically, in these trials, participants saw one of the two response feedback options that did not match their actual response (e.g., if they entered a fast and correct response, they would see either a clock or a frowning face instead of a smiley face), with an equal probability for each option. Thus, mismatched feedback could result in a worse or better outcome than would have been given with the correct feedback. Matching and nonmatching response feedback was randomly mixed within the Rigged condition. Participants did not receive any instructions informing them about feedback fairness in either condition.

Each trial started with a central black fixation cross on a blue background for 250 ms, followed by the flankers for 400 ms. The target then replaced the fixation cross in the middle of the flankers until a response was entered or the RT limit was reached, whichever came first. Then there was a blank screen for 500 ms before the response feedback was displayed for another 500 ms. The following inter-trial interval (second blank screen) was jittered between 500 and 750 ms. The time limit was initially calculated as 1.25 × the mean RT during the practice trials and was then adjusted online after each trial in a staircase fashion (regardless of trial congruency): it was increased by 17 ms after an error or no response and decreased by 17 ms after a correct response. This procedure ensured that the task would be equally challenging for all participants and all three feedback options (smiley face, clock, or frowning face) would be frequently presented (Canen & Brooker, 2017; Checa et al., 2014; Hadley et al., 2020).

Each condition started with 16 practice trials with no time limit, followed by eight speeded trials with the same time limit as for test trials. Test trials were presented in blocks of 60, with a total of 240 test trials (120 trials per condition). To keep participants engaged, the stimuli (fish or cats) changed from one condition to the next and the stimuli–condition combinations were counterbalanced across participants.

2.3 | Data recording and processing

2.3.1 | Response times

RTs were analyzed for correct responses after removing outliers, that is, values above M + 3*SD* or under M – 3*SD* (1.5%), and were log-transformed to control for skew. For the sake of clarity, reported values were back-transformed. Following Papenberg et al. (2013), RT variability was measured by the squared root of RT standard deviations, in order to correct for deviations from normality within age group distributions (Tabachnick & Fidell, 2007).

2.3.2 | EEG data

EEG data were recorded using a BioSemi ActiveTwo system with 64 channels (BioSemi BV, Amsterdam, the Netherlands) and a 512-Hz sampling rate. Impedances were kept below 50 kΩ during data acquisition. The data were processed offline using EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon & Luck, 2014), and custom scripts. The continuous data were re-referenced to the average of the two mastoids and high-pass filtered (0.1 Hz). The data were segmented from −1 to 2 s after target onset and only trials with either a correct response or no response were retained (i.e., trials with errors were excluded). This maximized the number of trials in the analysis, ensuring the robustness of the EEG measures, and avoided underestimating (trials with errors) or overestimating (trials with correct responses only) the efficiency of conflict monitoring and resolution. Bad channels were automatically rejected (Kurtosis threshold = 5). The channels were visually inspected and any remaining bad channels were manually removed (total bad channels: M = 3.4, SD = 2.1). An independent component analysis (ICA) was run to correct for eye-blinks and other eye-movement artifacts, using ADJUST (Mognon et al., 2011). Missing channels were then replaced through spline interpolation. The initial epochs were converted back to continuous data and segmented again in ERPLAB for further preprocessing in ERPLAB as indicated below.

2.3.3 | Midfrontal theta power

The data were segmented from −1000 to 1500 ms around target onset, with the 300 ms period going from −1000 to −700 ms before target onset (i.e., −350 to −50 ms before the fixation cross) as baseline. This baseline was selected to avoid flankers-related activity contaminating target-related power while ensuring adequate estimation of low frequencies. Segmented data were Laplacian transformed (current source density; Cohen, 2014) to increase topographical specificity and attenuate volume conduction (Kayser & Tenke, 2015). Remaining artifacts were rejected using a 200-ms peak-to-peak moving window with 200-Hz maximum amplitude threshold and a 100-ms window step. All participants in the final sample had at least 10 good segments per experimental cell. To compute total power, which reflects both phase and nonphase-locked activity at the single trial level, time–frequency decomposition was performed by convolving target-locked single-trial data with complex Morlet wavelets of 30 frequencies, which increased from 2 to 30 Hz in logarithmically spaced steps (Cohen, 2014). Wavelet cycles varied from 3 to 10 as frequency increased. To avoid edge artifacts, the data were reflected on both side before time–frequency decomposition and the reflected data were cut out afterward. Power values were normalized and decibel (dB) transformed[1] at each frequency using the average power across all experimental cells between −1000 and −700 ms before target onset as baseline. The procedure to extract mean power was adapted from Gyurkovics and Levita (2021). Mean power was averaged at FCz across the 4–8 Hz frequency band separately for each time point between 100 and 500 ms after target onset. For each experimental cell of each participant, mean power was extracted for a 50-ms window around the latency for the peak power value.

2.3.4 | Inter-trial phase clustering

Besides power, Inter-trial phase clustering (ITPC) was calculated during time–frequency decomposition in order to examine the synchrony of midfrontal theta oscillations across trials. For each frequency and time point, ITPC reflects the similarity of the oscillatory phase angles across trials. ITPC values range from 0 (no synchrony across trials) to 1 (perfect synchrony across trials). Mean ITPC values were extracted at FCz for 4–8 Hz between 100 and 500 ms after target onset. As ITPC calculation is inherently scaled to, and thus influenced by, the number of available trials (Buzzell et al., 2019), we used a subsampling procedure to equate the number of trials across all experimental cells and participants. The minimum number of trials per experimental cell observed across participants was 13. Thus, a subsample of 13 trials per experimental cell and participant was randomly selected for

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[1] Recent work suggests that, when non-oscillatory 1/f background “noise” differs between groups, as may be the case across age groups, dB transformation of power may distort the magnitude of the observed effects, and other baselining methods (e.g., baseline subtraction) may be preferrable (Gyurkovics, Clements, Low, Fabiani, & Gratton, 2021). However, we elected to use dB transformation for the sake of ease of interpretation and comparability with previous studies.

TABLE 1 Mean percentage of correct responses, no responses, and errors as a function of condition, congruency, and age group

		Fair		Rigged	
		Congruent	Incongruent	Congruent	Incongruent
Children	Correct	66.7 (6.8)	48.9 (13.1)	65.6 (12.6)	50.1 (12.8)
	Error	7.7 (4.6)	17.3 (12.3)	10.7 (9.0)	17.3 (10.6)
	No-response	25.6 (6.4)	33.8 (8.9)	23.7 (11.9)	32.5 (14.9)
Adults	Correct	63.8 (9.6)	43.1 (9.2)	70.2 (10.6)	44.4 (7.7)
	Error	6.3 (7.3)	15.3 (11.9)	5.0 (7.8)	14.4 (12.2)
	No-response	29.9 (9.0)	41.5 (11.1)	24.8 (10.6)	41.3 (13.9)

Note: Standard deviations are provided in parenthesis.

ITPC computation and this procedure was repeated 20 times. The ITPC values were then averaged across the 20 iterations. (The data were not reflected during this procedure, as the window of interest was far enough from the segment edges to avoid artifacts.) ITPC values were extracted following the same procedure as for power values.

2.3.5 | Target-locked N2 and P3

For ERPs, the data were processed in the same way as for time–frequency analyses, but with the following exceptions: (1) the data were low-pass filtered (30 Hz), (2) the segments were shorter (from −200 to 1000 ms) with the initial 200 ms as baseline period, and (3) the data were not Laplacian transformed. As the N2 was maximal over Fz and FCz, these channels were used to extract mean amplitude between 325 and 375 ms in children and 225 to 275 ms in adults in order to adequately capture the N2 peak in each age group, based on visual inspection. The P3 was maximal at CPz in both age groups during windows going from 450 to 650 ms in children and 300 to 400 ms in adults, which were used to calculate mean amplitude in each age group. Outliers over 100 μV or M + 3*SD* or below −100 μV or M – 3*SD* were removed (0.7%). For both components, there were on average 45 good segments per experimental cell in children and 53 in adults.

2.4 | Data analysis

The data were analyzed with a series of ANOVAs including age group (children, adults), congruency (congruent, incongruent), and condition (fair, rigged) as predictors. As gender distribution differed between age groups, $\chi^2(1) = 4.61$, $p = .031$, gender was entered as a covariate in all models. In addition, the number of trials was also entered as a covariate for all models except ITPC. Relations among variables were probed with Pearson correlations. For correlations, N2 amplitudes was averaged across Fz and FCz and flipped so that higher values denoted more pronounced (i.e., more negative) amplitudes. For the sake of clarity and because we observed no effects of response feedback condition on conflict monitoring indices, response feedback conditions were collapsed in the correlation analyses.

3 | RESULTS

3.1 | Behavior

3.1.1 | Error rates

Staircase adjustment of the RT limit purposefully kept accuracy relatively low: .57 overall. However, given that incorrect trials could correspond to either no responses or errors, we analyzed error rates, which were higher in incongruent (.16) than congruent trials (.08), $F(1, 47) = 51.19$, $p < .001$, $\eta^2_p = .521$ (Figure 2a). No other effects were significant, *p*'s > .268. Percentages of correct responses, errors, and no responses as a function of age group, condition, and congruency are provided in Table 1.

3.1.2 | Response times

RTs on correct trials (Figure 2b) were slower in children (441 ms) than adults (287 ms), $F(1, 47) = 53.37$, $p < .001$, $\eta^2_p = .533$, and incongruent (378 ms) than congruent (336 ms) trials, $F(1, 47) = 85.21$, $p < .001$, $\eta^2_p = .645$. Congruency interacted with condition, $F(1, 47) = 7.64$, $p = .008$, $\eta^2_p = .139$, due to a larger congruency effect in the Rigged condition (52 ms, $p < .001$) than the Fair condition (33 ms, $p < .001$). Specifically, RTs were slower in the Rigged than Fair condition in incongruent (389 ms vs. 368 ms, $p = .022$), but not congruent trials (337 ms vs. 335 ms, $p = .790$). No other effects were significant, *p*'s > .168.

RT variability (Figure 2c) was larger for children (9.65) than adults (6.81), $F(1, 47) = 21.93$, $p < .001$, $\eta^2_p = .314$, and congruent (8.49) than incongruent (8.03) trials, $F(1, 47) = 14.96$, $p < .001$, $\eta^2_p = .241$. No other effects were significant, *p*'s > .116.

3.2 | EEG: Conflict monitoring

3.2.1 | Midfrontal theta power

Theta power (Figure 3) was greater in adults (2.54 dB) than children (1.73 dB), $F(1, 47) = 5.64$, $p = .021$, $\eta^2_p = .107$, and in incongruent

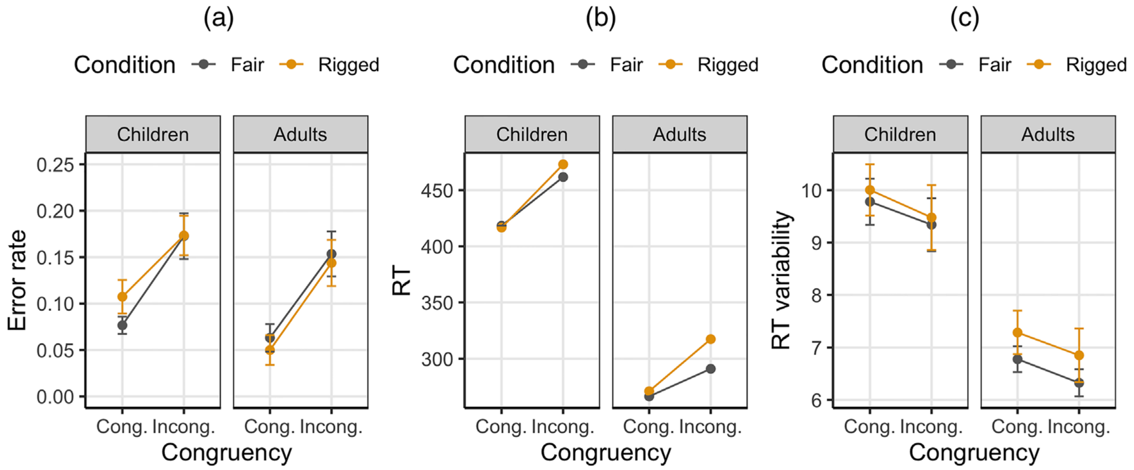

FIGURE 2 Error rates (a), response times (b), and response time variability (c)
Note: Error bars denote standard errors. Participants made more errors and responded slower in incongruent than congruent trials. The congruency effect on response times was more pronounced in the Rigged than Fair condition. RT variability was larger in children than adults, and congruent than incongruent trials. Abbreviations: Cong., congruent; Incong., incongruent; RT, response time.

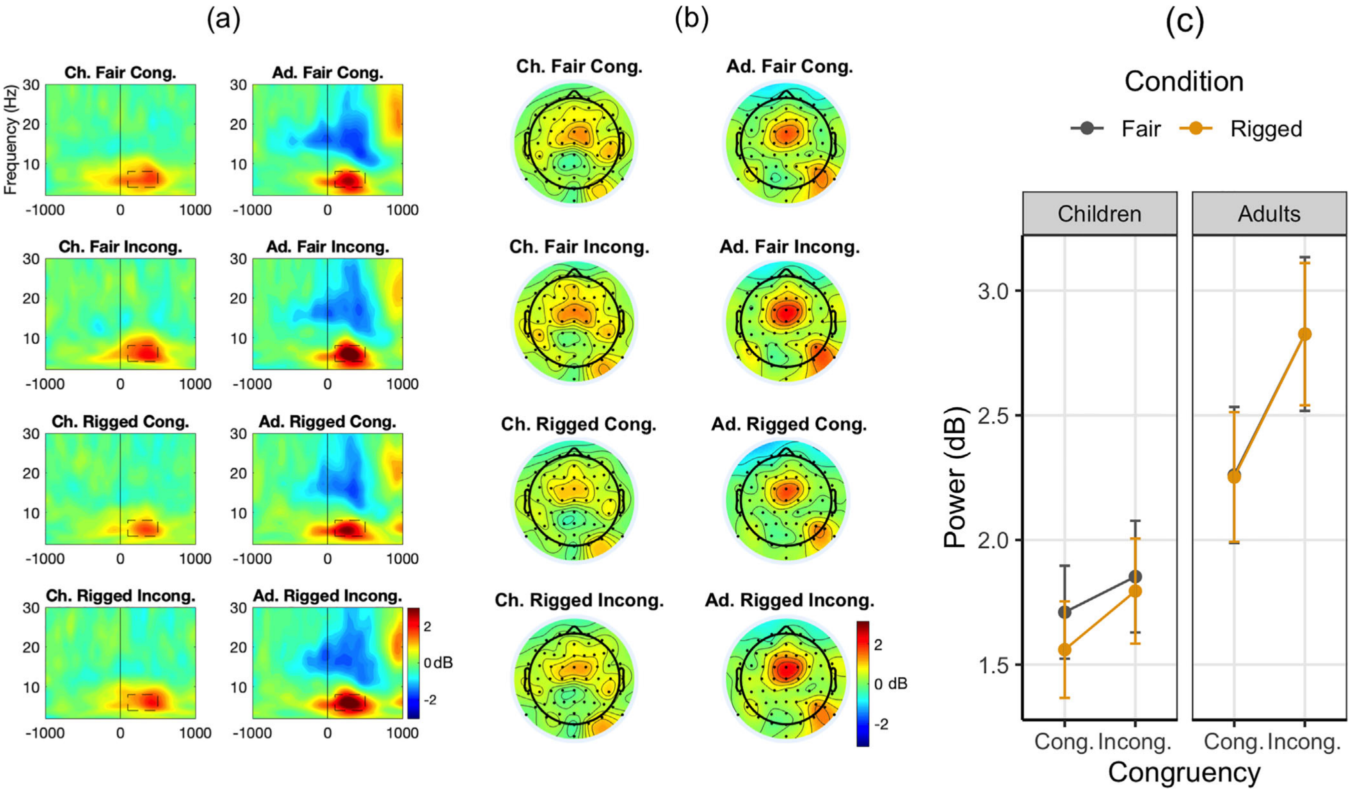

FIGURE 3 Midfrontal theta power (4–8 Hz). (a) Event-related spectral perturbations at FCz. The vertical bar indicates target onset. The black rectangle shows the window used to extract values for analysis. (b) Topographies of mean theta power between 100 and 500 ms after target onset. (c) Mean midfrontal theta power
Note: Error bars denote standard errors. Children showed overall lower midfrontal theta power and a smaller congruency effect than adults. Abbreviations: Ad., adults; Ch., children; Cong., congruent; Incong., incongruent.

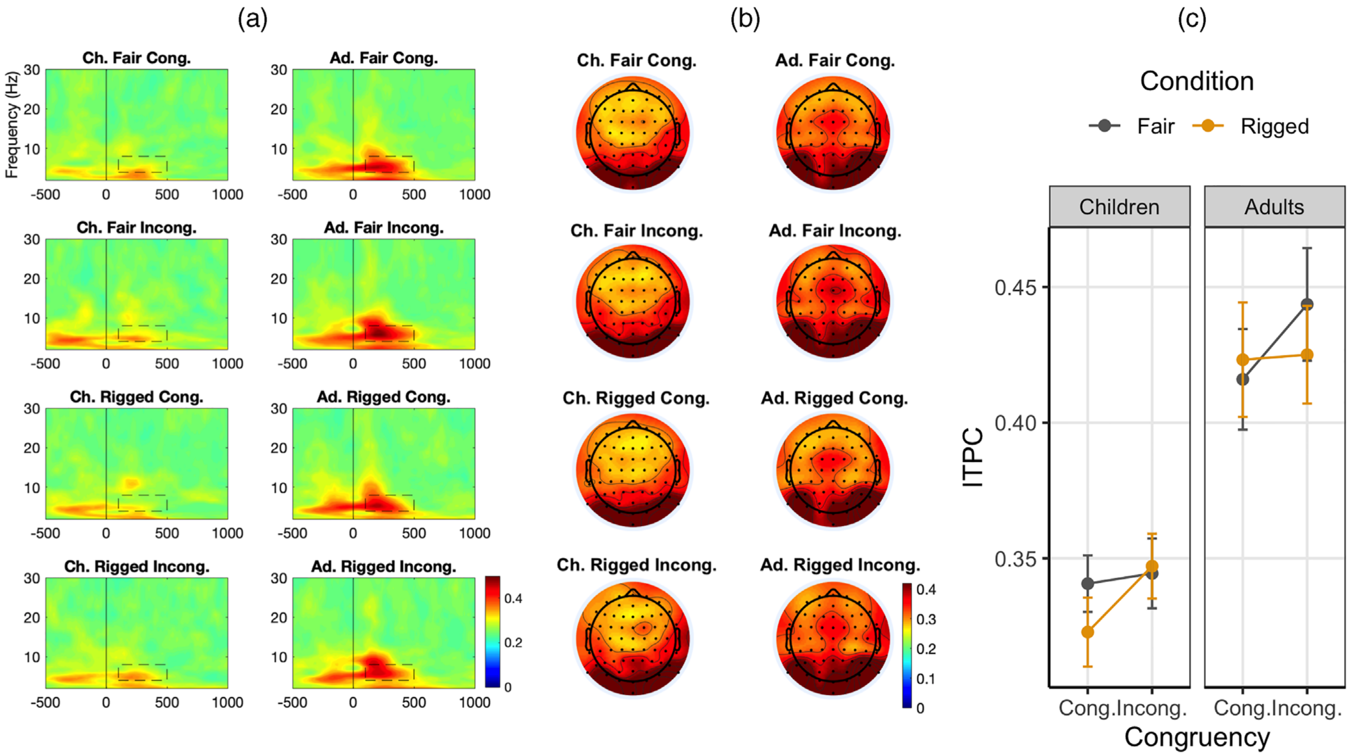

FIGURE 4 Midfrontal theta inter-trial phase clustering (ITPC, 4–8 Hz). (a) ITPC at FCz. The vertical bar indicates target onset. The black rectangle shows the window used to extract values for analysis. (b) Topographies of mean theta ITPC between 100 and 500 ms after target onset. (c) Mean midfrontal theta ITPC

Note: Error bars denote standard errors. Midfrontal theta ITPC was lower in congruent than incongruent trials and in children than adults. Abbreviations: Ad., adults; Ch., children; Cong., congruent; Incong., incongruent.

(2.31 dB) than congruent (1.94 dB) trials, $F(1, 47) = 18.52$, $p < .001$, $\eta^2_p = .283$. Age group interacted with congruency, $F(1, 47) = 4.37$, $p = .042$, $\eta^2_p = .085$, due to a smaller congruency effect in children (.19, $p = .085$) than adults (.57, $p < .001$). No other effects were significant, p's > .562.

3.2.2 | Midfrontal theta ITPC

Midfrontal theta coherence (Figure 4) was greater in adults (.427) than children (.339), $F(1, 47) = 11.31$, $p = .001$, $\eta^2_p = .194$, and in incongruent (.389) than congruent (.375) trials, $F(1, 47) = 7.38$, $p = .009$, $\eta^2_p = .136$. No other effects were significant, p's > .218.

3.2.3 | N2

N2 amplitude (Figure 5) was more pronounced in incongruent (–3.42 μV) than congruent trials (–1.39 μV), $F(1, 47) = 19.08$, $p < .001$, $\eta^2_p = .289$. There were significant age group × channel, $F(1, 47) = 8.84$, $p = .004$, $\eta^2_p = .158$, and age group × congruency × channel interactions, $F(1, 47) = 7.36$, $p = .009$, $\eta^2_p = .135$. Children showed a significant congruency effect at both Fz (3.50 μV, $p < .001$) and FCz (2.70 μV, $p = .005$), whereas adults showed a significant congruency effect at FCz (1.11 μV, $p = .033$) but not Fz (0.75 μV, $p = .110$). No other effects were significant, all p's > .081.

3.3 | EEG: Conflict resolution

3.3.1 | P3

P3 amplitude (Figure 6) was more pronounced in the Fair (9.97 μV) than Rigged (8.27 μV) condition, $F(1, 47) = 4.34$, $p = .042$, $\eta^2_p = .085$, and in incongruent (10.42 μV) than congruent (7.81 μV) trials, $F(1, 47) = 8.98$, $p = .004$, $\eta^2_p = .160$. Age group interacted with congruency, $F(1, 47) = 4.33$, $p = .042$, $\eta^2_p = .084$, due to a larger congruency effect in children (3.75 μV, $p < .001$) than adults (1.43 μV, $p = .008$). No other effects were significant, p's > .493.

3.4 | Correlations among RT and EEG indices

Raw and partial correlations controlling for age are provided in Table 2, and we report here significant partial correlations. In children, faster RTs were associated with greater midfrontal theta power (r = –.44,

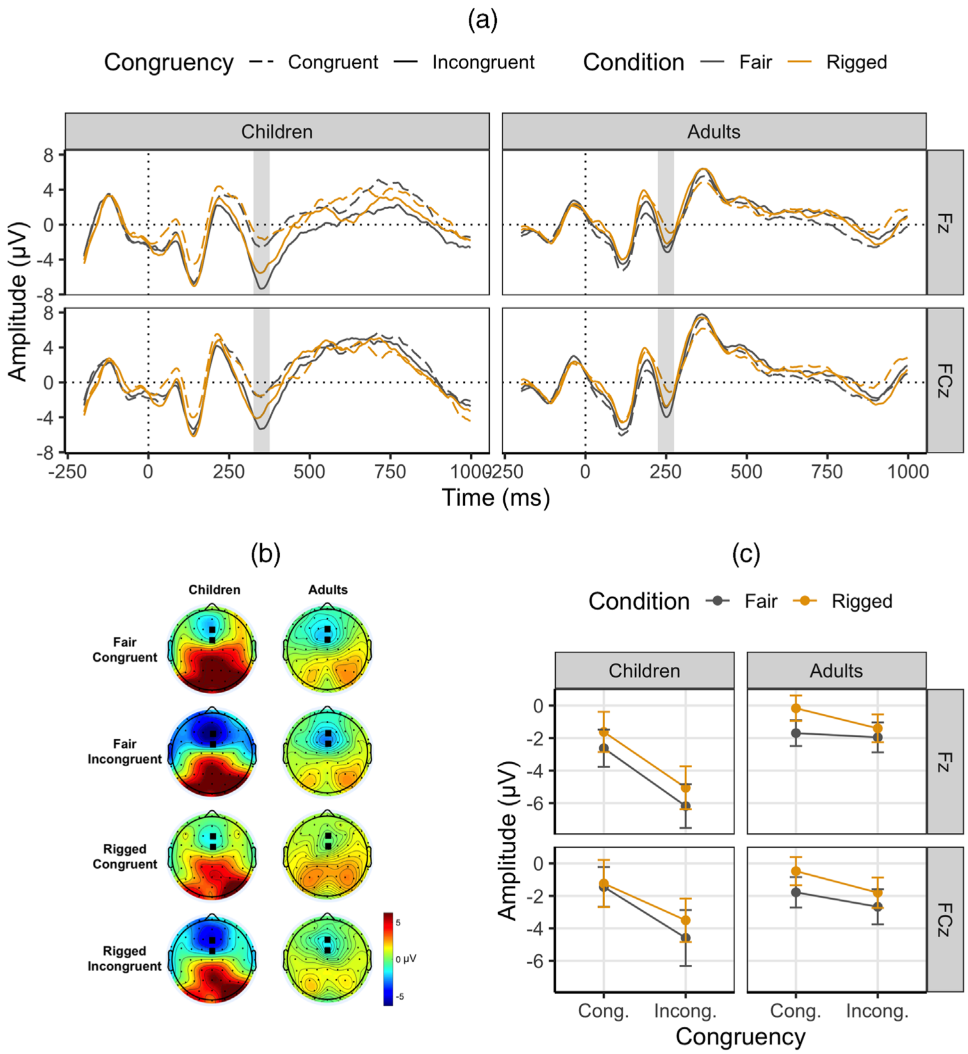

FIGURE 5 Target-locked N2. (a) Waveforms. The vertical dotted line indicates target onset. The time windows used to compute mean N2 amplitudes are shown in gray. (b) Topographies. Mean amplitudes over the window of interest for each age group. The black squares represent channels Fz (top) and FCz (bottom). (c). Mean N2 amplitudes

Note: Error bars denote standard errors. The congruency effect on N2 amplitudes was significant at both Fz and FCz in children and FCz in adults. Abbreviations: Cong., congruent; Incong., incongruent.

p = .03). The congruency effects on RTs and RT variability were positively correlated ($r = .54$, $p = .01$). Greater RT variability was associated with lower N2 amplitudes ($r = -.66$, $p < .01$) and a greater congruency effect on ITPC ($r = -.46$, $p = .02$). Greater midfrontal theta ITPC was associated with greater N2 amplitudes ($r = .65$, $p < .01$).

In adults, the RT congruency effect correlated negatively with P3 amplitudes ($r = -.54$, $p = .01$) and positively with RT variability ($r = .62$, $p < .01$). N2 and P3 amplitudes were negatively correlated ($r = -.61$, $p < .01$), as well as their respective congruency effects ($r = -.58$, $p < .01$). In addition, greater N2 amplitudes were associated with greater midfrontal theta power ($r = .56$, $p = .01$). Greater ITPC was associated with lower RT variability ($r = -.43$, $p = .04$) and greater midfrontal theta power ($r = .73$, $p < .01$). A greater congruency effect on midfrontal theta power was associated with greater congruency effects on both midfrontal theta ITPC ($r = .56$, $p = .01$) and RTs ($r = .43$, $p = .04$).

4 | DISCUSSION

This study examined midfrontal theta activity in children and adults while performing a speeded flanker tasks. Midfrontal theta power was greater in incongruent than congruent trials, although the difference did not reach significance in children. Further, both age groups showed significant congruency effects on midfrontal theta coherence, N2, P3, and RTs, and were similarly affected by response feedback fairness. These similar profiles suggest that children used the same neurocognitive processes as adults to monitor and resolve conflict but with less efficiency, and that theta oscillations likely play a key role in coordinating these processes across development (see also Adam et al., 2020). This is in line with growing research suggesting similar control adjustment dynamics in children and adults (Ambrosi et al., 2020; Gonthier et al., 2021; Larson et al., 2012; Surrey et al., 2019).

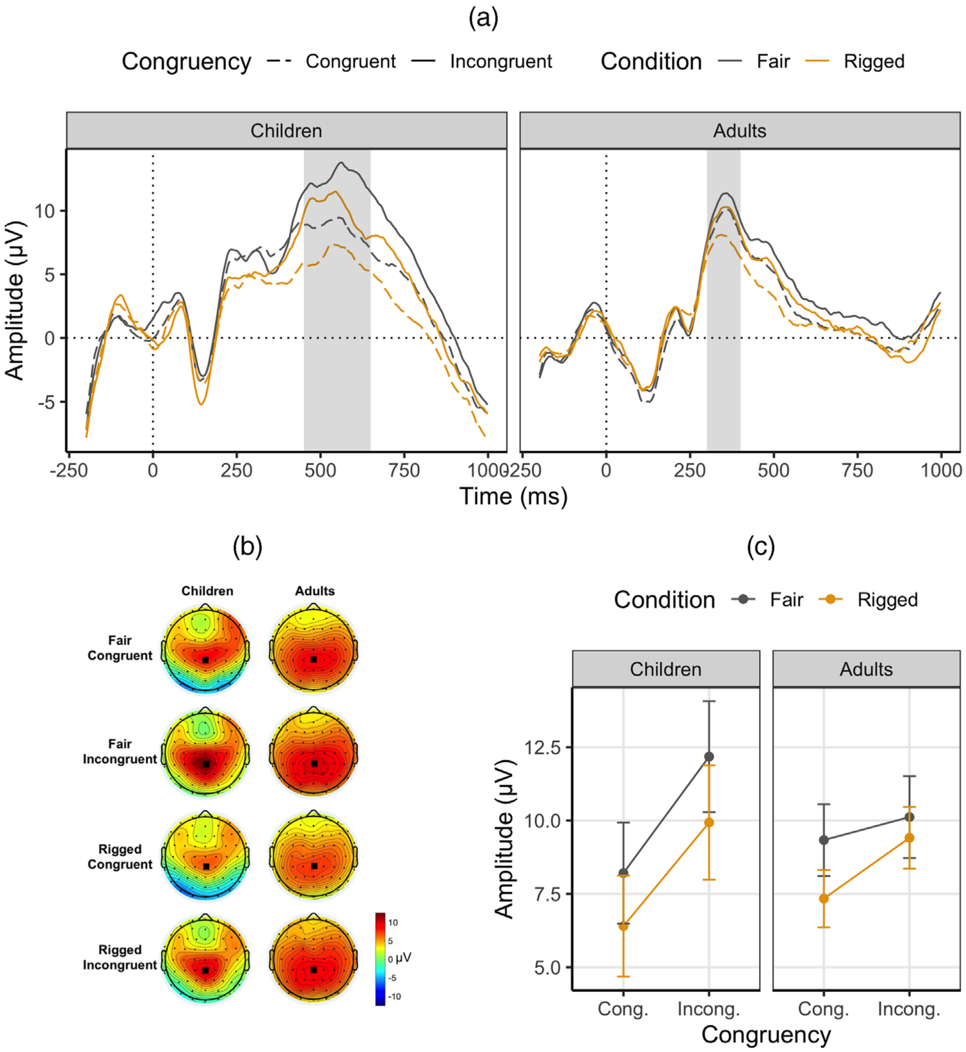

FIGURE 6 Target-locked P3. (a) Waveforms. The vertical dotted line indicates target onset. The time windows used to compute mean P3 amplitude are shown in gray. (b) Topographies. Mean amplitudes over the window of interest for each age group. The black square represents channel CPz. (c). Mean P3 amplitudes

Note: Error bars denote standard errors. P3 was overall more pronounced in the Fair than Rigged condition, and the congruency effect on P3 amplitude was more pronounced in children than adults. Abbreviations: Cong., congruent; Incong., incongruent.

However, some important differences in theta activity did emerge between children and adults. Children showed a smaller congruency effect in midfrontal theta power (which did not reach significance), and both power and coherence were overall much weaker than in adults. These findings are consistent with prior reports of age-related increases in midfrontal theta power and coherence during childhood and adolescence in tasks tapping cognitive control (Gyurkovics & Levita, 2021; Liu et al., 2014; Papenberg et al., 2013). They speak to less efficient conflict monitoring and signaling of the need for control in children than adults. Increasing signal strength for conflict detection and the need to adjust top-down control accordingly may account, at least in part, for more dynamic tailoring of PFC recruitment and control engagement as a function of changing task demands with age (e.g., Chevalier et al., 2019; Durston et al., 2002; Niebaum et al., 2019). It may reflect more efficient communication within and across the cingulo-opercular and frontoparietal networks with age, which has been related to cognitive control progress during childhood and adolescence (Baum et al., 2017; Dosenbach et al., 2007; Luna et al., 2015).

In this study, greater midfrontal theta power and coherence were associated with faster RTs in children and lower RT variability in both age groups, respectively, even when controlling for age. These effects, which are consistent with prior studies (Liu et al., 2014; Papenberg et al., 2013), further stress the direct link between midfrontal theta oscillations and behavioral performance. Midfrontal theta coherence likely is determinant in the temporal reliability of the coordination of conflict monitoring processes, as suggested by its relation with RT variability in both age groups. As such, both midfrontal theta power and coherence appear as a key feature of cognitive control efficiency.

Furthermore, the congruency effect on N2 amplitudes was notably significant in both age groups. It is interesting that the N2

TABLE 2 Raw and partial correlations (controlling for age) among response time and EEG indices

Children		1	2	3	4	5	6	7	8	9	10	11	12
	1. RT	1	-0.38	**0.65****	-0.19	**-0.60****	-0.20	-0.39	0.17	-0.23	-0.08	0.12	-0.08
	2. RT CE	-0.30	1	-0.15	**0.56****	0.15	0.28	-0.19	-0.14	0.00	0.06	-0.34	-0.03
	3. RT var	0.37	0.01	1	-0.27	**-0.47***	-0.21	**-0.47***	0.32	**-0.63****	-0.09	0.26	0.12
	4. RT var CE	-0.08	**0.54****	-0.21	1	0.16	0.22	-0.20	-0.21	0.00	0.27	-0.14	-0.18
	5. Power	**-0.44***	0.04	-0.27	0.08	1	0.18	0.29	0.00	0.13	-0.05	-0.11	-0.16
	6. Power CE	-0.14	0.25	-0.15	0.2	0.12	1	0.06	-0.28	0.14	0.26	-0.04	-0.07
	7. ITPC	-0.18	-0.32	-0.33	-0.29	0.15	0.01	1	0.31	**0.67****	0.11	-0.11	-0.04
	8. ITPC CE	0.32	-0.16	**0.46***	-0.22	-0.04	-0.29	0.30	1	-0.03	-0.27	-0.23	-0.03
	9. N2	-0.14	-0.05	**-0.66****	-0.04	0.05	0.12	**0.65****	-0.04	1	0.18	-0.24	-0.09
	10. N2 CE	-0.09	0.05	-0.10	0.27	-0.07	0.26	0.11	-0.28	0.18	1	0.10	-0.35
	11. P3	-0.10	-0.29	0.14	-0.10	0.01	0.00	-0.02	-0.22	-0.21	0.11	1	0.15
	12. P3 CE	-0.10	-0.04	0.17	-0.18	-0.19	-0.07	-0.05	-0.03	-0.09	-0.36	0.16	1
Adults		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	1. RT	1	-0.21	-0.29	-0.21	0.10	-0.05	0.37	-0.10	0.02	0.13	-0.15	0.01
	2. RT CE	-0.22	1	**0.62****	0.19	-0.10	**0.43***	-0.36	-0.05	0.10	0.40	**-0.54****	-0.35
	3. RT var	-0.30	**0.62****	1	-0.28	-0.12	-0.07	-0.43	-0.25	0.06	0.02	-0.38	-0.19
	4. RT var CE	-0.23	0.19	-0.29	1	-0.11	0.26	-0.27	0.18	-0.28	0.03	0.17	0.04
	5. Power	0.15	-0.10	-0.11	-0.08	1	0.22	**0.73****	-0.01	**0.57****	0.04	-0.11	0.09
	6. Power CE	-0.06	**0.43***	-0.07	0.26	0.23	1	0.11	**0.54****	0.29	0.30	-0.33	-0.03
	7. ITPC	0.39	-0.36	**-0.43***	-0.26	**0.73****	0.11	1	-0.04	0.36	0.09	0.06	-0.01
	8. ITPC CE	-0.07	-0.05	-0.25	0.21	-0.06	**0.56****	-0.06	1	0.16	0.27	-0.02	-0.09
	9. N2	0.04	0.11	0.07	-0.27	**0.56****	0.29	0.36	0.14	1	-0.05	**-0.60****	0.10
	10. N2 CE	0.15	0.41	0.02	0.05	0.01	0.31	0.08	0.26	-0.06	1	-0.15	**-0.58****
	11. P3	-0.16	**-0.54****	-0.38	0.17	-0.11	-0.33	0.06	-0.02	**-0.61****	-0.15	1	0.22
	12. P3 CE	-0.01	-0.35	-0.20	0.02	0.12	-0.04	0.00	-0.07	0.12	**-0.58****	0.22	1

Note: Pearson raw correlations are provided above the diagonal and partial correlations controlling for age below the diagonal. Significant correlations are shown in bold.

Abbreviations: CE, congruency effect; ITPC, midfrontal theta inter-trial phase clustering; Power, midfrontal theta power; RT, response time; RT var, response time variability.

$^{*}p < .05$

$^{**}p < .01$.

congruency effect did not follow the same pattern as midfrontal theta power (i.e., was not smaller in children than adults). What is more, N2 amplitudes and midfrontal theta power, which both measure conflict monitoring, were correlated in adults but not in children (with a significant difference between the two r values, $z = -1.7$, $p = .045$). The lack of correlation in children is intriguing given that both indices capture conflict monitoring, and phase-locked midfrontal theta oscillations contribute to the N2 (Cavanagh & Shackman, 2015; Huster et al., 2013). However, we measured total power, which captures both phase-locked and nonphase-locked theta oscillations. Lower midfrontal theta coherence in children suggests lower temporal alignment of nonphase-locked oscillations relative to adults. This lower temporal alignment may have contributed to masking any potential link between the N2 and midfrontal theta power in children.

That said, as midfrontal theta power includes nonphase-locked oscillations (that do not contribute to the N2) and the N2 arises not only from theta, but also delta oscillations (Harper et al., 2014), the two measures may reflect partially distinct aspects of conflict monitoring that may be more consistent in adults than children. Indeed, dissociations between N2 and midfrontal theta power effects have been reported in patients with schizophrenia (Hong et al., 2021). The N2 may primarily capture conflict detection or threshold adjustment, that is, inhibition of motor output upon conflict detection, which may correspond to an implicit form of control that develops early (Erb & Cavanagh, 2019; see also Gonthier et al., 2021). Midfrontal theta power, in contrast, may reflect the signaling of the detected conflict for control adjustment, which may show a more protracted developmental course intrinsically related to functional brain network development. Greater consistency between conflict detection and signaling may contribute to more efficient conflict monitoring in adults than children. This interpretation, however, is speculative and needs to be tested directly in future research.

Children also showed a larger congruency effect on P3 amplitudes than adults, which suggests that children engaged more control than adults to resolve conflict during target processing. Given that both age groups showed a similar congruency effect on RT, children may have needed to implement greater control to attain the same level of behavioral performance as adults. Indeed, in adults larger P3 amplitudes were associated with a smaller RT congruency effect, and a similar trend was found in children. The greater P3 congruency effect in children may reflect (1) less efficient implementation of control in childhood, (2) compensation for less efficient theta-band neural communication associated with monitoring and signaling of the need for control, or (3) both. Given prior evidence for both less efficient conflict monitoring and neural communication within and across networks in children (Baum et al., 2017; Grayson & Fair, 2017), children's need to implement greater control than adults likely reflects both, but more research is needed to clarify this point.

The effect of response feedback fairness did not differ between age groups. Specifically, both children and adults showed a larger congruency effect on RTs and overall, less marked P3 amplitudes in the rigged than fair condition, despite a similar P3 congruency effect regardless of feedback fairness. Thus, contrary to our hypothesis, reliance on external feedback for performance monitoring was not greater in children than adults. Importantly, response feedback fairness did not influence conflict monitoring (or at least, if it did, the effect was too subtle to be detected), suggesting that even though both performance and conflict monitoring are supported by midfrontal theta oscillations, the two processes may be relatively independent. However, although participants were not informed about feedback fairness in each condition, the unreliability of feedback in the rigged condition was readily apparent, making it likely that participants became aware of it quickly. Although we did not systematically measure awareness of the feedback manipulation, most children complained about unfair feedback in the rigged condition. Awareness of the feedback manipulation may have decreased the influence of feedback unreliability on conflict monitoring by leading children to monitor conflict in a way that countered the potentially detrimental effect of rigged feedback. Indeed, encouraging children to reflect on their performance by generating their own feedback helps them engage control in a more mature fashion (Hadley et al., 2020). It is difficult to determine whether awareness of feedback unreliability influenced the lack of observed link between performance monitoring difficulty and conflict monitoring, but this question should be revisited in future studies, which may feature either subtle manipulations that children may not be aware of (e.g., providing feedback based on RTs only rather than accuracy) or remove response feedback completely.

By contrast, rigged feedback had a detrimental effect on conflict resolution. Again, this is consistent with behavioral findings suggesting that conflict monitoring may represent a more implicit form of control and develop earlier than conflict resolution (Erb & Marcovitch, 2018, 2019; Gonthier et al., 2021). It is difficult to draw a firm conclusion on the exact reason why conflict resolution was costlier in the rigged condition. Internal monitoring may be more effortful than with external aid, leaving less resources for control implementation. Alternatively, rigged feedback may have interfered with internal performance monitoring or having to ignore this information may have added to the cognitive demands of the task. Finally, receiving an overall smaller proportion of positive feedback and greater proportion of negative and "too late" feedback than in the fair condition may have decreased motivation, resulting in less efficient conflict resolution.

The speeded version of the flanker task employed here is both a strength and a limitation. On the one end, this procedure, which ensured that participants sampled all three possible feedback options in each condition, allowed us to examine EEG correlates of cognitive control while ensuring that the task was similarly challenging to all participants and equating performance between the two age groups. On the other hand, this procedure may generally increase motivation and cognitive control engagement, and results in the inclusion of only the fastest trials in the RT values, hence potentially underestimating age-related differences in performance and decreasing comparability with studies using a standard (i.e., nonspeeded) version of the flanker task. As such, and given that this procedure also reduces the number of trials included in the RT analyses, RT findings should be interpreted with caution. Further, this study is limited by the modest sample size, which reduced the generalizability of the findings, and the large age range in the child group (from 5 to 10 years of age) may have masked age-related changes potentially occurring during middle childhood that will need to be further investigated in the future. Finally, correlations should be interpreted with caution given the small sample size and the lack of correction for multiple tests.

In conclusion, children present similar but dampened patterns of theta oscillatory activity, suggesting that children already engage the same neurocognitive processes as adults to monitor conflict albeit with less efficiency. Increase in neural communication efficiency contributes to conflict monitoring improvement and better signaling of the need for control from childhood to adulthood. In both children and adults, conflict monitoring, unlike conflict resolution, seemed relatively independent of performance monitoring difficulty.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. The code is available on the Open Science Framework https://osf.io/me2r7/

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