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Relationship Between Implicit Conflict Monitoring, Metacognitive Monitoring, and Cognitive Control Demand Avoidance in Children and Adults

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Objective: Unlike adults, children often fail to coordinate their behavior away from unnecessary cognitive demands to conserve effort. The present study investigated whether greater conflict monitoring may contribute to metacognitive monitoring of cognitive demands, which in turn may support greater cognitive demand avoidance with age. ***Method:*** Electroencephalogram data were recorded while 54 adults and fifty-four 5- to 10-year-old children completed a demand selection task, where they chose between versions of a task with either higher or lower demands on cognitive control. ***Results:*** Both adults and children avoided the high-demand task, showing that, in some circumstances, children as young as 5 years can avoid unnecessary cognitive demands. Critically, midfrontal theta power predicted awareness of cognitive demand variations, which in turn predicted demand avoidance. The relationship between midfrontal theta power and demand awareness was negative and did not change between age groups. ***Conclusion:*** Together, these findings suggest that metacognitive monitoring and control are based in part on conflict monitoring in both children and adults.

Key Points

Question: Whether children and adults monitor conflicts efficiently and adjust their behaviors from unnecessary demands in cognitive tasks, and whether it can be predicted by midfrontal theta oscillations. ***Findings:*** Both adults and children showed demand avoidance, and midfrontal theta power predicted awareness of cognitive demand variations, which in turn predicted demand avoidance. ***Importance:*** Metacognitive monitoring and control are based in part on conflict monitoring in both children and adults. ***Next Steps:*** Future research should investigate the relationship between metacognitive monitoring, metacognitive control, and implicit conflict monitoring across a broader range of cognitive tasks and a more diverse, generalizable sample that includes a wider age range.

Keywords: effort avoidance, conflict monitoring, metacognition, cognitive control, children

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When children pay attention in class, refrain from eating snacks or drawing pictures during an examination, they exert cognitive control over their attention and behavior according to social expectations and norms. Cognitive control can be defined as the goal-directed regulation of attention and actions through adjustments in the selection of perceptual information, response biasing, and maintenance of contextual information (Botvinick et al., 2001). Cognitive control is effortful and engaging cognitive effort to meet cognitive demands is aversive (Ganesan & Steinbeis, 2021). Efficient cognitive control entails metacognitive adjustment of control engagement as a function of changing demands, including strategic avoidance of unnecessary demands (i.e., cognitive

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demands that are not likely to result in greater gain or learning). Adults efficiently adjust their cognitive control depending on motivation and cognitive demands to avoid unnecessary effort (Kool et al., 2010). In particular, when adults are given a choice between two tasks that require different amounts of cognitive effort with equal or no reward, they preferentially choose the task that is less demanding so as to conserve cognitive effort (Dixon & Christoff, 2012; Kool et al., 2010; Lin et al., 2020; López-García et al., 2020; Westbrook et al., 2013; Wu et al., 2023).

In contrast, children under 10 years do not show as much demand avoidance as adults do (Ganesan & Steinbeis, 2021). When instructed to choose between a high-demand task that required frequent rule switching and a low-demand task that required only infrequent switching in the Demand Selection Task, 6- to 7-year-old children selected both tasks at the chance level, whereas 11- to 12-year-old children and adults preferentially chose the low-demand task (J. C. Niebaum et al., 2019). At first glance, these results may seem counterintuitive given that cognitive control is less efficient in children than adults (e.g., Chevalier, 2015; Diamond, 2013; Munakata et al., 2012), which should give children an even greater incentive to conserve cognitive effort. However, demand avoidance requires not only the motivation to conserve effort but also metacognitive abilities to represent variations in cognitive demands and coordinate behavior away from unnecessary demands. Thus, children's emerging metacognition may limit their ability to avoid unnecessary cognitive demands.

Following Nelson and Narens (1990), two major aspects of metacognition are generally distinguished. *Metacognitive monitoring* refers to evaluating the current circumstances, including cognitive demands, and making judgments about one's performance based on past experience, proficiency, and feedback, whereas *metacognitive control* refers to coordinating one's behaviors toward the optimal outcome (J. Niebaum & Munakata, 2020; O'Leary & Sloutsky, 2019). Although metacognitive control seems to lag behind metacognitive monitoring, both show sustained progress throughout childhood (Bryce et al., 2015; Destan et al., 2014; Krebs & Roebers, 2010). When choosing between tasks that vary in cognitive demands, optimal decision-making requires weighing cognitive effort based on task requirements and task performance (i.e., monitoring) and forming a strategy to conserve unnecessary effort (i.e., controlling), whether implicitly or explicitly (Nadurak, 2023; O'Leary & Sloutsky, 2019; Qiu et al., 2018). In the Demand Selection Task, younger children's at-chance selections of the low-demand task suggest that they may not metacognitively monitor variations in task demands or, at least, that they do not form explicit representations of task demands. Consistently, explicitly telling children that one of the tasks is more demanding than the other increases demand avoidance (O'Leary & Sloutsky, 2017), suggesting that greater demand avoidance with age is driven by growing metacognitive monitoring.

An open question is to what extent children's metacognitive monitoring of cognitive demands, as evidenced by awareness of demand variations, may rely on implicit monitoring of conflict between task-relevant and task-irrelevant information. This question relates to the broader issue of whether and to what extent the development of explicit, metacognitive adjustment of control may build on more implicit forms of control adjustment (e.g., Gonthier & Blaye, 2021). Conflict monitoring can be measured via midfrontal theta (MFT) oscillations typically observed over midfrontal channels in the electroencephalogram (EEG; Adam et al., 2020; Buzzell et al., 2019; Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Clayton et al., 2015; Cohen, 2011; Lange et al., 2022). MFT oscillations, which originate in the anterior cingulate cortex, may serve as a signal for the need for enhanced cognitive control through implicit monitoring of conflict, error, and uncertainty (Botvinick et al., 2004; Cavanagh & Frank, 2014; Dreisbach & Fischer, 2012; Watanabe et al., 2021). For example, in conflict tasks in which participants need to react to stimuli presented alongside either congruent information that supports the correct response or incongruent information that interferes with the response, MFT power is greater in incongruent trials than congruent trials (Gyurkovics & Levita, 2021). Increasingly, efficient conflict monitoring with age, as suggested by increasingly mature patterns of MFT power throughout childhood (Chevalier et al., 2021; Z. X. Liu et al., 2014; Papenberg et al., 2013), may contribute to greater awareness (explicit representation) of variations in cognitive demands across tasks (metacognitive monitoring), which in turn may lead to more optimal demand avoidance (metacognitive control).

The current study investigated the potential relations between implicit conflict monitoring, metacognitive monitoring of cognitive demands, and demand avoidance in children and adults. Specifically, we tested the hypothesis that greater implicit conflict monitoring may contribute to greater explicit awareness of variations in cognitive demands across tasks, which in turn leads to greater avoidance of unnecessary cognitive demands. Less efficient monitoring of demand variations in childhood may thus contribute to lower demand avoidance in children than adults. We collected EEG data while children and adults performed a Demand Selection Task (DST, Kool et al., 2010) combined with the Flanker Task, a measure of inhibitory control in which conflict monitoring is associated with clear MFT markers. We targeted 5- to 10-year-olds because as previous research suggests, compared with adults, children that age do not yet show as much demand awareness and demand avoidance in DST (e.g., J. C. Niebaum et al., 2019) or efficient conflict monitoring (e.g., Chevalier et al., 2021). In DST, after an initial familiarization phase with two tasks that only differ in difficulty, adults and children completed a choice phase in which they repeatedly chose which of the two tasks they wanted to perform. Conflict monitoring during the familiarization phase was indexed via MFT power, while demand avoidance was measured by the proportion of low-demand task selections in the choice phase, and questions after the choice phase were used to assess awareness of cognitive demand variations, as a proxy for metacognitive monitoring. We hypothesized that (1) children would show less efficient conflict monitoring than adults, as evidenced by lower MFT power; (2) children would show less demand avoidance than adults; (3) greater awareness of task demand variations should be associated with greater demand avoidance; (4) critically, participants showing higher MFT power, reflecting better monitoring and detection of demand variations, should show both (4a) greater demand avoidance and (4b) greater awareness of task demand variations. Finally, we conducted a mediation analysis as an exploratory analysis. We hypothesized that (5) the awareness of task demand variations should mediate the link between conflict monitoring and demand avoidance.

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Method

Participants

Fifty-four adults (range = 18–71 years[1]) and 54 children (range = 5–10 years) were recruited to participate in this study. One additional child was recruited but removed from the data set because they did not complete the whole session. Due to the wide age range within our sample, preliminary analyses were conducted on the within-group age effect on task performance and MFT power but showed no significant effect of age (Supplemental Materials B). Forty-five child participants had at least one parent who had obtained a bachelor's degree and above. Descriptive statistics are presented in Table 1. No a priori exclusion criterion was used (besides age) to ensure that the samples were as representative as possible of the general population. However, we checked for potential outliers during data analysis. As none were identified, all participants were kept in the analyses. An a priori power analysis on linear multiple regression with three predictors showed that, with a medium effect size (Cohen's f^2 = .15), at least 77 participants are required to achieve 80% power at a significance criterion of α = .05 using G*Power Version 3.1 (Faul et al., 2007). Thus, 108 participants in this study would be sufficient to achieve 80% power.

Participants had nonverbal reasoning ability within the average range of the general population, as indicated by their *T*-score on the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence–II (Wechsler, 2011; Table 1). Matrix Reasoning was not administered to the 5-year-old participants (*n* = 6) since the test starts at age 6. Further, as we prioritized the DST, matrix reasoning was administered last. As a consequence, another 10 children did not complete it due to time constraints. Independent sample *t*-test showed that there was a difference between adults and children in their matrix reasoning scores, $t(90) = 2.48$, $p = .02$, $d = .52$. This result should be interpreted with caution, as it may reflect greater fatigue in children than adults.

Adult participants were recruited from the university's volunteer panel and through flyers. They participated either in exchange for course credits or voluntarily. Child participants were recruited through advertisements on social media and local schools. Caregivers were compensated £10, and children received a science certificate and an age-appropriate prize. Adult participants and caregivers provided written, informed consent and filled in a demographic questionnaire. All child participants provided verbal assent. Children who were 7 years of age or older also provided written assent (younger children did not because of their limited reading and writing abilities).

Table 1
Descriptive Statistics of Participant Information

Variable	Children (*n* = 54) *M*	Children (*n* = 54) *SD*	Adult (*n* = 54) *M*	Adult (*n* = 54) *SD*
Age	7 years 10 months	19.7 months	24.59 years	10.50 years
Matrix reasoning *T*-score	49.92 (*n* = 38)	8.16	54.40 (*n* = 54)	8.70

Variable	Children *n*	Children %	Adult *n*	Adult %
Gender				
Female	24	44.44	38	70.37
Male	30	55.56	16	29.63
Ethnicity/race				
White	41	75.93	23	42.59
Asian or Asian British	4	7.41	28	51.85
Mixed or multiple ethnic groups	8	14.81	2	3.70
Other	1	1.85	1	1.85

Procedure

Two trained experimenters tested participants in a 90-min session in a sound-proof EEG lab. After the EEG cap application, participants were seated comfortably in a chair 70 cm away from the screen. They completed the DST, answered questions regarding the tasks, and completed the matrix reasoning subtest of the Wechsler Abbreviated Scale of Intelligence. Each caregiver or adult participant was debriefed after the session. Specifically, they were told about the study aims and how they were experimentally tested.

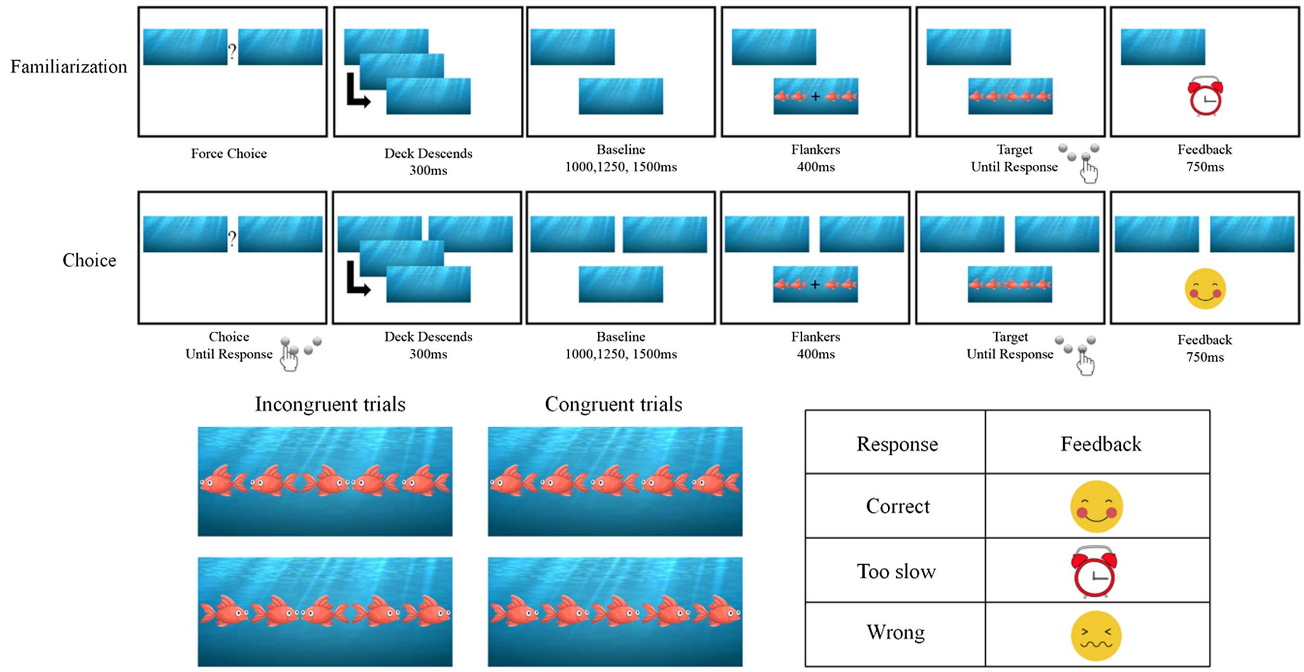
Demand Selection Task

The DST (E-Prime 3, Psychology Software Tools, Inc., Pittsburgh, Pennsylvania) was adapted from J. C. Niebaum et al. (2019) but featured a flanker task, adapted from Eriksen and Eriksen (1974) rather than cued task-switching (Figure 1). In the DST, participants were first familiarized with the low-demand and the high-demand flanker tasks, then completed a choice phase in which they had to select before each trial which of the two flanker tasks they wanted to play next. In each trial, participants saw a series of five horizontally aligned fish and had to press the response button on the side that the central fish (target) faced. In congruent trials, the flankers on either side of the target pointed in the same direction as the target. In incongruent trials, the flankers and the target pointed in different directions, hence creating conflict and increasing cognitive demands, as suggested by prior research showing higher error rate and slower response time (RT) in incongruent than congruent trials (Albrecht et al., 2009; Eriksen & Eriksen, 1974). Each task corresponded to one of the two decks displayed at the top of the screen. The high-demand deck/task contained 90% of incongruent trials, whereas the low-demand deck/task only contained 10% of incongruent trials. The two decks depicted identical oceans to avoid participants developing a preference for one deck over the other based on superficial features such as deck shape or color. The positions of the low-demand and high-demand deck (i.e., left and right) were counterbalanced across participants.

At the start of each trial, a virtual blank card moved down from one of the decks to the center of the screen (300 ms). It remained blank for a period that randomly varied between 1,000, 1,250, and 1,500 ms. Then, a central fixation cross flanked with two distractors on each side was displayed for 400 ms. The fixation was then replaced with the central target until a response was entered. Finally, response feedback was displayed for 750 ms after a response. A smiley face and a sad face were displayed after a correct response

[1] The age range extended over 40 years of age, reflecting the demographics of our participant database. 94% of adult participants were under 40 years. We included the three participants who are over 40 years in our data analysis since excluding them did not change the results.

Figure 1
Illustration of the Demand Selection Task



Note. In the familiarization phase, participants completed trials from both decks in a predetermined order. In each trial of the choice phase, they freely chose the deck the next trial would come from. See the online article for the color version of this figure.

and an incorrect response respectively. A clock was displayed if the RT exceeded 1.25 × Mean RT during the practice trials (see below).

Following prior studies, participants were provided with explicit hints about deck differences but were not told that decks differed in difficulty nor which deck was more demanding. Specifically, all participants were notified that there were differences between decks, and that in one of the oceans, all the fish swam in the same direction more often, while in the other ocean, some of the fish swam in different directions more often. Such scaffolding has been found to help adults and children grasp the task demands and facilitate demand avoidance in younger children (Gold et al., 2015; O'Leary & Sloutsky, 2017). Thus, the scaffolding and response feedback aimed at making the task more child-friendly and supporting metacognitive monitoring.

Demo and Practice

After the introduction of the game, participants learned about the feedback rule and were instructed to keep both hands on the button box. The experimenter completed four demo trials jointly with participants, which could be repeated if needed. Then, participants completed 12 practice trials on their own with the instruction to respond as fast and accurately as possible. The RT limit to be used in subsequent phases was calculated for each participant based on their mean RT on correct trials.

Familiarization Phase

The familiarization phase ensured that participants would get the same amount of experience with both decks before they were asked to choose between decks in the subsequent phases. Specifically, participants completed 40 trials from the low-demand deck and another 40 trials from the high-demand deck (i.e., 80 familiarization trials in total). Deck selection was forced (i.e., participants did not choose which deck to play next), and deck order was counter-balanced across participants. Participants were instructed to attend to the position of the current deck. For example, participants were reminded that the flankers would come from the left deck. A virtual card from the left deck then moved down automatically before the flankers appeared. Simultaneously, the right deck disappeared so that participants were constantly reminded that they were playing the flanker task from the left deck.

Practice Choice Phase

Participants were instructed to practice choosing between the decks over 24 trials. This process was intended to help participants become familiar with using two hands to press the four buttons on the button box. Specifically, they were asked to press the outer buttons to choose the left and right deck and to press the inner buttons (as in the familiarization phase) to respond to the target's orientation.

Choice Phase

During the free choice phase, participants could choose the deck based on their preference. They were instructed to try both decks at the beginning and feel free to move from one deck to another. They were also informed that if they began to like one of the decks better, they could choose that deck more often. The free choice phase

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contained 80 trials in total, separated by two breaks (27, 27, and 26 trials, respectively).

Questions

Upon completion of the choice phase, participants were asked which deck they preferred and which deck seemed easier to them. Three options were presented for the questions: the left deck, the right deck, and none of them. If they chose the third option, the same question was repeated but with an additional phrase: "If you had to choose one deck."

Data Recording and Processing

Response Times

Extreme RTs (>10,000 and <200 ms; 3.29%) and RTs for incorrect trials were excluded. RTs that were 3 *SD* above or below each participant's mean were removed. RTs were log-transformed for analysis to correct for skew.

EEG Data

EEG data were recorded using a BioSemi ActiceTwo system with 64 channels (BioSemi Besloten Vennootschap, Amsterdam, the Netherlands). The impedances were kept under 50 kΩ, and the sampling rate was 512 Hz (the data were not subsequently downsampled). The data were processed using EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon & Luck, 2014), and custom MATLAB scripts. EEG data were rereferenced to the average of the two mastoids and high-pass-filtered at 0.1 Hz. Epochs were extracted from continuous data from −1.5 s to 1.5 s relative to task onset in the familiarization phase for correct trials only. Bad channels were automatically rejected using EEGLAB (Kurtosis threshold = 5) and manually rejected by visual inspection (Table 2). Missing channels were interpolated through spline interpolation. Independent component analysis was run to identify components (e.g., eye blinks) for subsequent removal. ADJUST was used for automatic component rejection which was then manually checked by a trained researcher to ensure that eye blinks, horizontal and vertical eye movement, and general discontinuities were correctly identified and corrected for. Missing channels were interpolated. The segmented data were converted back to continuous data in ERPLAB for further analysis. The continuous data were segmented from −1 to 1.5 s around the target onset and Laplacian transformed (Cohen, 2014) to increase topographical specificity. Artifact rejection was performed using a 200-ms peak-to-peak moving window with a 200-Hz maximum amplitude threshold and 100-ms window steps. Data from participants who had less than 10 good segments per condition were removed at this stage. Mean good segments of low-demand deck and high-demand deck for each age group are presented in Table 2. Due to unsuccessful recording, technical errors,[2] and insufficient good segments, 29 participants were excluded from the familiarization. This resulted in 79 participants remaining in the EEG analysis. Independent sample *t* tests showed that there was no difference in age between the excluded and included participants in both age groups, $p > .11$. Descriptive statistics are reported in Table 2.

MFT Power

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). The wavelet cycles varied from 3 to 10 in logarithmically spaced steps. The data were reflected on both sides to avoid edge artifacts, and the reflected data were cut out after the time-frequency decomposition. Power values were normalized using a decibel (dB) transform at each frequency and were baseline-corrected from −1000 to −700 ms before target onset to avoid contamination of previous trial activities. Consistent with prior studies, MFT power was maximal over channel FCz (Cohen, 2011; Cohen & Donner, 2013). Following prior studies (Chevalier et al., 2021; Gyurkovics & Levita, 2021), power at FCz was averaged across the theta frequency band (4–8 Hz). Then, for each experimental cell of each participant, mean power was extracted for a 50-ms window around the latency for the peak power value between 100 and 600 ms after target onset.

Data Analysis

All analyses were performed with the R software. All models included the age group and the interaction between the age group and the other predictors. As there was a significant gender/sex difference between the two age groups ($\chi^2 = 5.91$, $p = .01$), due to a greater proportion of female participants in adults than children, gender/sex was controlled for as a between-subject covariate in all analyses that compared between age groups. Given that our hypotheses were not related to gender/sex and our limited sample size, we did not examine potential interactions with gender/sex in statistical models.

Familiarization

Repeated-measure analyses of variance were conducted with mean log-transformed RT, mean accuracy, MFT power during the familiarization respectively as outcome variables, deck type as within-subject predictor, and age group as between-subject predictor. The analysis of MFT power allowed us to test Hypothesis 1 (i.e., children should show less efficient conflict monitoring than adults). Correlation analyses were conducted to investigate whether MFT power correlated with task performance.

Choice Phase

Consistent with previous DST studies (e.g., J. C. Niebaum et al., 2019), a one-sample *t*-test was conducted to examine whether participants selected the low-demand deck above the chance level in the choice phase. Analyses of variance were conducted to examine whether low-demand selections differed between age groups, hence

[2] Due to a hardware setup issue, there was a connection failure between the EEG recording equipment and E-Prime during some sessions, resulting in a loss of triggers for those sessions. Although the EEG signals were intactly recorded, data analysis in EEGLAB could not be performed due to the lack of event triggers. As adults were recruited and tested at a faster pace than children and this technical issue started late in the recruitment phase, it affected more children than adults. EEG data from all the excluded participants were still uploaded to the Open Science Framework for transparency.

Table 2
EEG Data Descriptive Statistics

Variable	Adult	Children
Excluded channels		
Range	0–7 channels	0–8 channels
M	Three channels	Five channels
Good segments		
Low-demand deck	36.7 segments	29.8 segments
High-demand deck	36.7 segments	30.5 segments
Range	24–40 segments	13–40 segments
Average (*SD*)	36.7 (3.2) segments	30.2 (6.8) segments
Exclusions		
Unsuccessful recording	Two participants	Three participants
Technical errors	Four participants	11 participants
Insufficient segments	Two participants	Seven participants
Age of excluded participants	$M = 32$ ($SD = 18.6$)	$M = 7$ ($SD = 1.6$)
	Detail: 18 ($n = 1$), 20 ($n = 1$), 22 ($n = 1$), 24 ($n = 2$), 26, ($n = 1$), 55 ($n = 1$), 68 ($n = 1$)	Detail: 5 ($n = 3$), 6 ($n = 6$), 7 ($n = 8$), 10 ($n = 4$)

Note. The mean number of excluded channels, good segments, and the number of excluded participants in each age groups were reported. EEG = electroencephalogram.

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allowing us to test Hypothesis 2 (i.e., children should show less demand avoidance than adults). In addition, although not directly related to our hypotheses, a generalized multilevel model was conducted with low-demand deck selections as outcome variable, age group, gender/sex, and trial number in the choice phase (from 1 to 80 for each participant) as fixed-effect variables and subject as random-effect variable to examine if the probability of choosing the low-demand deck increased with trials, as such effects have previously been reported in the literature (e.g., Kool et al., 2010).

Question Phase

Reported deck preference and awareness of cognitive demand variations were assessed with the questions that participants answered at the end of DST. Answers (i.e., low-demand deck, high-demand deck, and none of the decks) were coded as categorical variables. Single proportion tests were used to test whether participants reported deck preference and awareness against chance level (i.e., 33.3%). Demand awareness was later coded as binary variables, with one assigned as low-demand deck and 0 for the other two choices. This could not be done for the forced choice question for demand awareness because answers to this question were not properly recorded due to technical issues with E-Prime. Chi-square analyses were used to test age group differences in reported deck preference and demand awareness, as well as associations between deck preference and demand awareness.

Relations Between MFT, Demand Awareness, and Low-Demand Deck Selections

A linear regression was conducted to examine Hypothesis 3, that is, demand awareness should predict demand avoidance (Hypothesis 3). A linear regression was performed to examine whether MFT power in familiarization predicted low-demand deck selections (Hypothesis 4a). A logistic regression was conducted to investigate whether MFT power predicted demand awareness and reported preference (Hypothesis 4b). A separate model was run for each predictor to avoid issues of collinearity.

Finally, given our theoretical hypothesis that demand awareness should mediate the relation between conflict monitoring and demand avoidance (Hypothesis 5), we also ran a mediation analysis using structural equation modeling and bootstrapping between MFT power and low-demand deck selections with demand awareness as the mediator.

Results

The collected data, the E-Prime program used in this study, and data analysis R script are available at https://osf.io/rfpsa/ (Huang et al., 2024).

Behavioral Performance During Familiarization

Age groups, $F(1, 106) = 70.88$, $p < .001$, partial $\eta^2 = .40$; deck type, $F(1, 106) = 49.28$, $p < .001$, partial $\eta^2 = .32$; and their interaction, $F(1, 106) = 7.35$, $p < .01$, partial $\eta^2 = .06$, had significant effects on RTs. Age group also influenced accuracy, $F(1, 106) = 14.84$, $p < .001$, partial $\eta^2 = .12$. Specifically, adults responded more accurately and faster than children, and both groups responded faster on the low-demand deck than the high-demand deck (Table 3). No other effects were significant, $p > .9$.

Table 3
Accuracy and Response Time During the Familiarization Phase

Variable	Low-demand deck	High-demand deck
Accuracy		
Adults	.94 (.09)	.94 (.12)
Children	.84 (.10)	.86 (.12)
Response time		
Adults	333 (134)	344 (126)
Children	667 (691)	687 (588)

Note. Data are presented as means (*SD*). Response times are reported in milliseconds.

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MFT Power During Familiarization

Children should show less efficient conflict monitoring than adults, as evidenced by lower MFT power (Hypothesis 1).

MFT power was greater in adults (2.48 dB) than in children (1.77 dB), $F(1, 77) = 6.60$, $p = .01$ (Figure 2). No significant difference in MFT power was observed between the two decks, and no interaction between decks and age groups was observed, *ps* > .53.

MFT power was positively correlated with response accuracy (Figure 3) after controlling for age, $r = .27$, $t(77) = 2.47$, $p = .02$, but not with RT, $p = .15$.

Choice Phase

Low-Demand Deck Selections

Children should show less demand avoidance (i.e., less frequent low-demand deck selections) than adults (Hypothesis 2).

The mean proportion of low-demand deck selections was significantly greater than chance in both adults (62%), $t(53) = 4.12$, $p < .001$, and children (58%), $t(53) = 1.97$, $p = .03$. There was no difference in low-demand deck selection between adults and children, $p = .41$. Furthermore, the probability of choosing the low-demand deck slightly but significantly increased across trials ($z = 2.04$, $\beta = .003$, $p = .04$; Figure 4).

Deck Preference and Awareness of Cognitive Demands

On the initial questions (with three response options, i.e., either of the two decks or none), children reported preferring the low-demand deck (54%) significantly more often than chance (i.e., 33%), $\chi^2 = 9.56$, $p < .01$, whereas adults did not (37%), $p = .63$. Indeed, more children than adults preferred the low-demand deck, $\chi^2 = 18.15$, $p < .001$. However, when forced to choose between the two decks, both children (59%) and adults (61%) preferred the low-demand deck significantly more than chance (i.e., 50%), adults: $\chi^2 = 18.05$, $p < .001$, children: $\chi^2 = 15.66$, $p < .001$, and the two groups did not differ in reported preference anymore, $p = 1$.

In addition, regarding demand awareness, both children (59%) and adults (52%) declared that the low-demand deck was easier, which was above chance (i.e., 33%), children: $\chi^2 = 15.67$, $p < .001$, adults: $\chi^2 = 7.85$, $p < .01$. There was no difference between age groups, $p = .56$. Statistics are presented in Table 4.

The awareness of cognitive demand was positively associated with low-demand deck preference, $\chi^2 = 54.05$, $p < .001$, indicating that greater awareness of the demand differences was associated with greater reported preference for the low-demand deck (Figure 5).

Relation Between Awareness of Cognitive Demand and Deck Preference to Low-Demand Deck Selections

Greater demand awareness should be associated with greater demand avoidance (i.e., more frequent low-demand deck selections; Hypothesis 3).

The awareness of cognitive demand significantly predicted low-demand deck selections, when potential interaction with age group was also entered in the model, $F(4, 103) = 19.31$, $p < .001$, adjusted $R^2 = .41$ (Figure 6a; Table 5). Reported low-deck preference also significantly predicted the proportion of low-demand deck selections, controlling for age group, $F(6, 101) = 26.32$, $p < .001$, adjusted $R^2 = .59$ (Figure 6b; Table 5).

Relation Between MFT Power and Low-Demand Deck Selections

Greater conflict monitoring (i.e., higher MFT power) should predict greater demand avoidance (i.e., greater low-demand deck selections; Hypothesis 4a).

MFT power in the familiarization significantly predicted low-demand deck selections ($\beta = -.05$, $t = -2.06$), $F(1, 77) = 4.24$, $p = .04$, adjusted $R^2 = .04$, such that participants who had a *lower* theta power would be more likely to select the low-demand deck more often (Table 6). However, when the interaction with age group and the effect of gender/sex were added to the model, the effect was no longer significant ($p = .09$, adjusted $R^2 = .09$).

Relation Between MFT Power and Cognitive Demand Awareness and Reported Deck Preference

Greater conflict monitoring (i.e., higher MFT power) should predict greater demand awareness (Hypothesis 4b).

MFT power negatively predicted demand awareness ($\beta = -.57$, $z = -2.12$, $p = .03$; Figure 7), and this effect did not interact with age ($p = .66$). In contrast, MFT power did not predict reported low-demand deck preference (neither the initial preference nor the forced preference), *ps* > .14.

Mediation Analysis

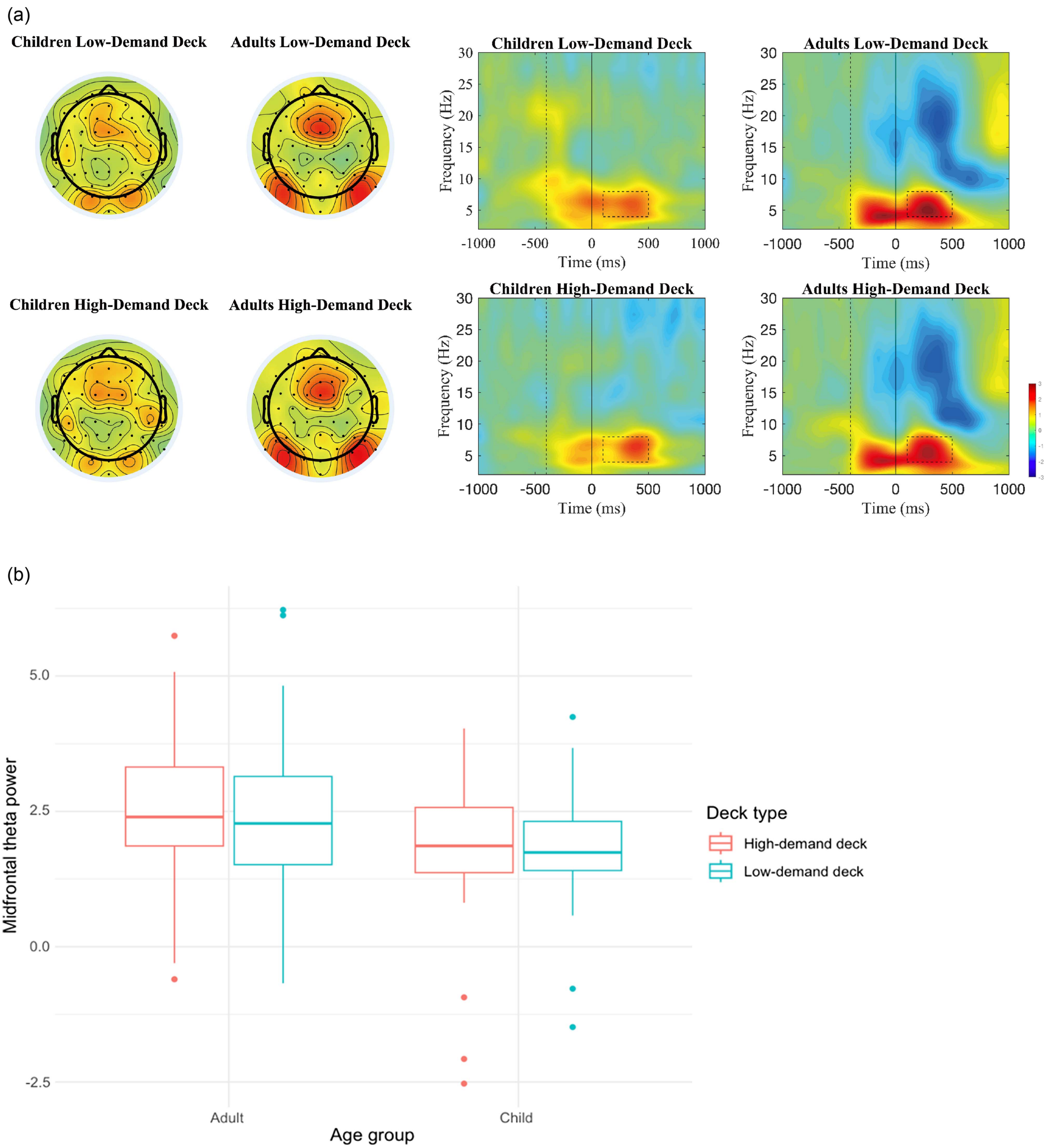
Demand awareness should mediate the link between conflict monitoring (i.e., MFT power) and demand avoidance (i.e., low-demand deck selections; Hypothesis 5).

According to our theoretical hypothesis, conflict monitoring should contribute to demand awareness, which in turn increases demand avoidance. As such, it suggests that demand awareness may mediate the link between conflict monitoring and demand avoidance. Thus, we ran a mediation analysis to explore this possibility. However, given our limited sample size, due to technical issues during EEG recording, this analysis should be interpreted with caution. It showed a significant total effect of MFT power on demand avoidance and a significant indirect/mediation effect on demand awareness. Path a (i.e., MFT power on demand awareness) and Path b (i.e., demand awareness on demand avoidance) were both significant. The direct effect between MFT power and demand avoidance (i.e., Path c) was not significant, suggesting that demand awareness may completely mediate the effect of MFT power on demand avoidance. Statistics and visual representations are reported in Figure 8.

Discussion

This study examined the potential relations between conflict monitoring, metacognitive monitoring, and metacognitive control in a DST in children and adults. Consistent with the hypothesis that conflict monitoring would be less efficient in children than adults (Hypothesis 1), children showed lower MFT power than adults. Although we expected children to show less demand avoidance than adults (Hypothesis 2), both age groups preferentially selected the

Figure 2
Midfrontal Theta Power for Each Deck Type and Age Group



Note. (a) Left: Event-related spectral perturbations at FCz. Right: Mean topographies between 100 and 600 ms after target onset. Children showed a lower amplitude of theta power than adults. (b) The boxes represent interquartile ranges: 25th, 50th, and 70th percentile of midfrontal theta power. Whiskers represent the 1.5 times the interquartile ranges from the box. Midfrontal theta power was greater in adults than children but did not vary between decks. See the online article for the color version of this figure.

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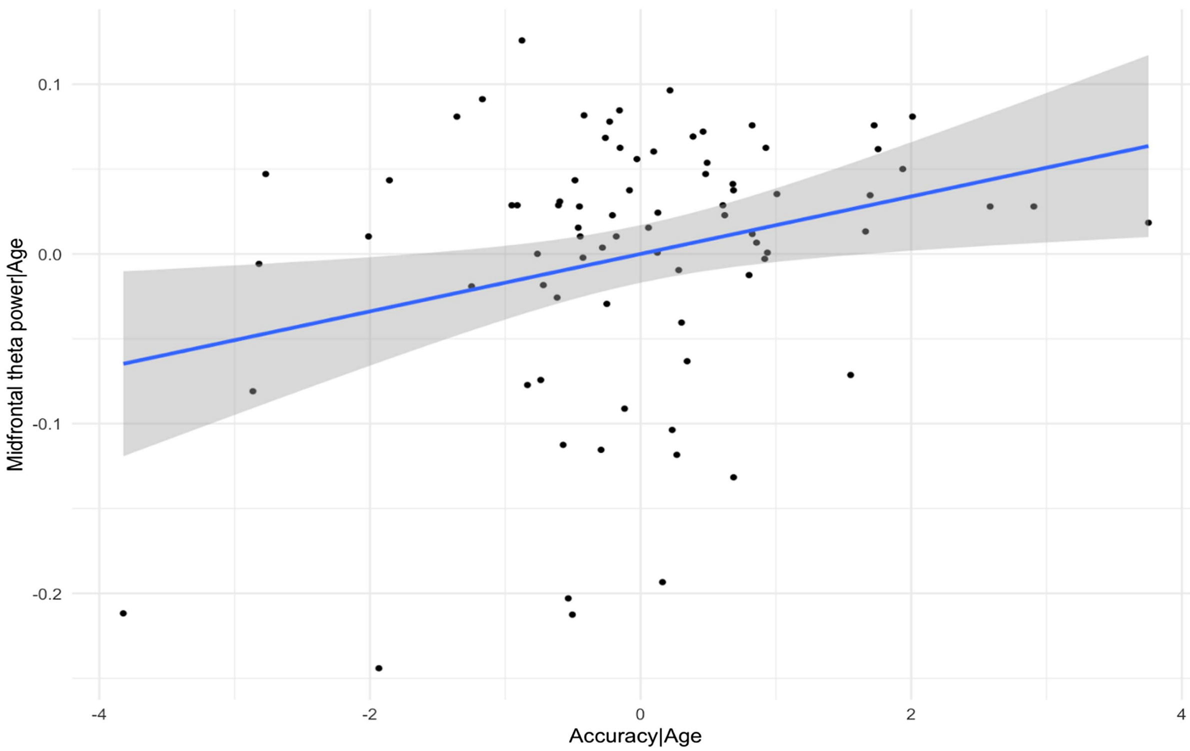
Figure 3
Partial Correlation Between Accuracy in Familiarization and Midfrontal Theta Power



Note. The *x*-axis and *y*-axis represent the correlation between accuracy and theta power after controlling for age. The blue line shows a positive correlation between accuracy and midfrontal theta power. See the online article for the color version of this figure.

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low-demand deck, hence demonstrating similar demand avoidance. As predicted (Hypothesis 3), demand avoidance was greater in participants who showed demand awareness. It was also greater in participants reporting a preference toward the low-demand deck. Critically, MFT power *negatively* predicted both low-demand deck selections and demand awareness. Thus, as expected, these three variables were related, but surprisingly the direction of this relation was opposite to our predictions (Hypotheses 4a and 4b). Finally, as expected (Hypothesis 5), demand awareness mediated the relation between MFT power and demand avoidance. Although these results suggest that conflict monitoring, as captured by MFT power, was associated with demand avoidance behaviors in both children and adults, they point to a more complex relation than expected.

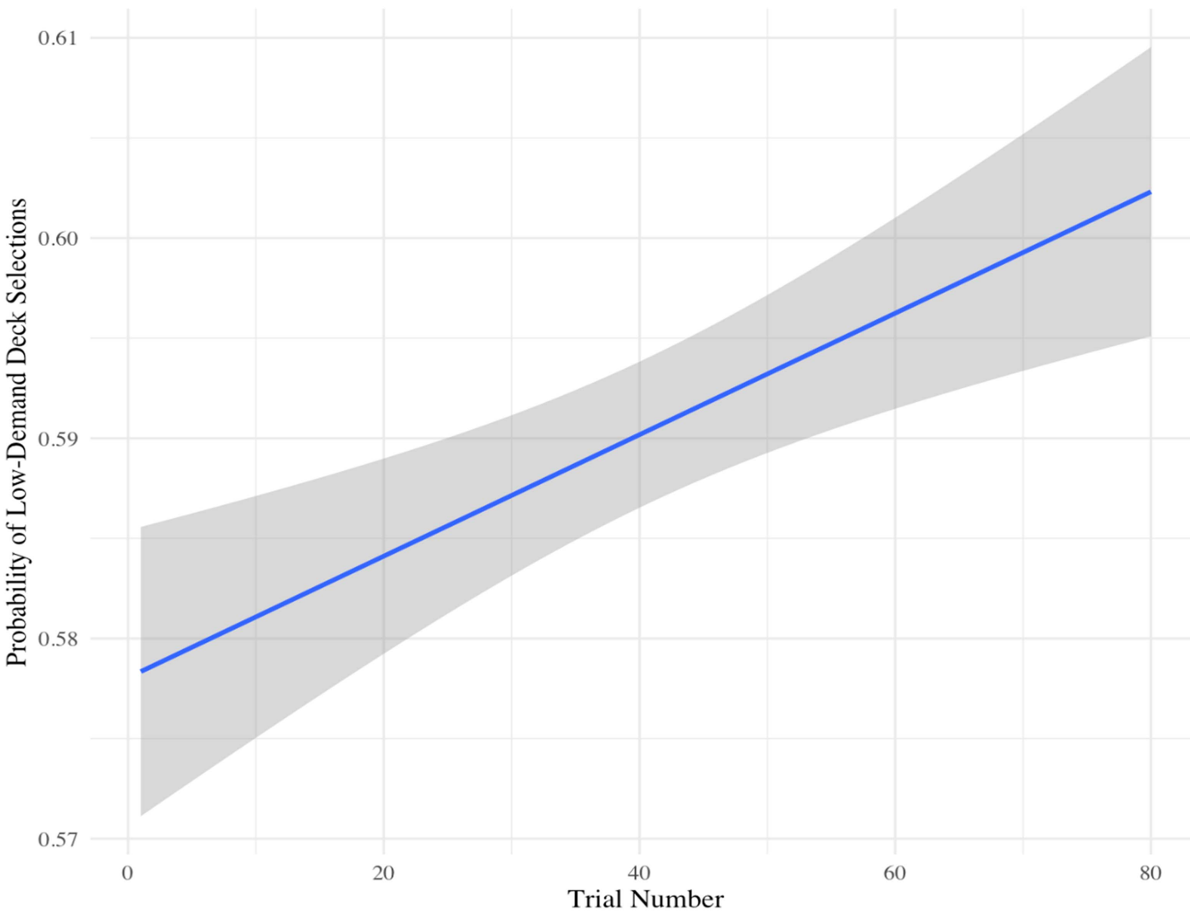
As this study employed DST with the flanker task in a developmental context for the first time, it was important to check whether the manipulation of cognitive demands was successful. As expected, RTs were faster in the low-demand than the high-demand deck during familiarization, pointing to a difference in difficulty between the two decks. Although MFT power did not differ between decks during familiarization, the analysis of event-related potentials during familiarization further speaks to the effectiveness of the demand manipulation. Relative to the low-demand deck, adults showed a more pronounced N2, and children showed a greater P3 for the high-demand deck (Supplemental Material A). These components have been associated with conflict monitoring and resolution, respectively (Groom & Cragg, 2015). Finally, and as previously observed in adults (Kool et al., 2010), the probability of selecting the low-demand deck increased across trials in the choice phase. Together, these findings, combined with above-chance selections of the low-demand deck in the choice phase, speak to the success of the cognitive demand manipulation.

Importantly, accuracy did not differ significantly between the two decks during familiarization, hence suggesting that potential awareness of demand variations after familiarization was more likely to arise from conflict monitoring and effort engagement rather than other signals such as differences in positive or negative feedback between the decks. That said, the fact that only some indices differed between the two decks in the familiarization phase may have created a relatively weak initial signal for variations in cognitive demands, which should be borne in mind while interpreting the present findings.

Contrary to our hypothesis that children would show less demand avoidance than adults, both children and adults showed demand avoidance, preferentially selecting the low-demand deck over the high-demand deck. This finding in adults is largely consistent with the existing literature (Adam et al., 2020; Gold et al., 2015; Kool et al., 2010; López-García et al., 2020; J. C. Niebaum et al., 2019), but it was much less expected in 5- to 10-year-old children, as children that age generally did not develop a preference toward easier tasks in prior studies (Ganesan & Steinbeis, 2021; J. C. Niebaum et al., 2019; O'Leary & Sloutsky, 2017). However, young children are already capable of monitoring conflict and making optimal decisions based

Figure 4

Probability of Low-Demand Deck Selections as Trial Progresses



Note. The *x*-axis refers to the trial number in the choice phase (a total of 80 trials). The *y*-axis refers to the probability of choosing the low-demand deck. The blue line represents that participants were more likely to choose the low-demand deck as trial sessions progressed in the choice phase. The shaded gray area represents the confidence interval of the fitted line. See the online article for the color version of this figure.

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on variations in task difficulty (and associated effort) and reward, although they do not do so as efficiently as adults (e.g., Chevalier, 2018; S. Liu et al., 2019). Importantly, the present study provided feedback and scaffolding (i.e., enhanced instructions) which likely helped young children monitor task variations and form control strategies, which is all the more probable given prior evidence in both children and adults (Gold et al., 2015; O'Leary & Sloutsky, 2017). Therefore, the current findings provide further evidence that, when provided with scaffolding in age-appropriate cognitive control tasks, children as young as 5 years are capable of efficiently monitoring conflict variations and making optimal decisions to avoid unnecessary effort.

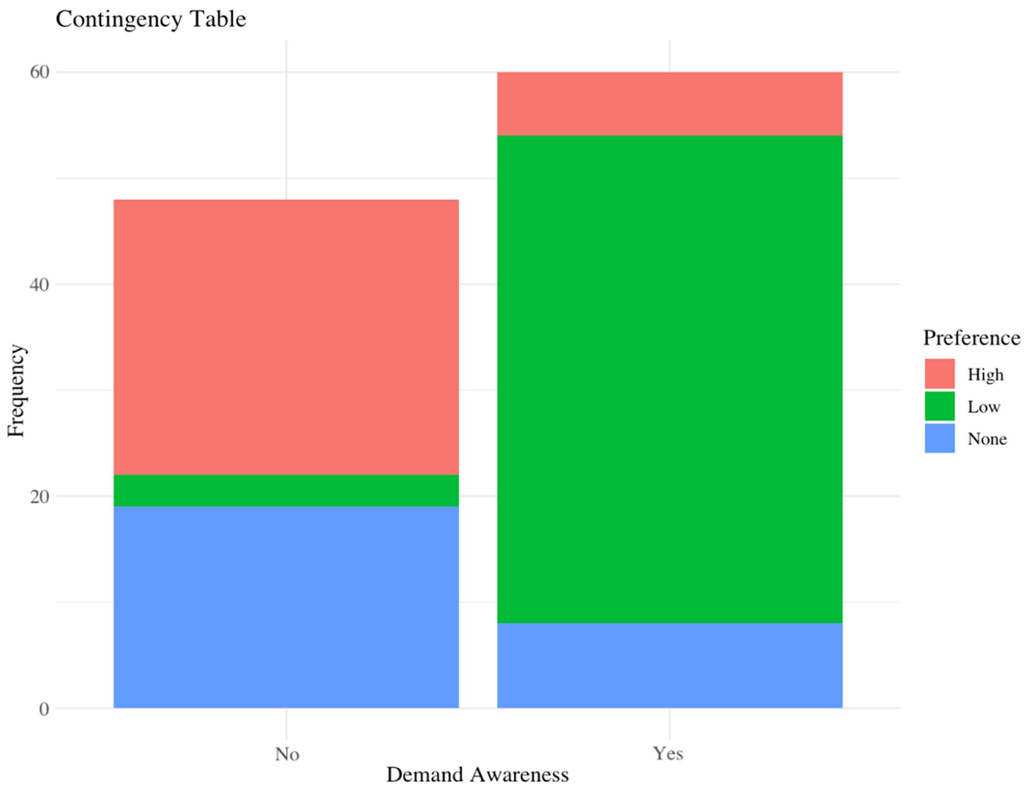
Table 4

Percentage of Low-Demand Deck Selection, Demand Awareness, Preference Toward Low-Demand Deck, and No Preference in Adults and Children

Variable	Adult (%)	Children (%)
Low-demand deck selection	62	58
Demand awareness	52	59
Low-demand deck preference	37	54
Forced preference—low-demand deck	61	59

In the present study, as expected, demand awareness predicted demand avoidance. However, given that demand awareness was assessed after the choice phase, it is difficult to ascertain that demand awareness arose after the familiarization phase and drove deck selections in the choice phase. Alternatively, demand awareness may have arisen during or even after the choice phase. The increase in low-demand deck selection across trials suggests either that demand awareness may have increased during the choice phase or at least that participants increasingly used this information to strategically avoid unnecessary cognitive demands over time. Either way, our findings complement previous studies showing that making children and adults aware of deck differences increases low-demand deck selections (e.g., Desender et al., 2017), suggesting that demand avoidance (i.e., metacognitive control) is dependent on metacognitive awareness of cognitive demands. More generally, these findings point to the interplay between metacognitive

Figure 5
Association Between Demand Awareness and Preference



Note. The *x*-axis represents demand awareness. Colors (i.e., red, green, blue) represent the preference toward high-demand deck (red), low-demand deck (green), and no preference (blue). The *y*-axis refers to the frequency of participants' preferences. If participants were aware of the demands, they were more likely to prefer the low-demand deck, as indicated by the greater portion of green. If participants were unaware of the demands between decks, they were more likely to prefer the high-demand deck or displayed no preference, as indicated by larger portion of blue and red. See the online article for the color version of this figure.

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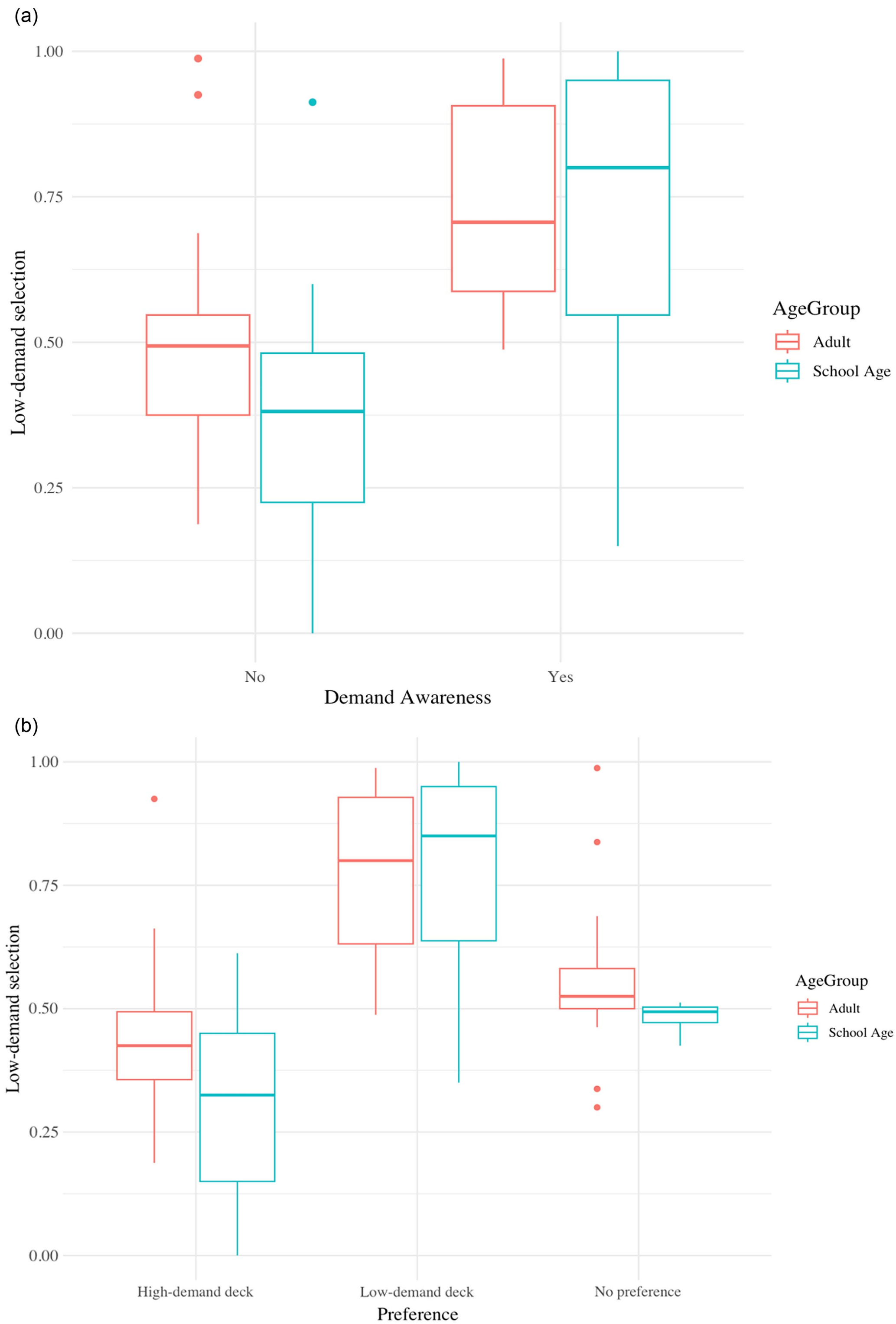
monitoring and metacognitive control (Bryce & Whitebread, 2012; Roebers, 2017).

The major aim of the present study was to investigate whether conflict monitoring, which is often considered implicit or automatic, contributed to explicit demand awareness. Contrary to our expectations, MFT power did not differ between the low- and high-demand decks during familiarization. This result is surprising in adults, as MFT power generally increases in adults when there is an increased need for control (Cavanagh et al., 2009; Cohen & Donner, 2013; Cooper et al., 2019; Gyurkovics & Levita, 2021), but less so in children, for whom variations in MFT power as a function of cognitive demands in prior work were not significant (Adam et al., 2020; Chevalier et al., 2021). Nevertheless, overall MFT power was positively correlated with response accuracy in the present study, suggesting that more efficient conflict monitoring is associated with better overall cognitive performance. This finding is consistent with prior reports of positive associations between MFT power and performance in children (Chevalier et al., 2021; Z. X. Liu et al., 2014).

Critically, we found that MFT power during familiarization predicted low-demand deck selection in the choice phase. Furthermore, we observed evidence suggesting this relation may be mediated by demand awareness, although the results of the mediation analysis should be interpreted with caution given our modest sample size for this type of analysis. Together these findings establish a link between conflict monitoring and metacognitive monitoring of task demands, and through the latter, metacognitive demand avoidance. However, contrary to our expectation, not greater but *lower* MFT power was associated with greater demand awareness and more frequent selections of the low-demand deck in the choice phase. Given the positive association between MFT power and response accuracy in familiarization, greater MFT power suggests highly efficient conflict monitoring across the board. Thus, participants with greater MFT power were less likely to become aware of slight variations in cognitive demands simply because these variations did not affect their high performance with both decks. These participants likely experienced only weak signals for deck differences and a low incentive to select the low- over the high-demand deck. Conversely, participants with lower MFT power performed less well and may thus have experienced a larger difference between decks, increasing their likelihood of becoming aware of deck differences and providing them with a greater incentive to select the low-demand deck frequently.

Figure 6

Demand Awareness (a) and Low-Demand Preference (b) Respectively Predicted the Low-Demand Deck Selection



Note. The box represents interquartile range: 25th, 50th, and 70th percentile of the low-demand deck selection. Whiskers represent the 1.5 times the interquartile range from the box. The dots are considered to be outliers. Participants who showed awareness of demand differences between decks or reported preferring the low-demand deck selected that deck more frequently in the choice phase. See the online article for the color version of this figure.

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Table 5
Summary of Regression Models

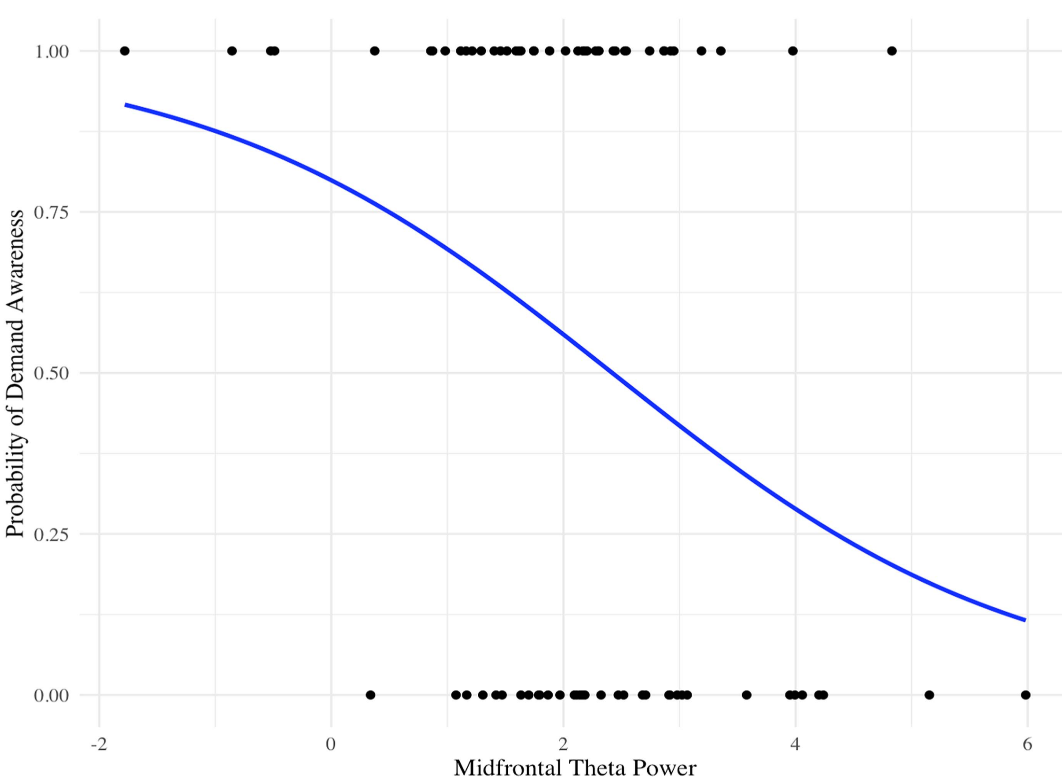
		Low-demand deck selection				Low-demand deck selection		
Step	Predictor	β	95% CI	*p*	Predictor	β	95% CI	*p*
Step 1	Demand awareness	.31	[.22, .39]	<.001***	Preference—low deck	.43	[.25, .51]	<.001***
					Preference—no deck	.18	[.09, .27]	<.001***
Step 2	Demand awareness	.25	[.14, .35]	<.001***	Preference—low deck	.34	[.22, .47]	<.001***
					Preference—no deck	.08	[−.04, .20]	.20
	Age group	−.15	[−.26, −.03]	.01*	Age group	−.18	[−.30, −.05]	.01**
	Gender/sex	.12	[.04, .20]	.005**	Gender/sex	.13	[.06, .20]	<.001***
	Demand Awareness × Age Group	.10	[−.05, .26]	.20	Preference—Low Deck × Age Group	.11	[−.04, .27]	.15
					Preference—No Deck × Age Group	.16	[−.06, .38]	.15

Note. CI = confidence interval.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Although this interpretation is post hoc, it could be tested in future studies, as it predicts that the relation between MFT power and demand awareness may reverse when participants need to choose between two difficult tasks (with one being even more difficult than the other). In such a configuration, participants with greater MFT power may be especially likely to become aware of demand variations because these variations may have a substantial impact on their performance. In contrast, participants with lower MFT power may be less likely to detect these variations in cognitive demands given their relatively low performance in both decks. Although this prediction needs be tested in future research, it suggests that the link between MFT power, demand awareness, and easier deck selections may be complex and reverse depending on the specific impact of demand variations on performance.

There are a few limitations to this study. First, as addressed earlier, similar response accuracy between decks during familiarization was a strength, as it maximized the chance that demand awareness be related to conflict monitoring, but also a weakness as it may have reduced the signal for the difference in cognitive demands between decks. It will be important to examine the relations between

Figure 7
Midfrontal Theta Power Negatively Predicted the Demand Awareness



Note. The blue line indicates that the higher the midfrontal theta power in familiarization, the lower the probability of recognizing the demand difference in the choice phase. See the online article for the color version of this figure.

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Table 6
Summary Regression Models

		Low-demand deck selection			Demand awareness			Forced Preference		
Step	Predictor	β	95% CI	*p*	β	95% CI	*p*	β	95% CI	*p*
Step 1	MFT power	−.05	[−.09, −.002]	.04*	−.57	[−1.05, −0.17]	.01*	−.28	[−0.68, 0.08]	.14
Step 2	MFT power	−.05	[−.10, .007]	.09	−.57	[−1.17, −0.09]	.03*	−.16	[−0.62, 0.28]	.50
	Age group	−.08	[−.32, .15]	.47	−.19	[−2.65, 2.50]	.88	.93	[−1.27, 3.47]	.44
	Gender/sex	.10	[−.01, .22]	.08	.52	[−0.49, 1.55]	.32	.29	[−0.68, 1.27]	.56
	MFT Power × Age Group	−.03	[−.13, .07]	.61	−.25	[−1.50, 0.79]	.66	−.63	[−1.81, 0.33]	.24

Note. MFT = midfrontal theta; CI = confidence interval.
* $p < .05$.

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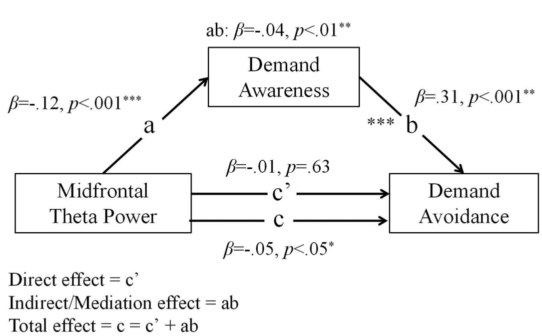
conflict monitoring, demand awareness, and demand avoidance in contexts where the options show more dramatic differences in future studies. Relatedly, conflict monitoring was measured via MFT power, as is usually done in the literature. Although it is difficult to isolate conflict monitoring from other cognitive control processes at the behavioral level or capture it through reported measures (e.g., trial difficulty rating after each response) due to its implicit nature, the lack of such a measure, which may have allowed validation of the construct, is a limitation of the present study. Second, as previously mentioned, demand awareness was assessed only after the choice phase, because of the risk of influencing subsequent deck selections by assessing demand awareness before deck selections. Nevertheless, by assessing demand awareness after deck selections, it is difficult to draw firm conclusions as to whether demand awareness drove demand avoidance, demand avoidance influenced demand awareness, or the two emerged concomitantly during the choice phase. Third, our sample size was limited (especially the reduced children's EEG data due to technical issues), reducing power, especially for the mediation analysis. Thus, future studies require a larger children sample size to replicate the current findings. Fourth, the sample was predominantly white (60% of participants), and skewed to a highly educated population (91% of our adult participants were university students and 82% of our children had at least one parent with a university education), limiting the generalizability of the findings. Fifth, the exclusion criteria of the present study did not include physical difficulties such as traumatic brain injury and psychopathological conditions including learning disorders, attention-deficit/hyperactivity disorder, and psychotropic medication. These conditions may impact children and adults' performance on cognitive tasks and EEG signals. Future studies are needed to examine the interaction between these confounding factors and explicit and implicit monitoring and cognitive control.

Three major conclusions can be drawn from the current findings. First, like adults, young children can efficiently monitor task variations and use this information to strategically avoid unnecessary cognitive demands, at least when instructions contain hints about deck differences. Thus, children and adults seem to employ similar neurocognitive processes to coordinate their behavior away from unnecessary cognitive demands. Second, avoidance of unnecessary cognitive demand was related to explicit awareness of cognitive demand variations, highlighting the relation between metacognitive monitoring and control in both children and adults. Third, the present study provides important, initial evidence for the relationship between conflict monitoring and metacognitive monitoring of task demands in both children and adults, although additional research is needed to disentangle the complexity of this relation.

Figure 8
Mediation Between Midfrontal Theta Power, Demand Awareness, and Demand Avoidance (i.e., Low-Demand Deck Selection)



Note. Demand awareness fully mediated the relation between midfrontal theta power and low-demand deck selections.
* $p < .05$. ** $p < .01$. *** $p < .001$.

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