Title
Charting the Developmental Trajectory of Children’s Sensitivity to Cognitive Demands and Preferences for Avoiding Mental Effort

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Charting the Developmental Trajectory of Children's Sensitivity to Cognitive Demands and

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<u>Dedication</u>

Mom

General Abstract

Whether we are at school, at work, running errands, or pursuing our hobbies, we are faced with tasks that place demands on our cognition. Cognitive demands are a core aspect of everyday life. Adults are sensitive to the cognitive demands of different tasks, and they use this sensitivity to adaptively calibrate their mental effort to the requirements of different tasks. Adults also use cognitive demands to guide their decision-making, typically to take courses of action that allow them to conserve their mental effort by avoiding unnecessary cognitive demands. As children grow up, they gain increasing independence in deciding for themselves which tasks to take on or avoid. Understanding how cognitive demands and how preferences for exerting or avoiding mental effort guide their decisions will be key to understanding cognitive development and children's behavior. In this dissertation, I present research that begins to chart when children become sensitive to cognitive task demands, when relative cognitive demands guide children's decisions to take on or avoid tasks, and how responses to different types of cognitive demands change across children's development.

Chapter 1 presents a synthesis of the available evidence, finding that although young children can monitor and adapt behavior according to cognitive task demands, spontaneous cognitive monitoring of demands to guide task selection only begins to arise across middle to late childhood. I build upon frameworks of metacognition to suggest putative cognitive mechanisms that may drive this developmental transition, as well as other social and environmental factors that may contribute to children's sensitivity and adaptations to cognitive demands.

Chapter 2 reports the results of a study designed to test sensitivity and adaptations to cognitive control demands, specifically task switching demands, across development. Participants were familiarized with two different tasks that required them to sort toys based on their color or shape. In one task, the sorting rules switched frequently, creating relatively higher cognitive demands; in another task, the sorting rules repeated frequently, creating lower demands. Like adults, older children aged 10 to 11 years showed sensitivity to these relative differences and avoided the more difficult switching task, as evidenced in their self-reported preferences and task decisions. However, younger children aged 6 to 7 years showed no such sensitivity and selected between the tasks at chance levels. Thus, these findings indicate that sensitivity and adaptive responses to cognitive demands emerges across childhood.

Chapter 3 reports the results of a study designed to test whether children are differentially sensitive to specific types of cognitive demands. As children age, they transition from engaging cognitive control more reactively, in the moment, to increasingly engaging control proactively to meet anticipated task demands. Children and adults were familiarized with two different tasks that required them to sort toys based on their color or shape but varied *when* cognitive control was needed. In one task, a sorting rule appeared prior to the toy, allowing participants to proactively prepare; in the other task, the sorting rule only appeared when the toy to sort appeared, requiring reactive control. Adults and 10-year-old children were sensitive to these differences between tasks, and adults strongly preferred the proactive task, maximizing their response efficiency by preparing to sort toys. Five-year-old children were unaware of these differences between tasks, supporting findings of cognitive demand monitoring emerging across older childhood. However, the subset of younger children who did report differences between tasks preferred the reactive task. These findings suggest that preferred adaptations to cognitive demands differ across development, depending on the type of cognitive task demands and age.

Chapter 4 incorporates a different task paradigm, the voluntary task switching paradigm, to assess mental effort avoidance in children and adults. In the voluntary task switching paradigm, participants choose when and how often to switch between tasks across trials. Switching between tasks requires mental effort, even when participants decide for themselves to switch tasks. Across three independent datasets, adults and older children exhibited evidence of decreasing their frequency of switching tasks over time, suggesting that they adaptively avoided cognitive task demands. In contrast, younger children did decrease their frequency of task switching over time, suggesting that younger children did not adapt their behavior to avoid cognitive demands. Overall, these findings suggest that older children and adults adapt their behavior in cognitive tasks to avoid cognitive demands but that younger children do not, providing further support for a developmental transition in the sensitivity to and avoidance of cognitive demands across late childhood.

Chapter 1

Deciding What to Do: Developments in Children's Spontaneous Monitoring of Cognitive Demands

Note: This chapter is adapted from Niebaum, J., & Munakata, Y. (2020). Deciding what to do: developments in children's spontaneous monitoring of cognitive demands. *Child Development Perspectives*, *14*(4), 202–207.

Abstract

How do children decide which tasks to take on? Understanding whether and when children begin to monitor cognitive demands to guide task selection is important as children gain increasing independence from adults in deciding which tasks to attempt themselves. In this article, we review evidence suggesting a developmental transition in children's consideration of cognitive demands when making choices about tasks: Although younger children are capable of monitoring cognitive demands to guide task selection, spontaneous monitoring of cognitive demands begins to emerge around 5 to 7 years. We describe frameworks for understanding when and why children begin to monitor cognitive demands and propose additional factors that likely influence children's decisions to pursue or avoid cognitively demanding tasks.

Key words: *cognitive development, decision making, metacognition*

Cognitive tasks that are more difficult typically require thinking harder than cognitive tasks that are less difficult. Adults are sensitive to these cognitive demands, reporting that more demanding tasks require more cognitive effort and that exerting cognitive effort *feels* effortful (Kurzban, Duckworth, Kable, & Myers, 2013; Saunders, Milyavskaya, & Inzlicht, 2015). Adults are usually miserly with their cognitive effort, avoiding exerting unnecessary effort by choosing less demanding tasks over more demanding tasks (for reviews, see Shenhav et al., 2017; Westbrook & Braver, 2015). Sensitivity to cognitive demands helps adults conserve effort and efficiently expend effort only on worthwhile tasks.

Are children as sensitive to cognitive demands as adults? Do children use cognitive demands to guide their selection of tasks? Answering these questions is fundamental for theoretical frameworks across education and cognitive development. For example, in achievement motivation theory, children's perceptions of effort and demands related to tasks are essential components driving their developing understanding of competence, which strongly predicts academic achievement (Nicholls, 1978; Rosenzweig, Wigfield, & Eccles, 2019). However, despite extensive research into children's motivation to achieve, perceptions of cognitive effort (framed as costs) have been largely unexplored, especially in children (Jiang, Rosenzweig, & Gaspard, 2018). Recent theoretical frameworks for the development of cognitive control have emphasized children's growing repertoire of cognitive control strategies (Munakata, Snyder, & Chatham, 2012), suggesting that age-related improvements in cognitive control are driven partially by better coordination of control strategies and effort in response to the demands of tasks (Chevalier, 2015).

Responding to cognitive demands relies on two components of procedural metacognition: *monitoring* to assess mental states while performing a cognitive task and *control* to coordinate behavior according to monitoring signals (Nelson & Narens, 1990; Shenhav et al., 2017). Investigations into the development of metacognition have focused primarily on declarative knowledge and perceptual decisions; in these, monitoring involves subjective confidence in learning and control leads to adapting behavior to improve learning (Ghetti, Hembacher, & Coughlin, 2013). In this article, we extend this framework to consider monitoring of the cognitive demands of tasks, and subjective effort and control in the form of coordinating task selection according to these demand signals. We outline an emerging literature suggesting that although young children can monitor and control behavior according to cognitive task demands, spontaneous cognitive monitoring of effort and task selection based on cognitive demands only begins to emerge at about 5 to 7 years. We then discuss factors that influence children's attention to cognitive demands in task selection, highlighting areas requiring additional research to understand more completely the complexity of children's decisions to pursue or avoid tasks.

Developments in Spontaneous Cognitive Demand Monitoring and Effort-Based Task Selection

Cross-sectional studies have indicated a potential developmental transition in spontaneously monitoring cognitive task demands, showing that children generally begin to monitor and coordinate behavior according to cognitive demands at about 5 to 7 years. Many of these studies have used demand selection tasks, in which participants are presented with two task options that differ in cognitive demands but are otherwise similar (e.g., Kool, McGuire, Rosen, & Botvinick, 2010). Participants typically gain familiarity with each option before deciding on their own which option to select across a series of trials.

For example, in a demand selection task contrasting cognitive control demands by manipulating the frequency of rule switches (e.g., sorting stimuli based on color versus shape; Monsell, 2003), the less demanding option switched task rules on only 10% of trials, whereas the more demanding option switched rules on 90% of trials. During familiarization with the different options, adults, 11-year-olds, and 6-year-olds all exhibited signals of demand, responding less accurately and more slowly on rule-switching than on rule-repeating trials (Niebaum, Chevalier, Guild, & Munakata, 2019). However, only adults and 11-year-olds preferentially selected the less demanding option, whereas 6-year-olds selected options at chance levels. Adults and 11-year-olds also reported the less demanding option as easier and preferred, but 6-year-olds did not, suggesting that only the older children and adults spontaneously monitored cognitive demands and avoided effort by selecting the less demanding option.

Young children also do not monitor differences between tasks that vary according to when cognitive control should be engaged. In another demand selection task, one option encouraged proactive engagement of control by showing a sorting rule prior to a stimulus to sort and removing the rule at the onset of the stimulus, whereas the other option showed the sorting rule and stimulus simultaneously, requiring participants to engage control reactively (Niebaum, Chevalier, Guild, & Munakata, 2020). Participants of all ages responded more quickly on the proactive option, but 5-year-olds were also more accurate on the reactive option. Adults selected the proactive option, reflecting their temporal control tendencies (Braver, 2012), and reported the temporal differences between task options. Ten-year-olds did not select either option more than chance but did monitor demands, with most reporting differences between options. Overall, 5-year-olds did not preferentially select either option or reliably report differences between task options. However, about half of 5-year-olds reported task differences; this subset preferentially selected the reactive option, suggesting that the 5-year-olds who spontaneously monitored task differences selected the option that enabled their preferred control mode and higher accuracy (Chevalier, Martis, Curran, & Munakata, 2015). This finding aligns well with research in adults indicating that awareness of demand differences is required for avoiding cognitive demands (Desender, Buc Calderon, Van Opstal, & Van den Bussche, 2017).

Another cross-sectional study used a demand selection task that taxed the approximate number system, requiring participants to decide which of two dot arrays had more dots. The easier option presented dot arrays at a 2:1 ratio (e.g., 10 versus 5 dots), whereas the difficult option presented arrays at ratios of 9:10 to 13:14 (O'Leary & Sloutsky, 2017, 2019). Adults could identify the easier option and preferentially selected it. However, even given similar differences in accuracy between the easy and hard tasks, 5-year-olds selected options at chance and commonly reported no differences in difficulty (O'Leary & Sloutsky, 2017). Seven-year-olds appeared to be in a transitional period, selecting at chance and reporting no differences in difficulty in some studies but selecting the easier option more often than chance in others, although only 30% rated their performance as higher on the easier option compared with the harder option (O'Leary & Sloutsky, 2019).

Children older than 7 years have consistently spontaneously monitored cognitive demands to select tasks. Children may increasingly view cognitive effort as costly like adults, preferring to avoid unnecessary cognitive demands and conserve their cognitive effort unless presented with enough incentives. For example, 8- to 12-year-olds chose to complete easier tasks that involved updating working memory for less reward over more difficult working memory updating tasks for more reward, similar to adults (Chevalier, 2018). Greater relative differences between the difficult and easy tasks in children's pupil dilation, a common index of cognitive effort, positively predicted the incentive needed to complete the harder task, suggesting that children who put forth more cognitive effort required greater incentive to complete the difficult tasks (Chevalier, 2018). When given the option to complete a trial for rewards or skip to a different trial, 9-year-olds tended to skip high-effort trials if offered a low reward but tended to accept low-effort tasks at all reward levels, indicating that these children considered effort as costly and integrated cognitive effort and reward when making decisions about the tasks (Gatzke-Kopp, Ram, Lydon-Staley, & DuPuis, 2018). Older children also report that more difficult academic tasks *feel* more effortful, like adults. For example, 10- to 13-year-olds rated more difficult arithmetic as requiring more effort and feeling more difficult (Efklides, Kourkoulou, Mitsiou, & Ziliaskopoulou, 2006), and in adolescents, a composite survey measure of costs associated with math, including perceptions of cognitive effort, strongly predicted self-reported avoidance of math schoolwork (Jiang et al., 2018).

The age when children begin to spontaneously monitor cognitive demands likely varies based on the complexity, length, and cognitive domain of the tasks involved. However, these results collectively indicate that spontaneously monitoring cognitive demands typically begins to emerge in children at about 5 to 7 years. Older children use demand signals more reliably to select tasks, adaptively controlling their behavior to avoid unnecessary cognitive effort.

Young Children Can Monitor Cognitive Demands

Although younger children do not spontaneously monitor relative cognitive task demands, they can select tasks based on demands when instructed to do so. For example, 5- and 7-year-olds can select an easier dot discrimination task when instructed to select the easier game before each trial, demonstrating that children can monitor and select tasks based on subjective signals of the tasks' difficulty, at least when relative differences in difficulty are high (~30% difference between options; O'Leary & Sloutsky, 2019). When provided only feedback on accuracy, 5- and 7-year-olds did not preferentially play the easier option, despite more accurately estimating their relative performance on each task compared to a condition without feedback. Thus, children at this age do not reliably avoid demand when not provided a goal to do so, despite differences in monitoring performance between task options.

Young children can also use unambiguous visual cues of task difficulty to select tasks. For example, 5- to 12-year-olds reported that puzzles with more pieces were more difficult, and children younger than 7 chose to complete easier puzzles, potentially to match their perceptions of competence (Nicholls & Miller, 1983). When choosing between toys that required different combinations of buttons to activate, 5- to 7-year-olds reliably chose to play with toys that had fewer buttons, inferring that toys with more buttons were more difficult to play (Bridgers, Jara-Ettinger, & Gweon, 2020). When choosing between sitting at one of two tables that varied in sticker rewards and the wait time needed to earn the stickers, 5-year-olds integrated described delay costs and rewards when deciding, choosing the table with longer wait times only if the number of stickers was sufficiently higher than at the other table (Liu, Gonzalez, & Warneken, 2019).

Why Do Children Begin to Incorporate Cognitive Effort into Task Selections?

Increasing Attention to Cues and Signals of Cognitive Demand

Shifts in what children pay attention to while completing cognitive tasks could change how they select tasks. For example, in task-switching paradigms, young children gazed preferentially at the target object before examining the sorting rule or even ignored the rule cue entirely, whereas older children and adults were more likely to examine the cue prior to looking at the target (Chevalier, Dauvier, & Blaye, 2018). Children's greater neglect of task cues could impede associations between effort and task options in demand selection tasks. For example, instead of associating difficult dot discrimination judgments with a specific option, children may only learn that arrays with more proximal ratios are more difficult.

Children also use feedback differently as they age, which could result in stronger associations between tasks and demands. For example, 8- to 9-years-olds performed less optimally after negative feedback than adults, whereas adults used negative feedback to subsequently correct their behavior (Van Duijvenvoorde, Zanolie, Rombouts, Raijmakers, & Crone, 2008). In the demand selection task requiring dot array discriminations, 5-year-olds overestimated their performance with and without feedback about performance (O'Leary & Sloutsky, 2019). If children do not use negative feedback to adapt behavior and overestimate their own performance, then they may have less motivation to select less demanding cognitive tasks, unless the differences in feedback between task options are especially high.

Adults use many cues about anticipated effort to select tasks, including past experiences of difficulty (Desender, Van Opstal, & Van den Bussche, 2017), even when objective signals of demand are equivalent across task options. In a demand selection task in which rotated words were read either horizontally or diagonally, adults preferred to read the words horizontally and rated horizontal reading as less demanding, even though the options had similar completion times, rates of error commission, and eyeblink rates, another proxy of cognitive demand (Dunn, Lutes, & Risko, 2016). If young children lack sufficient experience in the cognitive domain assessed, they will not be able to make inferences about anticipated cognitive demands when selecting tasks. Young children do select physical tasks based on anticipated difficulty, potentially because prior experience enables inferences about the success or failure on a task. For example, 4- to 5-year-olds assigned harder or easier ball- and ring-toss tasks to themselves or other children according to age, giving older children more difficult tasks than themselves and younger children easier tasks (Magid, DePascale, & Schulz, 2018).

Increasing Capacity to Maintain Task Performance and Monitor Demands

Strategies to monitor task demands and coordinate behavior away from demands may not benefit overall performance on the task. For example, after memorization strategies in learning paradigms, young children did not benefit as much as older children from using good strategies, referred to as a "utilization deficiency" (Clerc, Miller, & Cosnefroy, 2014). Young children often struggle to translate these strategies into new but similar tasks, either failing to use a strategy or performing less optimally despite using a good strategy. Young children may have limited attentional capacity or working memory to monitor task demands while both executing the learned strategy and performing the task (Clerc et al., 2014). In tasks assessing monitoring and adaptation of cognitive demand, young children may be unable to perform the local task, like selecting a majority dot array, while spontaneously monitoring demands and selecting easier tasks. Young children may also fail to establish associations between task options and relative cognitive demands because their attention is usually directed toward local task goals through task instructions rather than toward maintaining a broader goal to avoid cognitive demands.

Decreasing Interest in the Task

Interest in a task attenuates perceptions of cognitive effort and reduces avoidance of cognitive demand in adolescents and adults. Interest in math predicted the proportion of time university and high school students spent on mental arithmetic tasks instead of watching videos or playing a video game, and individuals with higher interest in math reported being less fatigued after the task, despite spending more time on the seemingly more effortful activity (Milyavskaya, Galla, Inzlicht, & Duckworth, 2018). Adults reported less fatigue from manipulating four-digit numbers than from watching number strings passively, suggesting that cognitive effort may be less tiring than boredom (Milyavskaya, Inzlicht, Johnson, & Larson, 2019). Adolescents with greater interest in math also reported that math was less effortful and that they were less likely to avoid difficult math schoolwork (Jiang et al., 2018; Song, Kim, & Bong, 2019).

Young children may be more interested in simple cognitive tasks than older children and adults, and interest in a task could influence how cognitive demands are used to select tasks with age. After an experimenter demonstrated three tasks varying in cognitive demands, 4- to 10-year-olds could select tasks based on difficulty when instructed to choose a task that was not too easy or too hard but “just right” (Danner & Lonky, 1981). Children’s choices matched not only their ability but also their self-reported interests in the tasks: Younger children rated the easier tasks as more interesting and played them more often, whereas older children rated the harder tasks as more interesting and played them more often. Simple cognitive tasks may cause greater boredom for older children, which may be used as a cost signal for selecting tasks, with boredom indicating that a task is not worth the effort (Westgate, 2020).

Emerging Associations Between Effort and Incentives

Although cognitive effort is typically rewarded, young children may not have developed the association between effort and reward. Higher rewards after greater effort can result in continued effort even in the absence of rewards, such as with learned industriousness, in which effortful tasks that were rewarded previously become rewarding in their own right because of prior associations with reward. Adults also revalue rewards based on the effort expended (for a review, see Inzlicht, Shenhav, & Olivola, 2018). However, effort and subsequent reward may be functionally separate for children younger than 6 years. For example, 4- and 6-year-olds completed high- or low-effort tasks until they obtained 10 attractive or unattractive stickers as rewards (Benozio & Diesendruck, 2015). Then, they completed a game in which they could distribute 10 attractive or unattractive stickers to another child or keep the stickers for themselves. Six-year-olds kept more stickers for themselves after the high- than the low-effort tasks, regardless of the attractiveness of the stickers, suggesting that 6-year-olds felt more deserving of the sticker rewards after effort. However, 4-year-olds kept similar amounts of attractive stickers for themselves regardless of effort, indicating consistent valuation of attractive rewards independent of effort. When distributing unattractive stickers, 4-year-olds gave away *more* stickers after effortful tasks, suggesting that the value of unattractive rewards did not increase following effort. Without a history of rewarded effort, younger children may be less likely to avoid unnecessary cognitive effort, whereas older children—who have had experience getting rewards—calibrate effort with anticipated rewards.

Children older than 7 years also choose to do more difficult tasks when they understand that completing these tasks carries a higher incentive value for external evaluation. For example, when asked to choose from puzzles labeled with different levels of difficulty, children ages 7 years and older preferentially selected the more difficult puzzles (Nicholls, 1978). These older children also reported that success on the more difficult puzzles would most please a teacher just before deciding on a puzzle. In contrast, children younger than 7 years did not reliably report that succeeding on more difficult puzzles would most please a teacher, indicating an immature understanding of this incentive of succeeding on difficult tasks.

Conclusions and Outstanding Questions

Children do not spontaneously monitor cognitive demands to select tasks reliably until after around 7 years, even though they can do so when instructed or when cognitive demands are made salient through other goals. Several developmental changes may lead to the emergence of spontaneous monitoring of cognitive effort in childhood. Children's increased prioritization of task cues and use of feedback likely help build associations between specific tasks and cognitive demands. Children's increasing cognitive capacities, especially working memory, could help them maintain meta-level strategies like avoiding more demanding tasks while still performing well. Interest in tasks likely changes with development, leading to differences in children's perceptions of effort and decisions about what to pursue. Lastly, children may increasingly establish an association between cognitive effort and reward and increasingly consider cognitive effort as costly.

Several outstanding questions remain. Sensitivity to and avoidance of cognitive demand are considered adaptive in adults, enabling the efficient use of cognitive resources (e.g., Kurzban et al., 2013; Shenhav et al., 2017). But whether the same holds true for children is less clear. Avoiding cognitive demands might preclude children from critical learning opportunities, but sensitivity to cognitive demands might foster learning opportunities that are just right. Assessments of cognitive demands in children have typically used self-reports or explicit choice measures; whether young children show discrepancies between physiological indices of demand, such as pupil dilation, and self-report or behavioral performance should be examined further. Individuals also differ in spontaneous demand monitoring and choices to avoid or seek demand, likely due to many factors that warrant additional investigation, including cognitive skills and traits (e.g., working memory, susceptibility to boredom). How demands are integrated into the broader contextual factors that influence task selections likely also changes with age. Decisions to tackle cognitively demanding tasks do not occur in isolation; in school and the broader community, other people and an individual's values and beliefs play a role (Doebel, 2020); perceptions of cognitive effort could reciprocally influence children's peers and the development of children's values and beliefs, including about how to invest cognitive effort and decisions about the value of education. Exploring how social and other contextual factors influence the monitoring of cognitive effort and task selection, and vice-versa, will be important for a more complete understanding of developmental changes in decisions about what to do.

Chapter 2

Adaptive Control and the Avoidance of Cognitive Control Demands Across Development

Note: This chapter is adapted from Niebaum, J. C., Chevalier, N., Guild, R. M., & Munakata, Y. (2019). Adaptive control and the avoidance of cognitive control demands across development. *Neuropsychologia*, *123*, 152-158.

Abstract

Young adults adaptively coordinate their behavior to avoid demands placed on cognitive control. We investigated how this adaptive coordination develops by having 6-7- and 11-12-year-olds and young adults complete a demand selection task, in which participants could select between two tasks that varied in cognitive control demands via differences in rule switch frequency. Adults and older children exhibited significant preference for selecting the less demanding task, and showed evidence of a metacognitive signal to guide adaptive demand avoidance across a variety of behavioral and self-report assessments. In contrast, despite evidence of differential demands on cognitive control, younger children did not coordinate their task selections to avoid higher demand. Together, these findings suggest that sensitivity and adaptive responses to control demands emerge with development and are consistent with gradual development of lateral prefrontal cortex, dorsal anterior cingulate cortex, and their functional connectivity, which support effort avoidance in adults.

Exerting cognitive control, the goal-oriented regulation of one's thoughts, actions, and emotions, is effortful (Kool, McGuire, Rosen & Botvinick, 2010; Kurzban, Duckworth, Kable, & Myers, 2013). Given a less demanding option, adults typically coordinate their behavior to avoid unnecessary cognitive demands (Dunn, Lutes, & Risko, 2016), and more specifically, effortful cognitive control (Gold, Kool, Botvinick, Hubzin, August, & Waltz, 2014; Kool et al., 2010; McGuire & Botvinick, 2010). Deciding when and the extent to which effortful control should be engaged is believed to rely on two metacognitive processes: a metacognitive awareness of one's subjective experience and valuation of cognitive effort and a metacognitive control process in which that information is leveraged in subsequent decision-making (Efklides, 2006; Destan, Hembacher, Ghetti, & Roebers, 2014).

However, little is known about how these processes supporting effort-based decision-making and cognitive demand avoidance develop. Sensitivity to control demands, as well as decisions regarding when and how to exert cognitive control, may drive and support cognitive control development (Chevalier, 2015; Chevalier, Martis, Curran, & Munakata, 2015; Munakata, Snyder, Chatham, 2012; Davidson, Amso, Anderson, & Diamond, 2006). Children's subjective experiences of cognitive control could influence when and how children implement control and the types of activities that children engage in. Children may be less sensitive to variations in control demands or less likely to utilize this information to avoid unnecessary demands than adults. However, cognitive control is typically poor overall in children relative to adults and becomes more efficient throughout development (Chevalier, Huber, Wiebe, & Espy, 2013; Davidson et al., 2006; Carlson, 2005); thus, children may be especially motivated to avoid demand by selecting a low- over a high-demand control task. Whether children are *more* or *less* likely than adults to avoid cognitive control demands remains to be clarified.

Control demand avoidance has been investigated in adults using a demand selection task (DST), in which participants are able to freely select between two tasks that differ in control demands (Kool et al., 2010). Participants were not instructed of task differences but could discover that one task option switched rules more frequently than the other, resulting in greater control demand (Monsell, 2003). Across a series of experiments, adults exhibited preference for the less demanding task, demonstrating sensitivity to and behavioral coordination away from cognitive control demands (Kool et al., 2010; Gold et al., 2015). Young children have been shown to coordinate behavior away from difficult task options within a DST paradigm. Children aged 5 years coordinated behavior away from the difficult task if provided feedback and explicit instruction to select the easier task when difficulty differences involved magnitude discrimination between two arrays of dots; without this scaffolding, however, 5-year-olds children did not coordinate behavior away from difficulty (O'Leary & Sloutsky, 2017). When provided by-trial feedback and extensive familiarization with each task option prior to choosing, 5yo also coordinated behavior away from difficulty and exhibited marginal evidence of correctly identifying difficulty differences between tasks (O'Leary, 2017).

Notably, this prior work taxed an automatic cognitive process, the approximate number system, rather than rule-guided cognitive control processes. Older children do appear to be sensitive to control demands within an N-back task framework. When given the option to play different levels of N-back tasks for reward after familiarization with the N-back options, children aged 7-12 years required great incentive to perform more difficult N-backs (e.g., 2-back vs. 1-back) (Chevalier, 2017). These results suggest that young children can recognize task difficulty and monitor performance and can also coordinate behavior away from task difficulty. Whether these findings in children extend to general control demand avoidance and whether control demand avoidance changes with age have not yet been investigated.

Overlapping brain networks involving lateral prefrontal cortex (lPFC) and dorsal anterior cingulate (dACC) have been implicated in both cognitive control and cognitive demand avoidance (Power & Peterson, 2013; Dosenbach, Fair, Cohen, Schlagger, & Peterson, 2008; Shenhav, Botvinick, & Cohen, 2013; Shenhav, Musslick, Lieder, Kool, Griffiths, Cohen, & Botvinick, 2017). In an fMRI study utilizing a task-switching DST paradigm, participants with the greatest difference in left lPFC activity between the low-demand and high-demand blocks also most strongly avoided cognitive demand (McGuire & Botvinick, 2010). dACC specifically has been implicated in monitoring task performance and effort (Shenhav, Cohen, & Botvinick, 2016; Shenhav et al., 2017) and subjective feelings of cognitive effort (Botvinick, Huffstetler, & McGuire, 2009). Functional connections from dACC to lPFC have also been suggested to initiate the top-down behavioral control and coordination necessary to avoid demands on cognition (Shenhav et al., 2017; Shenhav et al., 2013; McGuire & Botvinick, 2010).

Throughout development, activation and circuitry between various regions within PFC and dACC reorganizes and integrates (Luna, Padmanabhan, & O’Hearn, 2010). During an inhibitory control task adjusted to equate performance across age, adults exhibited increased dACC and PFC activation compared with 10-17-year-old children and adolescents (Rubia, Smith, Taylor, & Brammer, 2007). Children aged 8-12 years exhibit less dACC activity differentiation between correct and error trials than adolescents and adults, even though these children are able to recognize trials on which they made an error (Velanova, Wheeler, & Luna, 2008). Additionally, children aged 8-12 years fail to recruit ventrolateral PFC regions during inhibitory control tasks relative to adults (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002), perhaps because young children receive a weaker effort signal to guide subsequent behavior. Although children exhibit behavioral evidence of differential control demands, the underlying neural mechanisms required to utilize these signals may be too immature in young children to drive adaptive behavior away from control demands.

To determine whether children exhibit sensitivity to and avoidance of control demands, we tested 6-7-year-old (6-7yo) and 11-12-year-old (11-12yo) children and adults on a child-adapted rule-switch DST paradigm. The two child age groups were chosen based on prior work demonstrating that 6-7- and 11-12-year-old children differ substantially from one another and from adults in their cognitive control profiles while still being able to understand and complete our DST paradigm (Destan et al., 2014; Lyons & Ghetti, 2013; Chevalier, 2015; Chevalier et al., 2015), such that we could test for differences in their ability to adaptively coordinate behavior based on cognitive control demands. Adults were included for age comparisons and to provide a conceptual replication of demand avoidance with our child-adapted DST paradigm. Participants were first familiarized with both tasks before being allowed to choose which task to play. Then, participants were asked which task they preferred, which task was easier, and why.

Materials and Methods

Participants

Forty-seven 6-7-year-olds (6yo: M=6.41, SD=0.39, range: 5.59-7.34; 26 male), 48 11-12-year-olds (9yo: M=11.73, SD=0.30, range=11.06-12.62; 27 male), and 45 undergraduate adults (M=19.53, SD=1.53, range=18-25; four age unknown; 21 male) were recruited to participate. Child participants were recruited from the participant database of the Cognitive Development Center maintained at the University of Colorado-Boulder. Informed consent was obtained from legal parents/guardians, and child assent (verbal and/or written) was obtained prior to participation. Parents/guardians received minimal monetary compensation for travel costs, and child participants received a moderate token for study participation, regardless of performance. Adult participants were recruited from the Department of Psychology and Neuroscience subject pool at the University of Colorado-Boulder for partial course credit. Written informed consent was obtained prior to participation. Participants were tested at the Cognitive Development Center at the University of Colorado Boulder, and the local Institutional Review Board approved all study procedures.

Demand Selection Task

The Demand Selection Task (DST; E-Prime 1.2, Psychology Software Tools, Inc., Pittsburgh, PA) was adapted for children from Kool and colleagues (2010). Several adaptations were made to the task in accordance with those in Gold and colleagues (2014), including making stable and superficially similar decks, adding a familiarization phase, and enabling deck choice after every choice trial. Critically, participants were still not notified of any differences between decks. The task was introduced as “The Santa Claus Game”, in which participants were asked to help Santa prepare for next Christmas by sorting toys (i.e., “targets”) according to their color or shape. Four targets were used (red or blue car or bear). Participants saw a smiley face and heard a positive sound after correct trials and a frowning face and negative sound after incorrect trials to provide immediate trial feedback. After each correct trial, participants were given a piece of digital candy shown at the bottom right of the screen; a candy piece was removed after incorrect trials or responses more than twice the participant's mean RT during the independent rule practice. The candy count enabled long-term tracking of general performance and provided continued motivation for participants to perform well throughout the task.

Rule Practice: Each sorting rule was explained in turn, followed by four practice trials with each rule and four mixed rule practice trials. Each set of practice trials could be repeated until participants understood the rule, and participants were instructed to respond to the target according to the cued rule as quickly and accurately as possible. Response buttons were identified via two multidimensional pictures (e.g., a red bear to indicate red and bear responses and a blue car to indicate blue and car responses) displayed on the bottom left and right of the screen, respectively, and also presented on the response pad horizontally beneath the response buttons. Response option sides were counterbalanced across participants. After practice trials, participants completed 20 mixed-rule practice trials without guidance from the experimenter. Mean RT was recorded to determine RT limits for each participant.

Baseline Deck Familiarization Phase: Participants were instructed that for the following trials, the toys would be drawn from two green card decks on the upper left and right of the screen, to continue to respond as quickly and accurately as possible, and to pay attention to which decks the toys came from. Green cards descended directly from the decks and were flipped when reaching the middle of the screen. If participants responded greater than twice their mean RT over the 20 mixed-rule practice trials but sorted correctly, a timer appeared indicating that the response was too slow. Negative feedback was presented if responses were incorrect, regardless of RT. Participants completed 40 baseline trials (20/deck) divided into 10-trial blocks. Critically, the decks differed in rule switch/repeat frequency; one deck (high-demand deck) contained 90% rule switches, and the other deck (low-demand deck) contained 10% rule switches. Low-demand deck placement (left or right side) was counterbalanced across participants.

Practice Deck Choice Phase: Upon completing this baseline phase, participants then practiced choosing both the left and right decks for ten trials each. Right and left deck selections were made with two response buttons between the target response buttons and were indicated beneath the response buttons with two rectangles. Prior to each trial, participants fixated on a plus sign between the two decks. A question mark appeared in place of the fixation cross to indicate that participants could now choose which deck to play. After selection, targets descended from directly beneath the decks.

Deck Choice Phase: After deck selection practice, participants were informed that they could choose whichever deck they preferred to play after every trial, that they were free to switch decks whenever they wanted, and that if they began to prefer one deck more than the other, they could play that deck more often or even all the time. Participants then completed 102 free-choice trials across three blocks (34, 35, and 33 trials, respectively).

When participants had completed all choice trials, the experimenter asked whether the participant preferred one deck more than the other and why and whether the participant thought one deck was easier than the other and why. If participants did not report a preference/easier deck, the experimenter asked the question again, prefaced with the phrase "If you had to choose…" Participant responses were recorded on paper by hand by the experimenter. Responses were then digitized and blinded for coding. For analyses regarding responses to these questions, answers to the initial question and the forced choice question were collapsed to form a single self-reported deck preference and reported easier deck. The DST typically ranged from 35 – 45 minutes in length.

Statistical Analysis

This project was preregistered with the Open Science Framework (https://osf.io/y2gbr/), and analyses were conducted as proposed unless otherwise noted. Additional analyses will be described as exploratory. For RT data, responses faster than 200 ms and slower than 10,000 ms were excluded, as well as RTs on incorrect trials. Low-demand deck preference was defined as the proportion of choice trials in which participants selected the low-demand deck. Because low-demand deck preferences were not normally distributed (Shapiro-Wilk normality test: overall: p<.001; all group ps<.09), Wilcoxon signed-rank tests against chance deck selection (i.e., 50%) were used to determine deck preference, as in Kool et al. (2011); additionally, Bayes factors testing specifically for demand avoidance are included. All analyses were performed with the open-source R software (https://www.rstudio.com/), and the analysis script and data are available at the Open Science Framework. Bayes factors were calculated using the BayesFactor package in R and are presented for all proportion tests and correlations. Data were visualized using the ggplot2 package in R.

Results

Four 6-7-year-olds and one 11-12-year-olds opted to quit the study session prior to completion, resulting in 43 6-7yo, 47 11-12yo , and 45 adult participants. Additionally, one 11-12yo declined to answer post-task preference and easy questions. Explanations for deck preference and easier deck questions were unavailable in an additional 11-12yo and one 6-7yo and unavailable for the easier deck question in another 11-12yo.

To preview, we first present behavioral results from the baseline deck familiarization phase and rule switch costs for accuracy and RT. Then, we examine evidence of avoidance of control demands, predictors of demand avoidance, and subjective awareness of deck differences. Overall, we observed consistent signals of control demand awareness and avoidance in adults and 11-12yo but not in 6-7yo.

Deck Familiarization Baseline Performance

Marginal group differences in overall accuracy were observed ($F_{(2,132)}$=2.469, p=.089; adults: M=89.21% (SD: 6.32); 11-12yo: M=85.41% (SD=8.82); 6-7yo: M=88.01% (SD=9.77)). RTs were averaged within participants and then log transformed. Significant group differences were observed between log RTs on correct trials ($F_{(2,132)}$=175.9, p<.001; adults: M=6.62 (SD=0.21); 11-12yo: M=6.93 (SD=0.30); 6-7 : M=7.67 (SD=0.29). We next confirmed the anticipated differences between switch and repeat trials during the baseline deck familiarization phase. As expected, all groups were significantly more accurate on repeat trials than switch trials (adults: M=6.93%, t=6.214, p<.001; 11-12yo: M=7.56%, t=6.0311, p<.001; 6-7yo: M=5.70%, t=4.586, p<.01), and differences in accuracy (accuracy switch costs) between switch and repeat trials did not differ between groups ($F_{(2,132)}$=0.609, p=.545). Correct log RTs were significantly faster on repeat than switch trials across groups (adults: M=0.101, t=6.108, p<.001; 11-12yo: M=0.114, t=5.045, p<.001; 6-7yo: M=0.078, t=3.261, p<.01), and differences in log RT on correct switch versus repeat trials (log RT switch costs) did not differ between groups ($F_{(2,132)}$=0.722, p=.488). Thus, all age groups exhibited similar signals of control demands to utilize for subsequent deck choice behavior. Descriptive performance statistics are presented in Table 1.

Cognitive Demand Avoidance

Across groups, low-demand deck preference was significantly greater than chance (M=57.88%; p<.01). Group differences in low-demand deck selections did not reach statistical significance (Kruskal-Wallis chi-squared=3.653, p=.161).[1] However, for adults and 11-12yo, low-demand deck selections were significantly higher than chance (adults: M=58.04%, p=.021, BF_{10}=1.59; 11-12yo: M=63.29%, p<.001, BF_{10}=87.50), whereas 6-7yo did not significantly differ from chance (M=52.27%, p=.755, BF_{10}=0.25) (Figure 2).[2] Thus, these results provide evidence that adults and 11-12yo children adapted their behavior away from unnecessary control demands but that 6-7yo children did not.

Switch Costs Predict Low-Demand Deck Preference in Adults and Older Children

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[1] A power analysis indicates 95% power with the current sample size to detect an effect size of Cohen's *d*=.75, estimated from Exp. 1 from Kool et al. (2010), which most closely matches our paradigm, against a similar distribution centered at chance deck selections (G*Power 3.1, Faul, Erdfelder, Buchner, & Lang, 2009). However, the substantially smaller adult demand avoidance and larger standard deviation observed here are likely reasons for the lack of significant group differences in low-demand deck selections.

[2] Given a high number of participants exclusively selecting the high-demand deck, especially in 6-7yo, we explored potential group differences deck switch frequency, reasoning that younger children may consistently repeat deck selections to reduce cognitive demands. Although these analyses are confounded by deck differences (and sensitivity to these differences), no group differences in deck switch frequency were observed ($F_{(2,132)}$=.636, p=.531). We also explored whether groups differed deck switching after error commission. No significant differences between groups deck switching after errors relative to correct responses were observed ($F_{(2,132)}$=2.192, p=.116), and no groups were significantly more likely to switch decks after an error relative to after correct responses (adults: t=0.253, p=0.803; 11-12yo: t=1.458, p=0.152, 6-7yo: t=-1.501, p=0.141).

Baseline switch costs in adults significantly correlated with low-demand deck preference (r=.346, p=.020, BF_{10}=2.89), as in Kool et al. (2010); however, this relationship was not observed in the 11-12yo or 6-7yo groups (11-12yo: r=-.094, p=.530; 6-7yo: r=-.041, p=.796) (Figure 3). Exploratory Fisher's *r*-to-*z'* transformations indicated that this correlation in adults was significantly different from the two child groups combined (z=2.14, p=.032).

Because baseline switch costs did not predict low-demand deck selections in children, we next explored whether accuracy costs, that is, difference in accuracy on switch relative to repeat trials, during the familiarization phase predicted subsequent low-demand deck selections. Accuracy switch costs predicted low-demand deck selections in only 11-12yo (r=.319, t=2.259, p=0.029, BF_{10}=2.18; adults: r=-.010, t=-0.067, p=.947; 6-7yo: r=-.163, t=-1.058, p=.296) (Figure 4). Exploratory Fisher's *r*-to-*z'* transformations indicated that this correlation in older children was significantly different from the two other groups combined (z=2.23, p=.026). This pattern of results suggests that different age groups might be sensitive to different demand signals for adapting later choices to reduce demand.

Subjective Awareness of Cognitive Demand

Chi-square tests were run to examine group differences in reporting the low-demand deck as preferred. 69% of adults and 78% of 11-12yo reported that they preferred the low-demand deck, whereas 6-7yo preferred the low-demand deck at chance levels (49%); significant group differences were observed in reported deck preference (χ^2= 8.846; p=.012, BF_{10}=5.544). We then tested whether each group differed from chance self-reported preference using a single proportion test against chance. Adults and 11-12yo preferred the low-demand deck significantly more than chance (adults: χ_1^2=6.422, p=.011, BF_{10}= 6.136; 11-12yo: χ_1^2=14.696, p<.001, BF_{10}= 316.30), whereas 6-7yo did not (χ_1^2=0.023, p=.879). The same analyses were performed for reporting the low-demand deck as easier. 71% of adults and 72% of 11-12yo reported that the low-demand deck was easier, whereas 6-7yo reported the low-demand deck as easier at near chance levels (44%); significant differences in reporting the low-demand deck as easier were observed between groups (χ^2=9.2691; p<.01, BF_{10}=6.297). Single proportion tests indicated that adults and 11-12yo reported the low-demand deck as easier significantly more than chance (adults: χ_1^2=8.022, p<.01, BF_{10}=12.861; 11-12yo: χ_1^2=8.696, p<.01, BF_{10}=17.578), whereas 6-7yo did not (χ_1^2=0.5814, p=0.446). A high majority of adults and 11-12yo were consistent in reporting the same deck for both questions (93.33% of adults and 93.48% of 11-12yo), whereas only 67.44% of 6-7yo were consistent; a chi-square test indicated group differences in answer consistency (χ^2:15.505; p<.001, BF_{10}=113.653), indicating that younger children switched decks between questions more frequently (Table 2). Analysis of explanations for deck self-reported deck preference and easy deck selections are reported in Appendix B, and all participant responses are provided in Appendix C.

Discussion

Younger children, older children, and adults all exhibited signals of control demands, with significantly higher accuracy and faster RTs on rule repeat than switch trials. Moreover, accuracy and log RT costs for rule switch trials were similar across groups, suggesting that all groups had similar signals of control demands. However, only adults and 11-12yos significantly avoided unnecessary cognitive control demands, whereas 6-7yo children did not (although the omnibus tests did not reach significance). Both older children and adults also exhibited evidence of subjective awareness of the differential control demands between decks. Adults and 11-12yo were significantly more likely than 6-7yo to report the low-demand deck as both preferred and easier, and adults and 11-12yo children also reported the low-demand deck as preferred and easier significantly more often than chance. The types of demand signals used to guide behavior also differed by age; response time switch costs predicted low-demand deck preference in adults, whereas accuracy switch costs predicted low-demand deck preference in older children. Neither response time nor accuracy costs predicted low-demand deck selections in 6-7yo. Thus, older children and adults appear to be sensitive to and subsequently adapt behavior away from unnecessary cognitive control demands in ways that 6-7yo children do not.

However, children as young as 5 years old have been shown to coordinate behavior away from difficult tasks taxing more automatic cognitive processes, such as the approximate number system, when receiving feedback and provided exposure to each task prior to being able to choose which task to play (O'Leary, 2017), similar to our DST paradigm. Notably, the accuracy differences between the high- and low-demand options in this dot discrimination task in 5yo (90% vs. 52%) were much higher than the accuracy switch costs for child groups in the DST (7.56% and 5.70% for 11-12yo and 6-7yo, respectively). Thus, the smaller accuracy costs in our paradigm might not provide a sufficient demand signal for 6-7yo children to detect demand differences. Still, that accuracy switch costs predicted low-demand deck selections in 11-12yo suggests that older children may specifically tune to their lower accuracy after rules switches and subsequently avoid task options that involve frequent rule switches. Trial feedback may provide additional support for children's assessments of cognitive control demands.

Our results coincide well with proposed mechanistic neural links to the avoidance of effortful cognitive control in adults. If the proposed ability of dACC to provide error and effort signals improves with age, then younger children, even with similar control demands, should have a weaker neural signal to guide adaptive behavior due to underdeveloped dACC functioning. An especially strong demand signal, such as the large discrepancy in accuracy between the high- and low-demand options in the dot discrimination in O'Leary (2017), may be needed for very young children to adapt behavior. Further, if functional connectivity between dACC and areas of lPFC is required for individuals to utilize a demand signal to adaptively coordinate behavior to reduce control demands, young children, whose control networks involving dACC and PFC are still reorganizing and strengthening (Luna et al., 2010), should be less able to coordinate behavior. Better working memory may also be needed to monitor task performance (Luna et al., 2010), and working memory continues to improve with age (Siegel & Ryan, 1989; Luna, Garver, Urban, Lazar, & Sweeney, 2004); the lateral PFC regions implicated in cognitive control and effort avoidance are also recruited in mature working memory (Curtis & D'Esposito, 2003), and activity in PFC regions during working memory tasks increases with age (Casey, Cohen, Jezzard, Turner, Noll, & Trainor, 1995).

Given that our DST version included both feedback and long-term performance tracking, striatum may also be implicated in a neurodevelopmental explanation of the current results. Striatum has been strongly implicated in feedback-related learning, with enhanced striatal sensitivity to feedback in adolescence relative to childhood and adulthood (Peters & Crone, 2017). Thus, the feedback provided may have supported older children in assessing relative cognitive demands. Additionally, striatum has been shown to reflect effort/reward trade-offs in cognitive control (Croxson, Walton, O'Reilly, Behrens, & Rushmore, 2009), and projections from dACC to striatal regions may mediate feedback-related signals in striatum (Shenhav et al., 2013). Further, functional connectivity between lPFC and striatal regions improves throughout development (Rubia, 2013), and thus, young children may not be able to effectively register the effort/reward trade-offs in response to feedback within our child-adapted DST. In sum, adaptive coordination may not be possible in young children due to working memory limitations in tracking long-term task-specific performance and immature development of dACC and lPFC, as well as still-forming connections between these regions including striatum, to provide effort signals and guide subsequent behavior.

Additional research with larger samples sizes is needed to determine the nature of potential differences in control demand avoidance across development. Future research could also instantiate greater differences in control demands between task options or parametrically manipulate control demand to examine effort sensitivity differences across development. Future research should also continue to investigate the types of cues needed to establish subjective awareness of control demands and how these cues may differ across ages. The heterogeneity in results of control demand avoidance in adults across studies suggests that individuals may differ in the types of cues and instructions leveraged to adapt behavior. Additionally, the neural mechanisms supporting subjective cognitive demand awareness and adaptive behavior control should be investigated across development. Sensitivity to control demands and adaptive response behavior appear to develop alongside cognitive control, and theories of control development should therefore also incorporate considerations of how and when children decide to implement cognitive control.

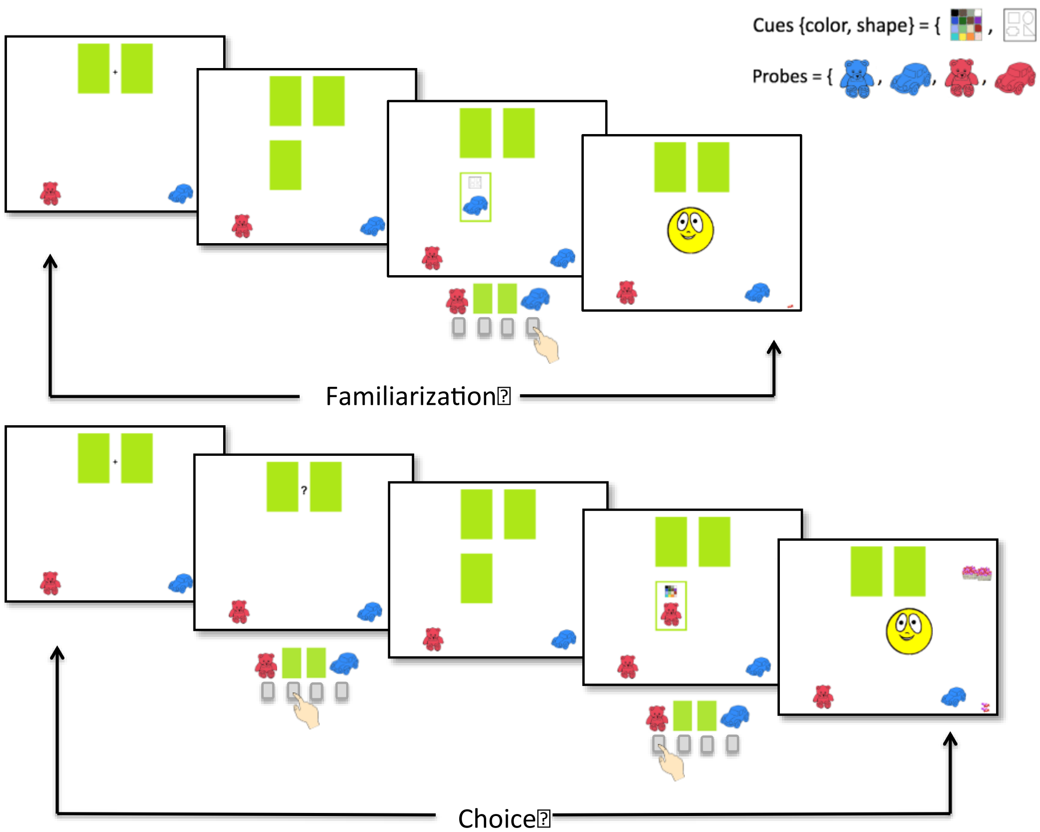

Figure 1. Demand Selection Task Flow. Participants completed 40 familiarization trials (20/deck), 20 forced choice trials (10/deck), and then 102 free choice trials. Probes were presented at the bottom of the screen for answer reminders. The left and right green rectangles depict decks of toys; one deck switched sorting rules on 90% of trials (high-demand), whereas the other deck switched on 10% of trials (low-demand).

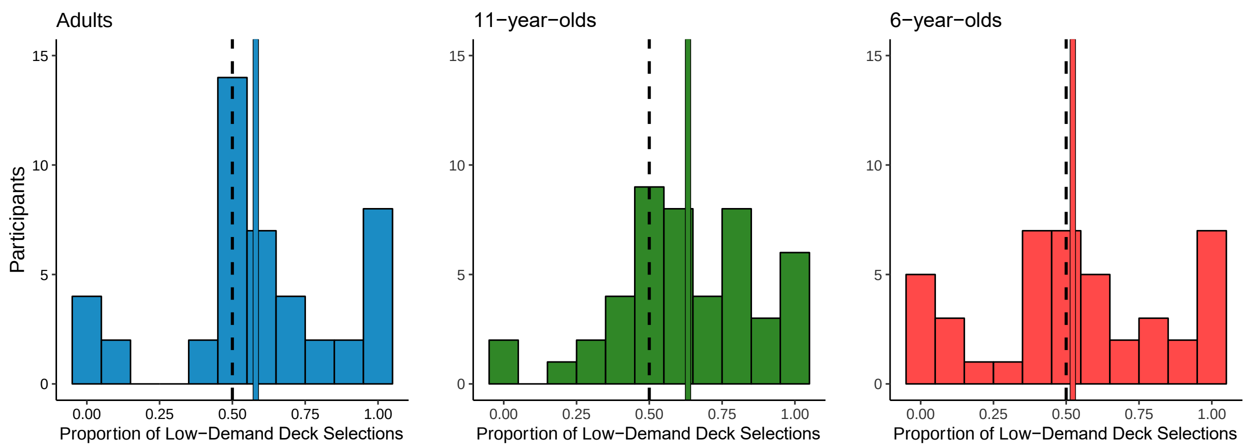

Figure 2: Proportion of low-demand deck selections across block and across groups. Older children (11-12yo) and adults selected the low-demand deck significantly more than chance overall (Wilcoxon signed-rank test, p<.05).

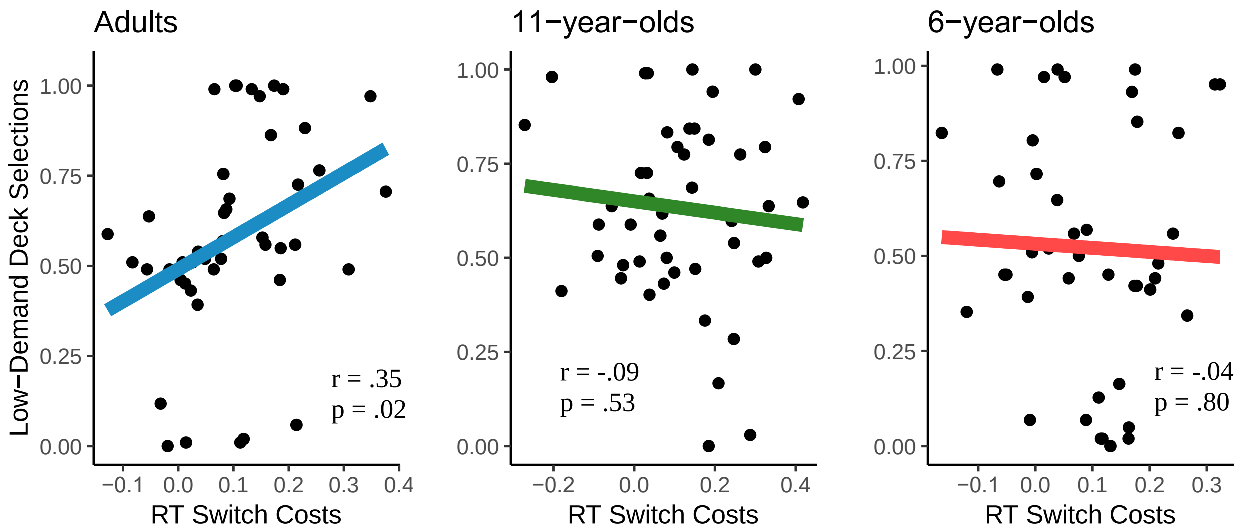

Figure 3: Log response time switch costs predicted the proportion of low-demand deck selections in adults (left) but not 11-year-olds (middle) or 6-year-olds (right).

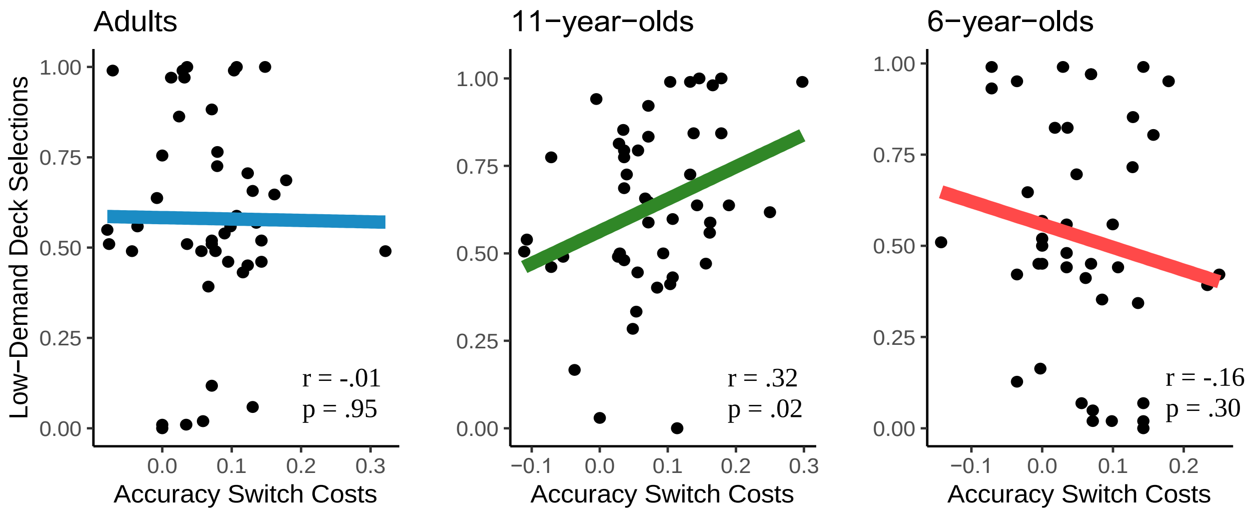

Figure 4: Accuracy switch costs predicted the proportion of low-demand deck selections in 11-year-olds (middle) but not adults (right) or 6-year-olds (left).

Table 1

Deck Familiarization Performance Across Age Groups

	Adults	11-12yo	6-7yo
Switch Trial Accuracy	85.81% (7.93)	81.67% (10.51)	85.28% (11.42)
Repeat Trial Accuracy	92.75% (6.46)	89.23% (8.97)	90.98% (9.71)
Accuracy Cost	6.93% (7.48)★	7.56% (8.60)★	5.70% (8.15)★
Switch Trial Response Time*	6.73 (0.18)	7.10 (0.29)	7.80 (0.34)
Repeat Trial Response Time*	6.63 (0.20)	6.99 (0.32)	7.72 (0.32)
Response Time Cost	0.101 (0.11)★	0.114 (0.15)★	0.078 (0.16)★

Data are presented as means (SD). Response times as reported as log-transformed from mean millisecond response times for each participant. * indicates significant group differences at $p<.001$. ★ indicates significant switch costs at $p<.001$.

Table 2

Low-Demand Deck Preferences and Awareness of Subjective Effort and Adaptive Behavior Across Groups

	Adults	11-12yo	6-7yo
Proportion of Low-Demand Deck Selections	58.04% (28.54)^	63.29% (24.83)*	52.27% (31.42)
Proportion Reporting Preference for the Low-Demand Deck	68.89%^	78.26%*	48.84%
Proportion Reporting the Low-Demand Deck as Easier	71.11%*	71.74%*	44.19%

Data are presented as means (SD). ^ indicates significant differences from chance at p<.05, and * at p<.01.

Supplementary Materials

Self-reported explanations for deck preference and easy deck selections

Three research assistants blinded to study hypotheses and age group coded responses to the post-task deck preference and easy deck questions using categories generated post hoc by the authors after consulting a subset of explanations that spanned groups with group identification removed. The categories were "Task-related/Performance-related", "Intrinsic/Body-related", or "Unclassifiable/No reason"; "Performance-related" explanations were considered "Unclassifiable" for the easier deck explanation question, as this reasoning is tautological. The full descriptions of categories provided to coders are as follows:

1) <u>Task-related/Performance-related</u>: Reasoning is related to task performance ("I got more"), and for the preference question, stating something akin to it being easier. OR, providing something task-specific that makes the task easier (i.e., a pattern with the task, more of a specific rule).
2) <u>Intrinsic/Body-related</u>: Providing a body-intrinsic or non-task related explanation (i.e., handedness, finger convenience, etc.).
3) <u>Unclassifiable/No reason</u>: No specific reason for preferences/non-categorizable reason/just re-stating preference or easy.

Explanations were combined across the initial and forced response questions. Instances of disagreement between reviewers were resolved with majority opinion. Inter-rater reliability statistics were calculated in R using the "irr" package. Moderate to substantial agreement was observed between coders (Fleiss' Kappa for deck preference explanation: .70; Fleiss' Kappa for easy deck explanation: .6) (Landis & Koch, 1977).

Significant group differences were observed for the explanations for deck preference (χ^2=10.55; p=0.032). Follow-up contingency tables were created using the “gmodels” package in R. 6-7yo were more likely to provide an unclassifiable/no reason explanation (standardized Pearson residual: 2.97) and less likely to provide a task-/performance-related explanation (standardized Pearson residual: -2.350), whereas adults were less likely to provide an unclassifiable/no reason explanation (standardized Pearson residual: -1.914) (“gmodel” package in R). Explanations for selecting which deck was easier were similar across groups (χ^2=1.66; p=0.798).

Chapter 3

Developing Adaptive Control: Age-related Differences in Task Choices and Awareness of Proactive and Reactive Control Demands

Note: This chapter is adapted from Niebaum, J. C., Chevalier, N., Guild, R. M., & Munakata, Y. (2021). Developing adaptive control: Age-related differences in task choices and awareness of proactive and reactive control demands. *Cognitive, Affective, & Behavioral Neuroscience*, *21*(3), 561-572.

Abstract

Developmental changes in executive function are often explained in terms of core cognitive processes and associated neural substrates. For example, younger children tend to engage control reactively in the moment as needed, whereas older children increasingly engage control proactively, in anticipation of needing it. Such developments may reflect increasing capacities for active maintenance dependent upon dorsolateral prefrontal cortex. However, younger children will engage proactive control when reactive control is made more difficult, suggesting that developmental changes may also reflect decisions about whether to engage control, and how. We tested awareness of temporal control demands and associated task choices in 5- and 10-year-olds and adults using a demand selection task. Participants chose between one task that enabled proactive control and another task that enabled reactive control. Adults reported awareness of these different control demands and preferentially played the proactive task option. Ten-year-olds reported awareness of control demands but selected task options at chance. Five-year-olds showed neither awareness nor task preference, but a subsample who exhibited awareness of control demands preferentially played the reactive task option, mirroring their typical control mode. Thus, developmental improvements in executive function may in part reflect better awareness of cognitive demands and adaptive behavior, which may in turn reflect changes in dorsal anterior cingulate in signaling task demands to lateral prefrontal cortex.

Cognitive control, the ability to coordinate thoughts and behaviors to accomplish goals, improves dramatically across childhood (Davidson, Amso, Anderson, & Diamond, 2006; Prencipe et al., 2011; Zelazo & Carlson, 2012). For example, children transition from primarily engaging control reactively, recruiting control as needed, to engaging control proactively, in anticipation of need, as they age (Chatham, Frank, & Munakata, 2009; Gonthier, Zira, Colé, & Blaye, 2019; Lucenet & Blaye, 2014). These improvements support children's behavior through an improving ability to keep information and goals in mind (Best, Miller, & Naglieri, 2011; Blair & Razza, 2007; Carlson & Wang, 2007; Cartwright, 2012), and children's cognitive control predicts important concurrent and future outcomes, such as academic achievement, health, and income (Ahmed, Tang, Waters, & Davis-Kean, 2019; Moffitt et al., 2011; Robson, Allen, & Howard, 2020).

Extensive research efforts have focused on understanding improvements in core cognitive processes, such as working memory, that might support the increased use of proactive control (e.g., Davidson et al., 2006; Munakata, Snyder, & Chatham, 2012). For example, increases in working memory capacity support the transition to proactive control as children age (Gathercole, Pickering, Ambridge, & Wearing, 2004; Troller-Renfree, Buzzell, & Fox, 2020). Such improvements have been linked to maturation of lateral prefrontal cortex (lPFC) and its increasing connectivity with other brain regions, including dorsal anterior cingulate cortex and striatum, that continue to emerge from young childhood into adulthood (Andrews-Hanna et al., 2011; Buss & Spencer, 2018; Ezekiel, Bosma, & Morton, 2013; Fiske & Holmboe, 2019; Lopez, Kandala, Marek, & Barch, 2019; Luna, Padmanabhan, & O'Hearn, 2010; Vink et al., 2014). lPFC is thought to support the flexible updating and maintenance of task rules (Koechlin

& Summerfield, 2007; Niendam et al., 2012; Wendelken, Munakata, Baym, Souza, & Bunge, 2012). Thus, developmental changes like the transition to increasingly proactive control may reflect increasing capacities for active maintenance dependent upon lPFC.

However, children must also become adept at selecting appropriate control strategies given their goals and environmental demands (Chevalier, 2015). Five-year-old children, who tend to engage control reactively, will engage control proactively when reactive control is made more difficult by removing a sorting rule prior to the target to be sorted, exhibiting both faster response times and pupillometric and ERP markers of proactive control (Chevalier, Martis, Curran, & Munakata, 2015). In contrast, older children will engage control proactively when possible and implement control reactively only when proactive preparation is prevented. Thus, younger children can engage proactive control but differ from older children and adults in the contexts in which they do so. Age-related improvements in cognitive control may thus reflect improvements in not only core cognitive processes but also in adaptively selecting what type of control to engage, when to do so, and the kinds of tasks to take on.

Children's awareness of control demands and adaptive task selection has been investigated using a demand selection task (Niebaum, Chevalier, Guild, & Munakata, 2019), in which participants chose between one task that switched between sorting rules more frequently than another, resulting in greater control demand (Monsell, 2003). Adults, 11-year-olds, and 6-year-olds were all slower and less accurate on rule switch trials and thus had demand signals to potentially use to select the easier task option. However, only 11-year-olds and adults reported awareness of these different control demand and preferentially selected the option with fewer rule switches (Niebaum, et al., 2019), supporting prior work in only adults

(Kool, McGuire, Rosen, & Botvinick, 2010; cf. Gold et al., 2015). In contrast, 6-year-olds were unaware of demand differences and selected tasks at chance.

What leads to these age-based differences? Young children may be less sensitive to task switching demands than older children and adults but more attuned to other developmentally relevant control signals. For example, due to age-related biases in engaging proactive and reactive control, younger children may be more sensitive to temporal control demands compared with other control demand signals, and select tasks enabling reactive control, their preferred control mode. Additionally, signals of demand may be different across age groups in different domains. For example, the relative benefits of proactive control may increase with age, which could result in differences in task choices and awareness of task demands across development.

We examined whether task choices and awareness of proactive and reactive control demands differ across development. Adults and 5- and 10-year-old children completed a demand selection task presenting two task options that encouraged either proactive or reactive control. Participants were asked to sort pictures from two card decks that differed in the temporal presentation of a sorting rule. One deck, the proactive deck, displayed the sorting rule before each picture, allowing participants to prepare for a sorting dimension, and occluded the rule during target presentation. The other deck, the reactive deck, presented the sorting rule and picture simultaneously, preventing such preparation. After being familiarized with both decks, participants were able to choose which deck to play.

We predicted that the proportion of proactive deck selections would increase with age. Because 5-year-olds tend to engage control reactively, we expected 5-year-olds to preferentially select the reactive deck if exhibiting awareness of the temporal control differences between decks. We expected 10-year-olds to preferentially play the proactive deck; however, 10-year-olds may also select decks at chance because 10-year-olds have been shown to use relative accuracy differences to select tasks but have not shown accuracy benefits with proactive control engagement (Chevalier et al., 2015; Niebaum et al., 2019). Because adults tend to engage control proactively and have previously been shown to prioritize relative efficiency signals to select tasks (Kool et al., 2010; Niebaum et al., 2019), we expected adults to select the proactive deck. Thus, we also expected that relative accuracy differences between decks would predict deck selections in 10-year-olds and that relative efficiency benefits for the proactive deck would predict deck selections in adults. Finally, we predicted that awareness of deck differences, subjective deck preferences, and awareness of performance differences between decks would differ between age groups.

Methods

Participants

We analyzed a sample of 42 5-year-olds (5yo: M=5.60, range: 5.07-6.09, 21 male), 40 10-year-olds (10yo: M=10.59 years, range: 10.07-11.02, 23 male), and 75 adult participants (M=20.22, range: 17.96-38.50, 3 not reporting, 33 male). We selected these ages to match prior work on the implicit coordination of proactive and reactive control to task demands and include adults for further comparison (Chevalier et al., 2015). Children transition from primarily engaging control reactively to engaging control proactively at about 6 years of age (Lucenet & Blaye, 2014); thus, we included young children biased towards implementing reactive control to contrast with older, typically more proactive children and adults. No upper age limit was used for adults because we had no hypotheses about changes in proactive deck selections after reaching adulthood. Five additional 5yo quit the study session prior to completion, one additional 10yo was excluded due to a parent describing deck differences during the study session, and 3 additional adults were missing behavioral data from the demand selection task due to program errors.

Our effect size estimate was based on the average effect size of two adult samples completing similar paradigms in pilot samples, in which the proportion of proactive deck selections, our primary outcome, was tested against a hypothetical sample of 50% proactive deck selections, indicating no preference for either the proactive or reactive deck (the upper range of our 5yo group prediction) with similar standard deviation. G* Power 3.1 indicated that 36 participants per cell were needed detect a Cohen's d=.7 at 90% power at an alpha of .05 using a traditional ANOVA because guidelines for conducting power analyses for Krustal-Wallis Tests have not been established (Faul, Erdfelder, Lang, & Buchner, 2007; McDonald, 2014). Because we anticipated non-normal distributions in the primary outcome variable and sought to increase power for additional analyses, we recruited at least 40 participants per group. Child participants were recruited until reaching the minimum sample completing the demand selection task. As child data collection typically requires more time, we continued to recruit adults to increase statistical power because our primary preregistered statistical tests are robust to differences in group size (McHugh, 2013; Meyer & Seaman, 2013).

Child participants were recruited from the participant database of the Cognitive Development Center maintained at the University of Colorado Boulder. Informed consent was obtained from legal parents/guardians, and child assent (verbal and/or written) was also obtained. Parents/guardians received minimal monetary compensation for travel costs, and child participants received a token for study participation. Adult participants were recruited from the Department of Psychology and Neuroscience subject pool at the University of Colorado Boulder for partial course credit. Written informed consent was obtained prior to participation. Participants were tested at the Cognitive Development Center at the University of Colorado Boulder, and the local Institutional Review Board approved all study procedures.

Demand Selection Task

The demand selection task was analogous to Niebaum et al. (2019) and programmed in PsychoPy v2.82 (Peirce et al., 2019). Critically, the decks differed in the temporal presentation of the sorting rule. For one deck, the proactive deck, the sorting rule was presented 1.5 seconds before the target and then occluded with a grey square when the target appeared, encouraging proactive control. For the other deck, the reactive deck, a grey square was presented in place of the sorting rule for 1.5 seconds, and then, the sorting rule and target were presented simultaneously, preventing proactive control. Participants were not notified of any differences between decks.

The task typically took 20-30 min and comprised 3 phases of Rule Practice, Baseline Deck Familiarization, and Deck Choice (Figure 1). In all phases, participants were asked to sort pictures (i.e., “targets”) according to their color or shape. Four targets were used (orange or green circle or triangle). Response buttons were identified via two multidimensional pictures (e.g., an orange triangle to indicate orange and triangle responses and a green circle to indicate green and circle responses) displayed on the bottom left and right of the screen and also presented on the response pad horizontally above the response buttons. Deck choice buttons were identified via two blue boxes above two buttons to the left or right of the target response buttons. Participants saw a smiley face and heard a positive sound after correct responses and a frowning face and negative sound after incorrect responses. After each correct trial, participants were given a piece of digital candy shown at the bottom right of the screen; a candy piece was removed after incorrect trials. We did not set an upper latency bound for positive feedback to prevent participants from selecting the proactive deck to avoid negative feedback from long response latencies, which is consistent with similar paradigms using these trial structures (Chevalier et al., 2015; Doebel et al., 2017). The candy count enabled long-term tracking of general performance and along with the positive audio feedback, helped to provide continued motivation for participants to perform well throughout the task, similar to other child-friendly task-switching paradigms (Chevalier et al., 2015; Chevalier, Dauvier, & Blaye, 2018; Niebaum et al., 2019).

Rule Practice Phase

Each sorting rule was explained in turn, followed by four practice trials with each rule and four mixed rule practice trials. Each set of practice trials was repeated until participants answered all four trials for each rule and the mixed rule practice correctly, and participants were instructed to respond to the target according to the cued rule as quickly and accurately as possible. For all practice trials, the sorting rule was displayed 1.5 seconds prior to the target and remained on screen during target presentation to prevent biasing participants towards implementing proactive or reactive control during rule practice.

Deck Familiarization Phase

Participants were then told that the pictures would be drawn from two blue card decks on the upper left and right of the screen and instructed to continue to respond as quickly and accurately as possible and pay attention to which deck the pictures came from. Blue cards transitioned to the center of the computer screen and were flipped when reaching the center. Participants completed 60 baseline trials (30 trials/deck) divided into 15-trial blocks. Proactive deck placement (left or right side) was counterbalanced across participants, and each deck presented the same series of rule switches and repeats during familiarization.

Deck Choice Practice Phase

Participants then practiced choosing both the left and right decks for five trials each. Right and left deck selections were made with two response buttons on the outside of the target response buttons and indicated above the response buttons with two blue rectangles. Prior to each trial, participants were told to fixate on a plus sign between the decks. A question mark appeared in place of the plus sign to indicate that participants could choose which deck to play. After selection, cards transitioned to the center of the screen and then revealed cues and targets.

Deck Choice Phase

After deck choice practice, participants were informed that they could choose whichever deck they preferred to play after every trial, that they were free to switch decks whenever they wanted, and that if they began to prefer one deck more than the other, they could play that deck more often or even all the time. Participants then completed 50 free-choice trials divided across two blocks.

Post-task questionnaire

After the Demand Selection Task, the experimenter read aloud six questions to all participants to assess awareness of deck differences and subjective experiences with each deck. Participants responded verbally, and responses were recorded on paper by the experimenter. Participants responded with the left or right deck for all questions except for the initial question, to which participants responded yes or no. Responses were later recoded as the proactive or reactive deck. The questions were as follows: Were there any differences between decks?; Did you like one deck more than the other?; Was one deck easier than the other?; Were you faster on one deck more than the other?; Did you get more right on one deck than the other?; and Did one deck make you think harder than the other?. If participants did not report a deck, the experimenter asked the question again, prefaced with the phrase, "If you had to choose…" For analyses regarding responses to these questions, initial and forced choice responses were collapsed.[3] Additionally, participants gave open responses to each question explaining their answer. Analyses of the free response data are included in the Supplementary Materials.

Statistical Analyses

This project was preregistered with the Open Science Framework (osf.io/ung52/), and analyses were conducted as proposed unless otherwise noted. All data and materials are also available at the project's OSF page. For each participant, mean response time for correct trials was calculated after removing outliers, defined as the mean + 3 SD and less than 200 ms or mean – 3 SD (1.98% of trials removed), in accordance with Chevalier et al. (2015). Because

[3] We also made a post hoc decision to exclude participants who refused to answer a question in analyses assessing whether age groups significantly differed from chance responding on the question. No more than 1 participant refused to answer any specific question.

response times were skewed on both proactive and reactive decks in all age groups during familiarization (all ps<.01), response times for each deck were log-transformed to reduce skew for correlations and to better meet assumptions for ANOVA for task performance (Meiran, 1996).

Proactive deck preference was defined as the proportion of choice trials in which participants selected to play the proactive deck. As predicted, the proportions of proactive deck selections were not normally distributed (Shapiro-Wilk normality test: overall: p<.001; all group ps<.05); thus, a Kruskal-Wallis test was used to test for group differences in the proportion of proactive deck selections, and Wilcoxon signed-rank tests against chance deck selection were used to determine deck preference. To ascertain performance metrics of relative demands, we calculated mean differences in response time and accuracy between the proactive and reactive decks for each participant.[4] Chi-square tests were conducted to test age group differences in binary responses to post-task questions, and single proportion tests were conducted within groups to determine whether responses significantly differed from chance responding. All analyses were performed with the open-source R software (RStudio Team, 2015). Bayesian analyses were conducted with the BayesFactor package (Morey, Rouder, Jamil, & Morey, 2015), and data were visualized using the ggplot2 package in R (Wickham, 2016).

Results

Rule Practice Performance

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[4] Age groups may differ in their weighting of speed-accuracy trade-offs between the two decks, which may influence perceptions of demand for each task. We did not have a priori hypotheses regarding age differences in these trade-offs across tasks, and this issue may be challenging to test (e.g., given low reliability of condition contrasts from drift diffusion model parameters; Enkavi et. al 2019) but could be explored in future work.

Age groups differed in the number of times participants needed to repeat a practice run to achieve 100% accuracy ($F_{(2,154)}=39.07$, $p<.001$). Additional rule practice was not correlated with Familiarization Phase accuracy in either child group (5yo: $r=-.17$ [-.45, .14], $p=.27$; 10yo: $r=-.13$ [-.42, .19], $p=.44$), indicating that additional practice did not confer a performance benefit. In adults, practice run repeats significantly negatively correlated with Familiarization Phase accuracy in the adult groups ($r=-.42$ [-.59, -.22], $p<.001$), indicating that adults who performed poorly in practice continued to perform poorly later in the task. Requiring all participants to meet the practice criteria to proceed ensured that all participants understood all rules.

Deck Familiarization Phase Performance

Age groups differed in overall accuracy ($F_{(2,154)}=16.44$, $p<.001$), overall log RT ($F_{(2,154)}=239.41$, $p<.001$), proactive deck accuracy ($F_{(2,154)}= 31.34$, $p<.001$), proactive deck RT ($F_{(2,154)}= 108.86$, $p<.001$), and reactive deck RT ($F_{(2,154)}=81.52$, $p<.001$). Age differences for reactive deck accuracy were marginal ($F_{(2,154)}=2.73$, $p=.069$), likely due to the high accuracy across groups. We focus here on differences in accuracy and response time between the proactive and reactive decks, our preregistered indicators of relative task demands. All groups were significantly faster on the proactive than the reactive deck (adults: M=0.46 (SD=.19), $t_{(74)}=20.70$, $p<.001$; 10yo: M=0.37 (SD=.17), $t_{(39)}=13.55$, $p<.001$; 5yo: M=0.21 (SD=.22), $t_{(41)}=6.29$, $p<.001$), and these correct log RT differences between decks also differed between age groups ($F_{(2,154)}=21.34$, $p<.001$). Follow-up Tukey's HSD were used to test all pairwise group comparisons to determine whether specific age groups differed in their relative performance between decks; differences in response times between the proactive and reactive decks was marginally larger for adults than 10yo (adjusted $p=.06$) and significantly larger than 5yo (adjusted $p<.001$) and larger for 10yo than 5yo (adjusted $p<.001$). These results suggest that the differences in response efficiency when playing the proactive deck compared with the reactive deck increased with age. As predicted, adults and 10yo showed no accuracy differences between decks (adults: M=-0.53%, $t_{(74)}=-0.69$, $p=.49$; 10yo: M=0.08%, $t_{(39)}=0.07$, $p=.95$), whereas 5yo were significantly more accurate on the reactive deck than the proactive deck (M=6.19%, $t_{(41)}=4.55$, $p<.001$). These relative accuracy differences differed between age groups ($F_{(2,154)}=10.98$, $p<.001$), driven by significant differences between the 5yo and both older age groups (Tukey's HSD, adjusted ps<.01). Thus, although 5yo responded faster on the proactive deck than the reactive deck, they were less accurate on the proactive deck. In contrast, the adults and 10yo were faster on the proactive deck but showed no decreases in accuracy. Descriptive performance statistics are presented in Table 1. Post hoc exclusion of four outliers in the 10yo group (1 outlier in accuracy differences and 3 outliers in response time between decks) did not change most results, and thus, all participants are included in the reported analyses. Further details on these analyses are available in the Supplementary Materials.

Selection of Proactive and Reactive Decks

Age groups differed in the proportion of proactive deck selections (Kruskal-Wallis chi-squared=18.61, $p<.001$). Adults selected the proactive deck more than 10yo ($p<.01$) and 5yo ($p<.001$), and 10yo and 5yo did not significantly differ ($p=.24$), as indicated by follow-up pairwise comparisons using the Wilcoxon rank sum test with Holm-Bonferroni adjusted p-values. As predicted, adults selected the proactive deck significantly more often than chance (M=70.27%, SD=31.62, $p<.001$), whereas the 10yo and 5yo did not significantly differ from chance (10yo: M=50.65%, SD=32.49, $p=.96$; 5yo: M=41.29%, SD=35.77, $p=.19$) (Figure 2).

We also conducted exploratory analyses with a linear code for age group and with age in days as continuous predictors of proactive deck selections. Similar results were obtained using a linear code for age group (chi-squared=18.61, p<.001), and age positively correlated with proportion of proactive deck selections (r=.39 [.23, .51], t=5.76, p<.001). Collectively, these results indicate that the proportion of proactive deck selections increased with age, confirming our primary prediction.

We also conducted exploratory hierarchical logistic regressions at the trial level. We predicted proactive deck selections with trial number, age group (using a linear code with 5-year-olds coded as 0), and their interaction, with random intercepts and trial slopes for participants (Table 1). We observed main effects of age group (B=0.24, z=2.87, p<.01) and trial number (B=-0.07, z=-3.76, p<.001), as well as a significant group by trial interaction (B=0.04, z=4.75, p<.001). Proactive deck selections increased with age and decreased across trials on average, but changes across trials varied by age group. Specifically, proactive deck selections increased across trials in adults (r=.70 [0.52, .82], p<.001, BF10=4.65 x 105), showed no significant change across trials in 10yo (r=-0.14 [-0.40, .14], p=.33, BF10=.49), and decreased across trials in 5yo (r=-0.46 [-0.66, -0.22], p<.001, BF10=60.84), as revealed by follow-up exploratory correlation tests.

Associations between performance during familiarization and deck selections

We conducted simple correlations between our performance metrics of relative demand, specifically response time and accuracy differences between decks, and the proportion of proactive deck selections in each age group. No correlations were observed between relative speed differences between decks and subsequent proportions of proactive deck selections for any age group (Figure 3, all ps >.15). Similarly, no correlations were observed between relative accuracy differences between decks and subsequent proportions of proactive deck selections for any age group (Figure 3, all ps >.18). Additionally, we ran Bayesian analyses to determine whether the evidence favored the null hypothesis of no relationship between performance metrics and proportion of deck selections or the alternative. Bayes factors for all correlations provided anecdotal evidence in favor of the null hypothesis (all BFs < 1) (Makowski, Ben-Shachar, & Lüdecke, 2019).

Subjective awareness and preferences for proactive and reactive decks

Age groups differed in their responses to all 6 post-task questions about the decks. Binary responses to the post-task questions are included in Table 2. First, age groups differed in reporting whether there were any differences between the decks ($\chi2=24.38$, $p<.001$). Adults and 10yo responded that there were deck differences more frequently than chance (adults: 86.49%, $\chi2=37.96$, $p<.001$; 10yo: 82.5%, $\chi2=15.63$, $p<.001$), whereas 5yo responded at chance levels (47.62%, $\chi2=0.02$, $p=.88$).

Although adults and older children thus differed from younger children in reporting whether there were any differences between decks, adults differed from both older and younger children on questions about subjective experiences and performance on the decks. Adults strongly preferred the proactive deck on post-task questions, whereas older children showed no significant leanings. Younger children preferentially reported the reactive deck on only some questions. On questions about subjective experiences with the decks, age groups differed in which deck was preferred ($\chi2=24.63$, $p<.001$), easier ($\chi2=35.34$; $p<.001$), and required more cognitive effort ($\chi2=15.13$, $p<.001$). Adults reported the proactive deck as preferred more than chance (78.67%, $\chi2=23.52$, $p<.001$), 10yo responded at chance (50%, $\chi2=0$, $p=1$), and 5yo reported marginal preference for the reactive deck (63.41%, $\chi2=2.44$, $p=.12$). Adults reported the proactive deck as easier (77.03%, $\chi2=20.55$, $p<.001$), 10yo responded at chance levels (40%, $\chi2=1.23$, $p=.268$), whereas 5yo reported the reactive deck as easier (76.19%, $\chi2=10.5$, $p<.01$). Adults reported that reactive deck required harder thinking (72.95%, $\chi2=14.76$, $p<.001$), whereas the 10yo and 5yo did not significantly differ from chance (10yo: 36.84% selected the reactive deck, $\chi2=2.13$ $p=.144$; 5yo: 41.46% selected the reactive deck, $\chi2=0.88$, $p=.349$).

For questions about performance differences between decks, age groups differed in which deck they reported as responding faster ($\chi2=12.31$; $p=.009$) and more accurately ($\chi2=18.88$; $p<.001$) on. Adults reported that they were more accurate on the proactive deck (69.01%, $\chi2=9.52$, $p=.002$), 10yo responded at chance levels (40%, $\chi2=1.23$, $p=.268$), and the 5yo reported that they were more accurate on the reactive deck (33.33%, $\chi2=4.02$, $p=.045$). Adults responded that they were faster on the proactive deck (73.61%, $\chi2=15.13$, $p<.001$), whereas the child groups did not differ from chance in their responses (10yo: 62.50%, $\chi2=2.03$, $p=.154$; 5yo: 41.46%, $\chi2=0.88$, $p=.349$).

Awareness of task differences predicts preferential task selection in 5yo and adults

In a prespecified exploratory analysis, we focused on participants who reported observing deck differences to determine whether individuals who successfully reported task differences systematically selected particular decks. This analysis was conducted to address the heterogeneity in reporting task differences in the 5-year-olds compared with the older age groups, which could confound analyses of deck selections with the full sample. We predicted that in this subset, adults (N=64) and 10yo (N=33) would play the proactive deck, whereas 5yo (N=20) would play the reactive deck. Age groups significantly differed in deck selections (Kruskal-Wallis chi-squared=25.78, p<.001). Adults played the proactive deck more than 10yo (p<.001) and 5yo (p<.001), and 10yo showed a trend toward playing the proactive deck more than 5yo (p=.06), as indicated by follow-up pairwise comparisons using the Wilcoxon rank sum test. As expected, adults chose to play the proactive deck more often than chance (M=74.09%, SD=28.97, p<.001); however, 10yo played decks at chance levels (10yo: M=51.88%, SD=30.85, p=.80). As predicted, 5yo chose to play the reactive deck significantly more than chance (5yo: M=34.7%, SD=29.35, p=.03).

We also conducted an exploratory hierarchical model predicting proactive deck selections using a linear code for age group (5-year-olds coded as 0), deck awareness (dummy coded as 1: Yes or 0: No for reported differences between decks), and their interaction, with random intercepts and trial slopes for participants. No main effects were observed (age group: B=-0.04, z=-.19, p=.85; deck awareness: B=-1.28, z=-1.58, p=.12), but a significant age group by deck awareness interaction was observed (B=0.82, z=2.03, p=.04). This interaction reflected the fact that deck awareness was increasingly associated with proactive deck selections with age. These results provide further support that aware 5-year-olds are more likely to select the reactive deck and that aware adults are more likely to select the proactive deck.

Discussion

The present study examined whether children and adults were aware of and selected tasks in response to cognitive demands based on the temporal dynamics of control. Five-year-olds, 10-year-olds, and adults all responded faster on the task option enabling proactive control than the option requiring reactive control, and these relative response time benefits increased with age; only 5-year-olds were less accurate on the proactive deck compared with the reactive deck, whereas the 10-year-olds and adults were similarly accurate across decks. Confirming our hypotheses, proactive deck selections and the percentage of individuals reporting differences between decks increased with age. However, despite clear indices of performance differences across all age groups, only adults preferentially selected the proactive control deck, and only adults and 10-year-olds consistently reported differences between decks. Adults reported better performance on the proactive deck and the proactive deck as preferable and easier, reflecting their deck choices. Although 10-year-olds reported deck differences, they did not systematically report either deck as easier or preferred or report performance differences between decks. Interestingly, 5-year-olds reported the reactive deck as easier and leading to better accuracy, despite not preferentially selecting the reactive deck, not reporting differences between decks, and not expressing a deck preference; however, the subset of 5-year-olds that reported deck differences preferentially played the reactive deck, and 5-year-olds overall selected the reactive deck with increasing frequency as the task progressed. Collectively, these results suggest that younger children are less aware of proactive and reactive control demands between tasks than older children and adults. Further, awareness of task differences leads to different task selections that vary by age, with younger children more likely to select the reactive deck and adults more likely to select the proactive deck.

Performance indices of control demands did not predict deck selections in any age group. One explanation for these null results is the restricted range in the accuracy and response time differences between task options observed in all groups compared with prior investigations (e.g., Kool et al., 2010; Niebaum et al., 2019), which limits statistical power to detect correlations. The difference in response times between decks was also very large for most adults. Thus, the response efficiency demand signal may have reached a minimum threshold to adapt task selection for adults. Further, task performance is typically only weakly predictive of task preferences in older children and adults (Chevalier, 2018; Westbrook, Kester, & Braver, 2013). Individuals may have developed task preferences utilizing additional factors beyond performance indices of cognitive demand.

Although the 5-year-olds reported better performance and ease on the reactive deck, they did not adapt task selection to maximize accuracy. Young children may not preferentially attend to performance signals to guide behavior, even when accurately reporting performance differences between tasks (O'Leary & Sloutsky, 2019). Young children may also track performance on different tasks without specifically attending to differences between tasks. The by-trial and long-term performance feedback included here may have aided children in monitoring response accuracy, especially for post-task responses. Systematic overestimations of performance accuracy in younger children, even with feedback, may further attenuate demand signals to guide task selection (Lipko, Dunlosky, & Merriman, 2009; O'Leary & Sloutsky, 2017, 2019; Schneider, 1998; Yussen & Berman, 1981).

Older children, who have been shown to avoid unnecessary control demands in a task-switching context, may prioritize accuracy to signal task demands (Niebaum et al., 2019). The accuracy performance feedback used here may have further biased children to attend to accuracy as a demand signal. Thus, the minimal accuracy differences between decks may explain why 10-year-olds did not preferentially select either deck. However, older children were proficient at reporting task differences, further suggesting that 10-year-olds successfully monitored task demands but that the relative demands instantiated may have been insufficient to guide task selection. Because proactive control is still improving throughout late childhood into adulthood (Andrews-Hanna et al., 2011; Vink et al., 2014), 10-year-olds may have less facility in engaging control proactively compared with adults, leading to lower preference for the proactive deck compared with adults.

Deciding when and how to implement control may rely on the effective engagement of brain regions supporting cognitive control. Connectivity between dACC and lPFC, regions associated with cognitive control, has been implicated in adaptively selecting tasks to reduce cognitive control demands (McGuire & Botvinick, 2010; Shenhav, Botvinick, & Cohen, 2013; Shenhav, Cohen, & Botvinick, 2016; Sheth et al., 2012; cf. Sayalı & Badre, 2019). Connectivity between lPFC and striatum has been further linked to cognitive effort-based decision-making in adults (Botvinick & Braver, 2015). Because functional connections between lPFC and dACC and lPFC and striatum increase with age (Ezekiel et al., 2013; Fiske & Holmboe, 2019; Grayson & Fair, 2017; Lopez et al., 2019; Luna et al., 2010; Vink et al., 2014), developmental differences in the awareness of control demands and adaptive task selection may reflect age-related differences in the neurological mechanisms supporting these processes.

The high proactive deck preference observed in adults could be viewed as challenging a typical characterization of proactive control as more demanding than reactive control. Specifically, reactive control is characterized by transient activation and recruitment of goal-relevant information rather than sustained activation in lateral prefrontal areas, so proactive control is typically considered more demanding on working memory (Braver, 2012; Marklund &

Persson, 2012). However, resolving response conflict is also demanding, resulting in slower response times and worse accuracy, and is associated with activity in dACC. Adults have been shown to preferentially select tasks with fewer response conflicts if aware of these relative demand differences (Desender, Buc Calderon, Van Opstal, & Van den Bussche, 2017; Schouppe, Ridderinkhof, Verguts, & Notebaert, 2014). In the current demand selection task, the conflict between rule cues and targets may have outweighed the effort to engage proactive control, given that the delays were brief and did not include distractors, minimizing demand for sustained representations of rule cues. Moreover, the proactive deck allowed for task preparation, which may have resulted in lPFC activation to bias attention towards only relevant stimuli dimensions (Brass & von Cramon, 2004). Thus, adults may have experienced attenuated demand signals from dACC while playing the proactive deck relative to the reactive deck, addition to the improved response efficiency on the proactive deck, which adults may rely on to select tasks (Kool et al., 2010; Niebaum et al., 2019).

Our results suggest that the dramatic developments children show in cognitive control may in part reflect their developing awareness of cognitive task demands. Interestingly, adults and 5-year-olds who reported differences between decks preferentially selected decks that enabled their preferred temporal control modes, with 5-year-olds choosing to play the reactive deck more often and adults choosing to play the proactive deck. Because preferential task selection was specific to the smaller subset of 5-year-olds who reported task differences, awareness of deck demands may be requisite for adaptive behavior, reflecting prior work in adults (Desender et al., 2017; Gold et al., 2015; cf. O'Leary & Sloutsky, 2019). Further, only about half of the 5-year-olds reported deck differences, whereas similar proportions of 10-year-olds and adults reported deck differences, suggesting that children may transition towards spontaneously monitoring cognitive task demands at around 5 years of age.

Although we provide evidence for age-related differences in task selection based on temporal control demands, our study has several limitations. First, our proactive control manipulation was still very short, as participants saw the target directly after the sorting rule. Increasing the duration between rule and target presentation, making proactive control more difficult, could make adults and older children prefer the reactive task. Our use of accuracy performance feedback could also influence task selections. Including response time feedback may bias individuals towards assessing demand via response efficiency, resulting in greater preference for the proactive task option. Removing feedback could also hinder individuals' ability to assess demand, especially children (e.g., O'Leary & Sloutsky, 2019). Although the post-task questionnaire yielded insight into age-related differences in awareness of task differences and preferences, young children also likely have limited ability to verbally report metacognitive knowledge compared with older children and adults, which may have influenced these analyses. Further, we are unable to confidently discern whether adults' proactive task preferences were due to improving response efficiency or avoiding conflict, or both, from only post-task questioning.

Additional research should investigate whether individuals monitor different signals of demand at different ages and how these signals influence task decisions and lead to potential benefits across development. Young children may be less likely to utilize signals of cognitive demands for guiding behavior relative to adults (Niebaum et al., 2019; O'Leary & Sloutsky, 2017); they may prioritize other signals such as novelty and interest when making task selections, which may benefit their learning. Developmental improvements in selecting tasks based on demand could also reflect faster learning of task demands with age. Understanding of cognitive development may thus be advanced by incorporating considerations of how and when children attend to signals of control demand, the different contexts in which children decide to engage control, the cognitive abilities supporting demand monitoring and adaptive task selections, and how these factors influence children's choices and outcomes.

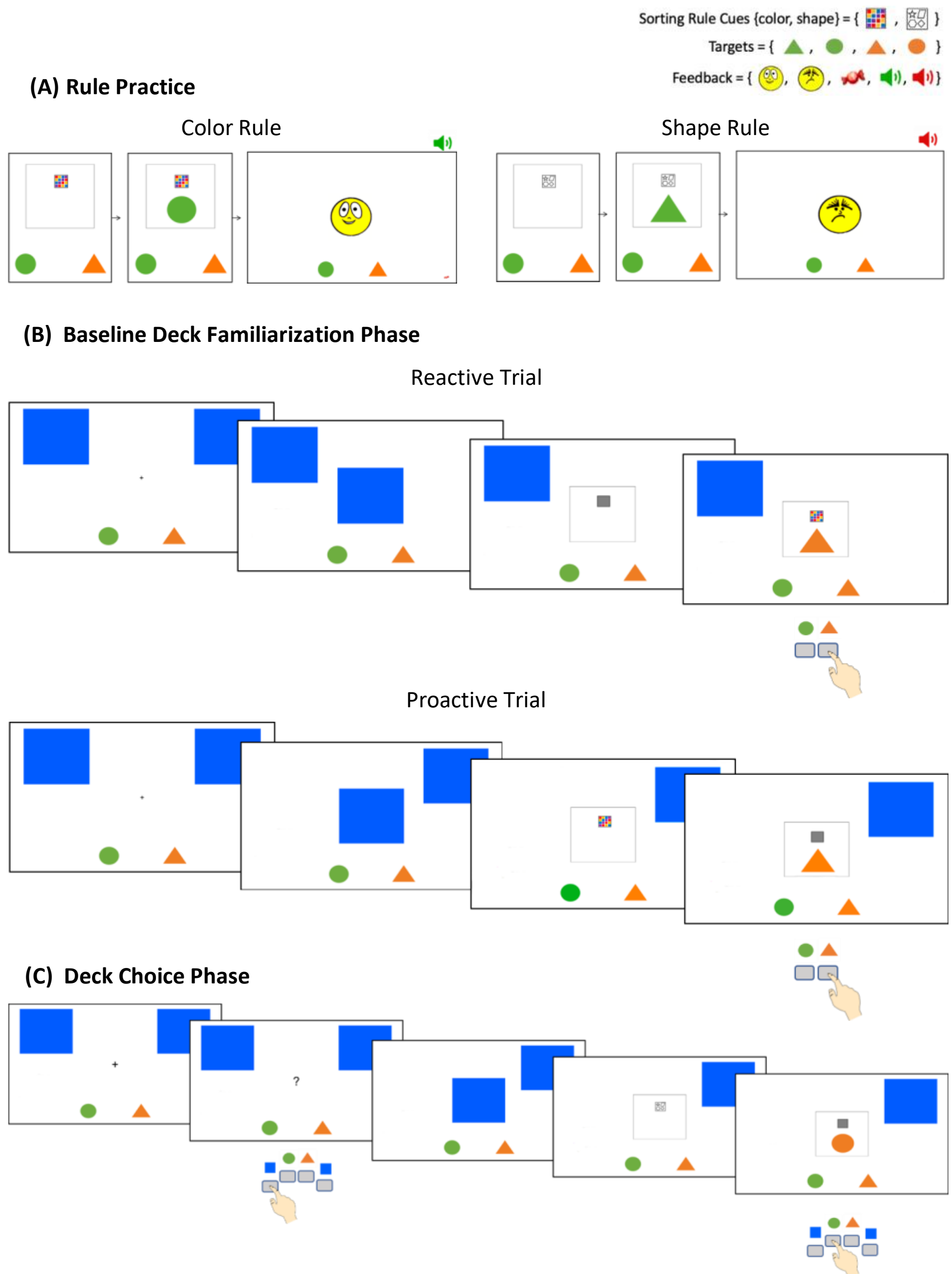


Figure 1: The Demand Selection Task flow. A) Rule Practice Phase: Participants practiced sorting by the shape and color sorting rules in isolation (4 trials/rule) and then together (4 trials). The rules were presented prior to the probe and remained visible for the entire trial. The final frame presents positive and negative trial feedback. Small digital candy was given or removed for correct and incorrect responses throughout the task at the bottom right of the screen. B)

Familiarization Phase (60 trials): Participants were familiarized with each of the two card decks. For the reactive trial deck, the right deck moved to the center of the screen and then flipped. A grey square occluded the sorting rule (1.5 sec), and the sorting rule and target are then presented simultaneously. For proactive trials, the rule is presented prior to the target (1.5 sec), and then removed when the target appears. C) Deck Choice Phase (50 trials): Participants selected which deck to play every trial by pressing the far left or far right button on the response pad (underneath blue squares) and then responded as before using the middle two buttons.

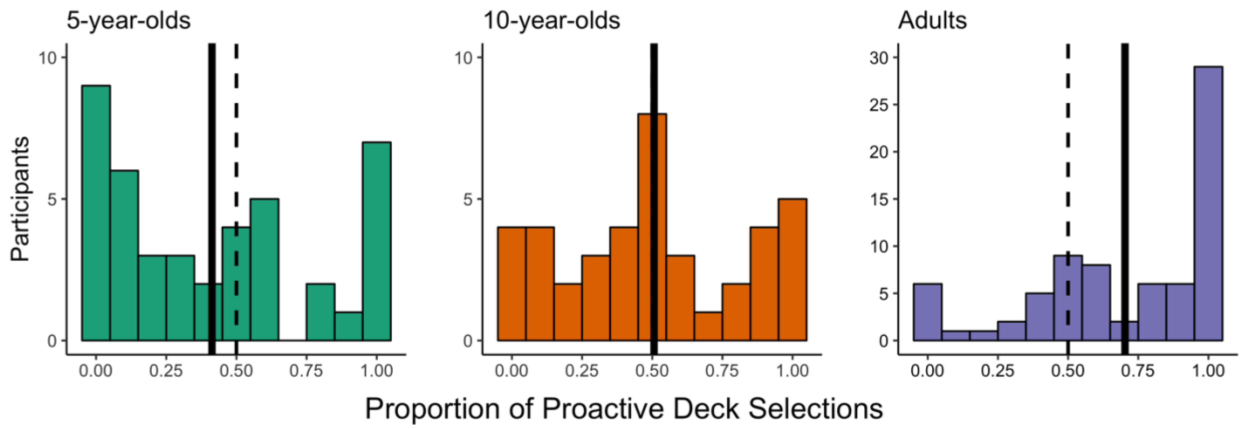


Figure 2: Histograms of the proportion of proactive deck selections across groups. The dotted black lines indicate chance selections, and the solid black lines indicate group means (5-year-olds: 41.29%; 10-year-olds: 50.65%; Adults: 70.27%). Proportions of proactive deck selections increased with age, with only adults selecting the proactive deck more than chance.

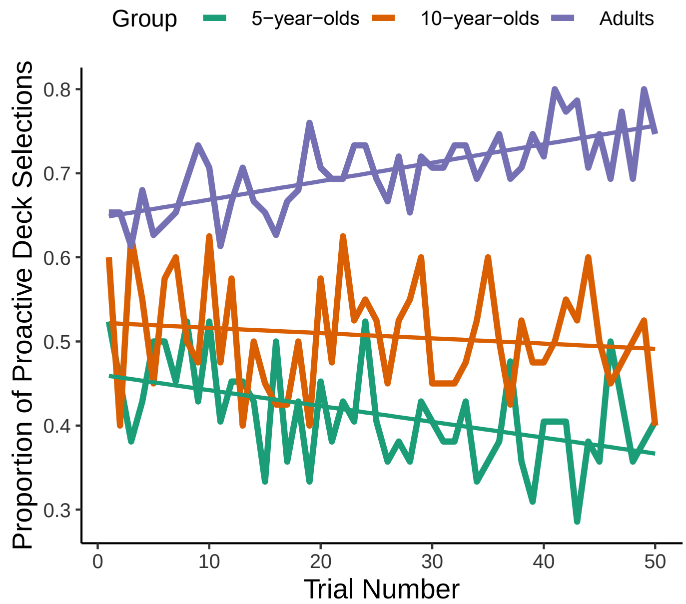


Figure 3: Trial number predicted proactive deck choices, with proactive selections decreasing across trials. Age group predicted additional variance after controlling for trial number, with older participants making more proactive deck selections. The interaction of age and trial number predicted additional variance in proactive deck choices, reflecting adults increasing their proactive deck selections across trials, 5-year-olds increasing their reactive deck selections across trials, and 10-year-olds showing no significant change across trials.

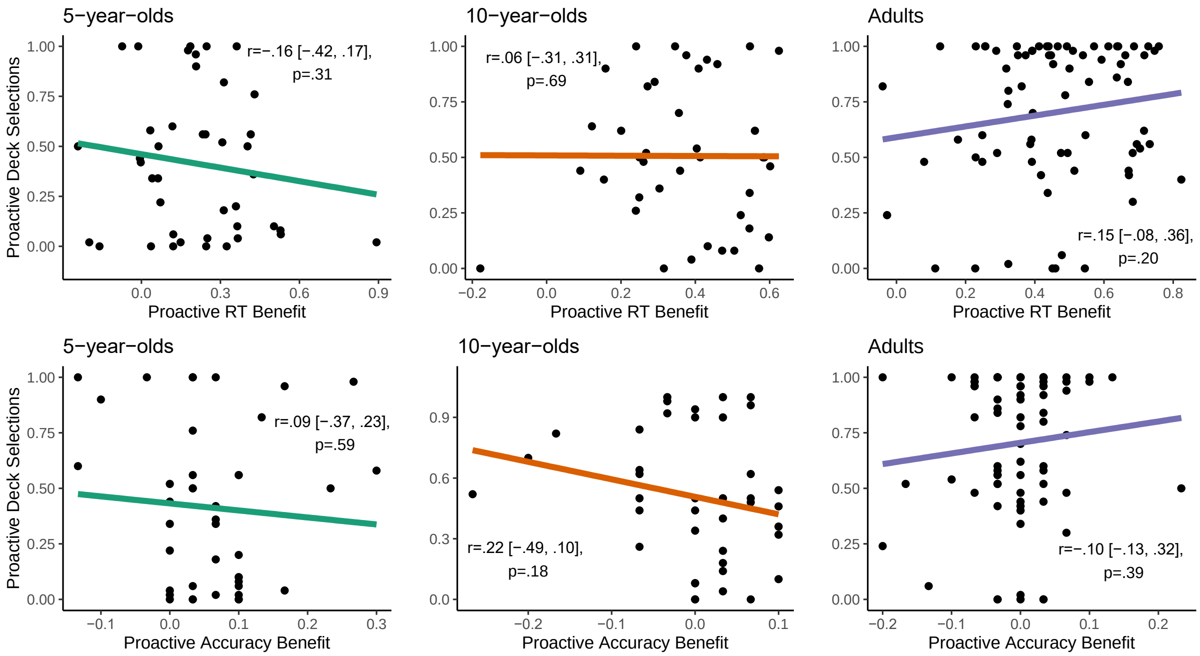


Figure 4: Across age groups, no significant relationships were observed between proactive deck selections and accuracy or response time differences between proactive and reactive decks during deck familiarization, in contrast with prior findings in the task-switching domain.

Table 1

Deck familiarization Performance Across Age Groups

	5-year-olds	10-year-olds	Adults
Overall Accuracy**	88.21% (8.05)	92.13% (5.39)	94.71% (4.56)
Overall Log Response Time**	8.04 (0.47)	7.20 (0.22)	6.78 (0.20)
Proactive Deck Accuracy**	85.16% (8.81)	92.08% (5.53)	94.98% (5.24)
Reactive Deck Accuracy*	91.27% (9.51)	92.17% (7.76)	94.44% (6.04)
Relative Accuracy Difference**	-6.11% (8.77)^	0.08% (8.08)	0.53% (6.67)
Proactive Deck Log Response Time**	7.94 (0.49)	7.02 (0.26)	6.55 (0.25)
Reactive Deck Log Response Time**	8.15 (0.47)	7.39 (0.22)	7.01 (0.19)
Relative Response Time Difference**	0.21 (0.22)^	0.37 (0.17)^	0.46 (0.19)^

Data are presented as means (SD). Response times are log-transformed from mean millisecond response times for each participant. Age groups differed in overall accuracy and response time, as well as in accuracy and response time differences between proactive and reactive decks: relative response time differences between decks increased with age, and 5-year-olds had greater accuracy differences between decks compared with the older age groups. * indicates a trend group difference (p=.067). ** indicates group differences at p<.001. ^ indicates differences from 0 at p<.001.

Table 2

Proactive Deck Preferences and Awareness of Deck and Performance Differences

	5-year-olds	10-year-olds	Adults
Proportion Reporting Deck Differences**	47.61%	82.50%^^	86.49%^^
Proportion Reporting Preference for the Proactive Deck**	36.59%	50.00%	78.67%^^
Proportion Reporting the Proactive Deck as Easier*	23.81%^	40.00%	77.03%^^
Proportion Reporting Faster Responses on the Proactive Deck*	41.46%	62.50%	73.61%^^
Proportion Reporting Better Accuracy on the Proactive Deck**	33.33%^	40.00%	69.01%^
Proportion Reporting Thinking Harder on the Proactive Deck**	58.54%	63.16%	27.03%^^

Data are presented as the proportion responses within group to binary post-task questions. * indicates group differences at p<.01, ** p<.001. ^ indicates significant differences from chance at p<.05 and ^^ at p<.001.

Supplementary Materials

Self-reported explanations for deck preference and easy deck selections

Three research assistants blinded to study hypotheses and age group coded open-ended responses to the post-task questionnaire using categories generated post hoc by the authors after consulting a subset of explanations that spanned groups. Research assistants first coded five random participants from each age group, blinded to group membership, and were given the opportunity to ask questions to the authors. Then, research assistants coded the remaining participants. The categories were as follows: Temporal rule presentation; Performance-related/task-specific (NOT temporal); Unclassifiable/body intrinsic (i.e., right-handed, see right better, etc.)/tautology. Performance-related explanations were considered “Unclassifiable” for the easier deck explanation question, as this reasoning is tautological. Explanations were combined across the initial and forced response questions. Inter-rater reliability statistics were calculated in R using the “irr” package (Gamer, Fellow, Lemon, & Singh, 2012). Almost perfect agreement was observed between coders in explanations for deck differences (Fleiss’s Kappa: .87), and moderate to low agreement was observed in the remaining five questions (range: .39 - .58) (Landis & Koch, 1977). For response analyses, instances of disagreement between reviewers were resolved with majority opinion; in cases of no majority opinion, classification was decided by the first author (~2% of all responses).

Age groups significantly differed on the free responses for all questions except for the question concerning deck easiness. Complete results are presented in Supplementary Table 1. A general pattern across all questions was observed, in which adults reported the temporal rule presentation difference between decks as the reason for the responses than 10-year-olds, who were in turn more likely to report temporal rule presentation as the reasoning behind their responses that 5-year-olds. Five-year-olds responses were generally more likely to be coded as "Unclassifiable" compared with the older age groups.

Exploratory exclusion of outliers in the 10-year-old group

We observed three outliers in relative deck performance in the 10yo group, one participant on relative response time (3.17 SDs from group mean) and three participants on relative accuracy (all >2.04 SDs from group mean). Exclusion of the accuracy difference outliers resulted in a small but significant accuracy benefit for the reactive deck, approximately 1 fewer trial correct on the proactive deck relative to the reactive deck during familiarization (M=1.8%, $t_{(36)}$=2.04, p=.048). However, post hoc exclusion of these participants only minimally changed quantitative results for all subsequent analyses and did not qualitatively change any test other test result; thus, these participants are included in all reported analyses. With removal of all 4 outliers, the proportion of proactive deck selections in 10yo was 49.24 (from 50.06). We also followed-up our predicted relationship between accuracy differences and proactive deck selections after removing accuracy difference outlier removals and found no significant relationship and only minimal qualitative change (from r=-.21 to r=-.18, p=.28).

Age did not predict proactive deck selections in 5-year-olds

In an additional exploratory analysis, we regressed age in the 5yo group on the proportion of proactive deck selections, as 5 to 6 years has been proposed as a transitional age in the transition from primarily engaging control reactively to engaging control proactively (Agnes & Blaye, 2014. A non-significant correlation in the predicted direction was observed (r=.17 [-.14, .45], t=1.08, p=.29).

Does Accurate Task Monitoring Depend on Clear Performance Signals?

One might argue that 5yo had more ambiguous demand signals to guide task selection, as they had faster speed but worse accuracy on the proactive deck and had the smallest speed benefit. In contrast, 10yo had a clearer demand signal, with larger speed benefits on the proactive deck and minimal accuracy costs, and adults exhibited the biggest speed benefit with no accuracy costs. To explore this possibility, we investigated the subset of 5yo without accuracy costs; these participants had a small speed benefit on the proactive deck but did still not reliably report deck differences (N=11; 36% report deck differences). Moreover, adults and 10yo with small speed benefits similar to these 5yo and no accuracy costs still reported differences between decks (adults: N=19; 94.74% report deck differences; 10yo: N=16, 81.25% report deck differences). In addition, when speed and accuracy demand signals were consistent and similar across age groups in a task-switching context, 6-year-olds were unaware of demand differences between task options, whereas 11-year-olds and adults reported awareness and adapted task selection towards the easier task (Niebaum et al., 2019). Young children have also been shown to be worse at reporting which tasks they performed better on in other domains compared with older children and adults (O'Leary & Sloutsky, 2017, 2019). Together, these findings suggest that young children are less aware of cognitive task demands to guide task selection.

Supplementary Table 1

	Unclassifiable/ body intrinsic	Performance-related/Task-specific	Temporal Rule Presentation	Chi-square	p-value
Were there any differences between the decks?				34.93	<.001
5-year-olds	28	6	8		
10-year-olds	7	7	26		
Adults	15	10	50		
Did you prefer one deck more than the other?				10.81	0.027
5-year-olds	21	9	11		
10-year-olds	16	6	18		
Adults	18	18	39		
Was one deck easier than the other?				5.21	0.269
5-year-olds	18	8	16		
10-year-olds	15	4	21		
Adults	20	12	42		
Were you faster on one deck than the other?				15.06	0.005
5-year-olds	25	12	4		
10-year-olds	15	9	16		
Adults	22	22	28		
Did you get more right on one deck than the other?				12.27	0.014
5-year-olds	23	16	3		
10-year-olds	18	12	10		
Adults	21	28	23		
Did one deck make you think harder than the other?				24.27	<.001
5-year-olds	18	15	8		
10-year-olds	6	7	25		
Adults	13	15	47		

Chapter 4

Using the Voluntary Task Switching Paradigm to Infer Adaptive Avoidance of Cognitive Control Demands Across Development

Abstract

Adults and older children are sensitive to the costs of mental effort and typically avoid exerting unnecessary effort, whereas young children are less sensitive to mental effort costs. However, such mental effort avoidance, particularly in children, has been assessed across a narrow range of paradigms, limiting the generalizability of claims. We thus analyzed mental effort avoidance in a novel way, via voluntary task switching paradigms, in which participants choose when and how often to switch between tasks across trials. Switching tasks often requires mental effort, even when people decide for themselves when to switch. In three independent studies with children and adults, performance improved throughout the task, consistent with practice effects and inconsistent with fatigue. In Study 1, switching frequency decreased in adults throughout the task, particularly when adults had less preparation time to select tasks. In Study 2, switching frequency decreased throughout the task in children aged 7 to 12 years, and children increasingly repeated the easier task option. In Study 3, switch frequency did not vary with trials; however, adults and older children but not younger children switched less overall after experiencing short preparation times. Overall, these results suggest that adults and older children increasingly avoid the mental effort of switching tasks across voluntary switch tasks, highlighting the generalizability of claims about the development of mental effort avoidance. Performance and behavior also systematically varied throughout the voluntary task switching paradigm with age and prior task experience, suggesting a potential source of meaningful individual differences.

Introduction

Exerting cognitive control, the mental processes that support flexible and goal-directed behavior, is effortful and costly (Shenhav et al., 2017; Kurzban et al., 2013). Adults report that tasks requiring cognitive control feel effortful (Inzlicht et al., 2015; Milyavskaya et al., 2019). Adults also typically avoid tasks that require more cognitive control in favor of easier control tasks and require greater incentives to complete more challenging cognitive control tasks (Desender et al., 2017; Dixon & Christoff, 2012; Dunn, Lutes, & Risko, 2016; Kool & Botvinick, 2014; Kool et al., 2010; Patzelt et al., 2019; Westbrook, Kester, & Braver, 2013).

Recent evidence has suggested a developmental transition in the sensitivity to and avoidance of mental effort (Niebaum & Munakata, 2020). Evidence for mental effort avoidance in children has mostly come from demand selection tasks, in which participants typically are familiarized with two task options before being instructed to choose for themselves which option to perform over series of trials (Ganesan & Steinbeis, 2021; Niebaum et al., 2019; 2021; O'Leary & Sloutsky, 2017; 2019). Such tasks have typically found that children younger than 7 years select tasks at chance but that children older than 7 years monitor the relative demands of tasks, reporting harder tasks as more difficult, and preferentially selecting easier tasks. For example, like adults, 11-year-old children reported a more difficult switching task as more effortful and less preferred and selected to play an easier switching task more often. In contrast, 6-year-old children chose the harder and easier switching tasks at chance levels and reported no systematic preferences for either task (Niebaum et al., 2019). Better sensitivity to cognitive task can help children more efficiently and economically allocate their mental effort. Further, as children grow up and become increasingly independent in deciding for themselves which tasks to take or avoid, understanding when and how an emerging sensitivity to cognitive task demands influences children's decisions is especially important.

However, preferences on demand selection task paradigms could be driven by factors outside of effort avoidance. Children may take longer to learn the relative mental effort demands of each option than adults but still prefer to avoid mental effort. Some studies finding no evidence for mental effort avoidance in 5- and 7-year-olds had substantially fewer choice trials than adult studies and less familiarization with either task prior to making choices, potentially restricting detection of effort avoidance (O'Leary & Sloutsky, 2017, 2019). Even adults have struggled to monitor relative differences in cognitive demands in some demand selection tasks (e.g., Gold et al., 2013; Desender et al., 2017). Demand selection tasks also pose meta-control costs; some participants could decide to always select the same task to reduce decision costs, which could incidentally look like mental effort seeking, even though participants are avoiding costs associated with decision-making. Thus, additional evidence using different paradigms is needed to better understand mental effort avoidance across development and how effort avoidance may influence participant behavior and performance in other paradigms.

The voluntary task switching (VTS) paradigm can address some of these concerns (for review, see Arrington, Reiman, & Weaver, 2014). In the VTS, participants are introduced to two different tasks and can decide when and how often to switch between each task. Commonly, participants are instructed to choose tasks randomly but equally often. Like other task switching paradigms, performance is typically worse on switch trials than repeat trials, as indexed via slower response times and worse accuracy (Monsell, 2003). Thus, the VTS also instantiates cognitive control costs, just like demand selection tasks used in children (Kool et al., 2010; Niebaum et al., 2019).

Given the task instructions, one may expect the overall frequency of task switching to be near 50%; however, a small bias to repeat tasks is often observed in adults, which has been interpreted as avoidance of mental effort (Arrington & Logan, 2005; Mittelstadt et al., 2018a; Mittelstadt et al., 2018b; Yeung, 2010). Increasing the ratio of cued switch trials to voluntary switch choice trials leads to more frequent voluntary task switching, potentially by decreasing decision costs for participants (Frober & Dreisbach, 2017). When task instructions do not strongly emphasize random task selection, stronger task repetition biases are observed (Arrington et al., 2014; Liefooghe, Demanet, & Vandierendonck, 2009), further suggesting that adults prefer to avoid the effort of task switching in VTS paradigms.

Adult behavior also changes across the VTS task (Orr & Imburgio, 2021), in ways that suggest increasing avoidance of mental effort. Across three different versions of the VTS task, accuracy increased or remained stable, and response times decreased, demonstrating improved task performance with practice (Karayanidis et al., 2003; Rogers & Monsell, 1995). Participants remained slower and somewhat less accurate after task switches than repeats, indicating that the cognitive control costs of switching tasks persisted. In two of the three paradigms, adults were increasingly likely to repeat tasks as the VTS progressed; in the third paradigm, cued task switch trials were intermixed with voluntary task switching trials and fewer voluntary trials were included within the paradigm, complicating analyses of change across the paradigm (Orr & Imburgio, 2021). Overall, the pattern of results suggests that adults maintained high performance and continued to be engaged with the task but increasingly avoided the mental effort required to switch tasks. These results are consistent with adults' preferences to avoid task switching demands (Sayalı & Badre, 2019; Kool et al., 2010; Niebaum et al., 2019; Patzelt et al., 2019). They also demonstrate that analyzing changes in switch rates across different VTS paradigms can provide valuable information about preferences to avoid mental effort, in addition to the more typical analyses involving participant or group averages (Arrington & Logan, 2004; Braem & Egner, 2017; Frober & Dreisbach, 2017; Mittlestadt et al., 2018).

The VTS has recently been administered in children (e.g., de Bruin, Samuel, & Dunabreitia, 2020; Frick, Brandimonte, & Chevalier, 2019), providing an opportunity to assess whether children's performance and avoidance of mental effort change across the VTS. Like adults, children were also slower to respond and less accurate on average after voluntary task switches than task repetitions and exhibited an overall repetition bias (de Bruin, Samuel, & Dunabreitia, 2020; Frick, Brandimonte, & Chevalier, 2019), suggesting avoidance of mental effort. However, children's changes in behavior across VTS paradigms has not yet been assessed and could provide insight into whether children increasingly avoid mental effort like adults or exhibit different patterns. For example, children could initially show a repetition bias but eventually begin switching equally often and randomly after extensive practice with selecting tasks. Alternatively, children could start with a repetition bias but begin switching tasks more often due to boredom. In adults, boredom increases exploration and task switching (Geana et al., 2016; Wolff & Martarelli, 2020), and children are more exploratory than adults, even when task characteristics are stable and well known (Blanco & Sloutsky, 2021; Sumner et al., 2019). Or, children could increasingly repeat tasks across the VTS, suggesting that children prefer to avoid the mental effort associated with switching tasks like adults. Given these possibilities, changes in children's behavior across VTS paradigms must be assessed to determine whether the overall repetition bias observed reflects improvements with practice, changes due to boredom, or increased demand avoidance.

The current study analyzes three datasets involving different VTS paradigms in three samples to test whether decisions to switch or repeat tasks change across VTS paradigms in adults and children. First, we analyze a publicly available dataset of adults completing the VTS to independently replicate prior results (Mittelstadt et al., 2018a; Orr & Imburgio, 2021). This study varied task presentation times across participants and varied the order of the standard VTS task with another manipulated version, enabling analyses of adult changes due to presentation times and overall task experience.

Second, we analyzed a publicly available dataset of bilingual 7- to 9- and 11-to 12-year-olds completing a VTS in which task switches required switching response languages (de Bruin, Samuel, & Duñabeitia, 2020). This dataset was used to analyze changes in switching frequency across the VTS in childhood. Further, because the tasks differed in difficulty, we were able to assess whether task selection preferences changed over time according to task difficulty and explore potential differences with age. Instructions for switching tasks were less explicit than in typical paradigm, enabling a more naturalistic assessment of changes in task switch frequency in children.

Lastly, we analyzed a dataset of 5-6-year-olds, 9-10-year-olds, and adults completing a VTS (Frick, Brandimonte, & Chevalier, 2019). In this VTS, the interval between choice trials was manipulated to examine the influence of longer and shorter preparation times on task selection. We used this dataset to replicate findings in older children in Study 2, test for distinct patterns in younger children, and assess whether manipulating decision preparation time influences behavior across the task. Further, task order was counterbalanced across participants, enabling assessments of differential performance changes over time based on specific task parameters. Overall, we predicted that children at all ages would show improvements in task performance with time, as indexed via decreased reaction time and improved accuracy, but still exhibit persistent switching costs. Further, we predicted that adults and children older than 7 years would exhibit decreased task switching frequency with increased time on task, consistent with mental effort avoidance in older childhood, but that children younger than 7 years would not decrease task switching frequency with increased time on task, consistent with young children showing limited sensitivity to mental effort costs.

Study 1

In Study 1, we analyzed a publicly available dataset originally examined in Mittelstädt et al. (2018). In this study, the timing of stimulus presentation and availability of stimuli were manipulated to examine the influence of these factors on decisions to switch or repeat tasks. These data were used to independently replicate prior findings in adults showing decreased trial switch frequency, stable or increased accuracy, and decreased response times across the task, consistent with increased avoidance of the mental effort associated with switching tasks with simultaneous performance benefits for practice on the tasks. Because some participants performed the standard VTS task prior to experimental manipulations of stimuli presentation but others performed the standard VTS task after experimental manipulations, we were able to examine macro-level changes in performance and task selection frequency over time. We subset this dataset to include only the baseline voluntary task switching task and excluded all data from the tasks containing experimental manipulations.

Method

Participants were native German-speaking adults (N=72, M_{age}=21.90 years) tested individually at the University of Freiberg, Germany, for small monetary compensation or course credit. Preprocessing steps were consistent with the original analyses, except that the first block of 72 voluntary switch trials were included here. For all analyses, the initial trial of each block was removed. For analyses of task switching frequency and response times, error trials, trials following errors, and response times exceeding 3 SD from participant task means were excluded, as in Mittelstädt et al. (2018) and Orr and Imburgio (2021).

Paradigm

Participants completed a double-registration VTS in which participants first selected whether to complete an addition or subtraction task (add or subtract two numbers) and then completed the selected task. For the addition and subtraction tasks, only solutions greater than 0 and less than 10 were used so that a single key could be used for responses. Task position on screen (top of screen or bottom of screen) was consistent within but counterbalanced across participants. Participants selected tasks via key press (“A” or “Y” for the top and bottom task, respectively) and responded to stimuli using the numeric keypad section of the keyboard.

Participants completed seven consecutive blocks of 72 trials each (504 total trials). Stimulus order was randomized. Participants were instructed to select each task equally often without applying any strategy and told to imagine a coin flip to determine each task choice to emphasize random task switching. For 24 participants, a blank screen was presented between trials for 500 ms (long task preparation time). For 48 participants, a blank screen was presented between trials for 100 ms (short task preparation time). This difference between groups was intended to maintain consistency in task preparation time with subsequent experimental manipulations in stimulus availability. Because increasing task preparation time can reduce overall switch costs and decrease repetition rates (e.g., Arrington & Logan, 2005; Butler, Arrington, & Weywadt, 2011; Butler & Weywadt, 2013; Liefooghe, Demanet, & Vandierendonck, 2009; Yeung, 2010), we include task preparation time as a covariate interacting with all other predictor variables in all trial-level analyses.

Participants took self-paced breaks between blocks, at which they received feedback about block duration and performance errors, as well as reminders to continue selecting tasks at random in the upcoming blocks.

Analyses

All analyses were conducted in R Studio, version 1.2.5042 (R Core Team, 2020). Response times were log-transformed prior to analysis to reduce skew (Mieran, 2003). For this dataset, task decision time was also recorded, providing an opportunity to assess whether task selection decision times also change across the VTS. Task decision time was also log transformed prior to analyses. To test for changes in behavior over time, we conducted multilevel models with trial number as the key predictor variable and with random intercepts and slopes for participants. To improve model convergence, trial number was centered and scaled. Thus, main effects of trial number indicate significant differences in the middle of the task. For all analyses, trial preparation time was included as a contrast-coded covariate (-.5 = short preparation time (100 ms); .5 = long preparation time (500 ms)). All multilevel models were conducted with the lmer4 package (Bates et al., 2007). First, we predicted the outcome variable with task choice (0 = repeat; 1 = switch), trial number, and their interaction. A significant interaction between trial type and trial number would indicate a change in switch costs over time. A second model was conducted if the interaction term was non-significant to assess main effects of trial number and trial type. We then conducted a logistic multilevel model predicting task choice with trial number. Given the differential pattern of results across trials for task preparation times, we conducted exploratory analyses including counterbalancing order (standard VTS first or experimental manipulation first) to determine whether participants' performance and task selections differed after performing other manipulated VTS conditions specific to the original paper's aims. Figures were created with the sjPlots (Lüdecke, 2018), ggpubr (Kassambara & Kassambara, 2018), and ggplot2 packages (Wickham, 2016).

To preview the series of analyses, we first predicted changes in response time, accuracy, and task decision time changes across trials, as well as task switch frequency. Then, we examined whether task counterbalance order influenced changes in performance and task switching across trials and overall.

Results

Response Time Decreased Across Trials

A significant interaction between trial number and task choice predicting log response time was observed ($B=-0.007$, $t=-2.799$, $p=.005$). No other significant interactions were observed (all $p>.109$). Significant main effects of trial number ($B=-.008$, $t=-2.522$, $p=.013$), task preparation time ($B=-0.021$, $t=-4.280$, $p<.001$), and task choice ($B=0.007$, $t=2.508$, $p=.012$) were observed (Figure 1A). These results indicate that participants responded faster across that task and responded faster in the long preparation condition than short preparation condition. Surprisingly, response time switch costs decreased across trials. Otherwise, these effects generally replicate prior findings in adults (Orr & Imburgio, 2021) and demonstrate that response times decreased across the task, consistent with practice effects.

Accuracy Remained Stable Across Trials

No interaction between trial number and task choice in predicting accuracy was observed (p=.560), indicating that accuracy switch costs did not significantly change throughout the task. No other interactions were observed (all p>.45). A second model removing the interaction terms found no significant main effects of task preparation time (B=-0.040, z=-0.282, p=.596), trial type (B=-0.026, z=-0.429, p=.661), or trial number (B=0.014, z=0.427, p=.669), indicating that accuracy remained stable across the task (Figure 2).

Task Decision Time Decreased Across Trials

No significant interaction was observed between trial number and task choice predicting task decision response time (p=.493), suggesting that decision time costs for switching tasks were consistent across trials within conditions. However, significant interactions between trial number and preparation time (B=0.146, t=3.431, p=.001) and task choice and preparation time (B=-0.220, t=-10.166, p<.001) were observed. Further, significant main effects of trial number (B=-0.204, t=-9.596, p<.001), task choice (B=0.048, t=4.389, p<.001), and preparation time (B=.481, t=3.974, p<.001) were observed (Figure 1B). These findings demonstrate that participants selected tasks more quickly as the task progressed, that task selection time quickened more in the short than long preparation condition, and that the cost of deciding to switch tasks was higher in the short than long preparation condition. Interestingly, participants in the long preparation condition experienced a reverse decision switch cost, in which they took longer to decide to repeat tasks than switch tasks.

Task Switching Frequency Decreased Across Trials

No interaction between trial number and task preparation time predicting the probability of switching tasks was observed ($p=.162$). After removing the interaction term, the probability of switching tasks significantly decreased with trial number ($B=-0.071$, $z=-2.705$, $p=.007$) (Figure 2). No main effect of preparation time was observed ($B=0.232$, $z=1.449$, $p=.147$).

Prior Task Experience Influences Changes in Response Time

Because half of this sample completed a separate 504-trial VTS paradigm with experimental manipulations of stimulus availability before completing the standard VTS paradigm, we next sought to explore whether prior task experience influenced performance changes within the VTS paradigm. Although we do not further subdivide analyses by specific experimental condition, these participants had all completed a substantial number of voluntary task switching trials prior to completing the analyzed paradigm. Given the lack of change in accuracy over time observed above, we focus our analyses on changes in response time, task decision time, and switch frequency. First, we test for differential changes in response time and task decision time. Continued decreases in response time and task decision time across trials for individuals who have already completed a separate VTS would indicate continued task engagement and improvements with practice. However, increases in response time and task decision time in this subset of participants would indicate task disengagement over time. Similarly, continued decreases in switch rates continue to decrease across trials within the subset of participants who have already completed a separate VTS would indicate further demand avoidance over time. However, increases in switch rates could suggest increased or better capacity to switch randomly and equally often over time. Given the potential differences in performance across trials between task preparation time conditions, we analyzed the long preparation time condition (N=24) and short preparation time condition (N=48) separately here. We replicated the above analyses including a contrast-code for task order (Experimental VTS First = .5; Standard VTS First = -.5) and an interaction with trial number. We visualize results using local regression to enable visual inspection stability of parameters across time beyond linear models. We focus analyses on response times and switch frequency because these parameters changed across trials.

In the long preparation time condition, log response time decreased with trial number ($B=-0.022$, $t=-3.705$, $p=.001$), and a trial number by task order interaction was observed ($B=0.018$, $t=2.085$, $p=.049$), suggesting that participants response times decreased across trials sooner when performing the standard VTS first (Figure 3A). No main effect of counterbalance order was observed ($p=.228$). In the short preparation time condition, log response time decreased with trials ($B=-0.017$, $t=-3.273$, $p=.002$), and a marginal trial number by task order interaction was observed ($B=0.015$, $t=2.003$, $p=.051$), suggesting that participants response times decreased across trials sooner when performing the standard VTS first (Figure 3B). No main effect of counterbalance order was observed ($p=.172$).

Prior Task Experience Influences Changes in Task Decision Time

In the long preparation time condition, log task decision time decreased with trial number ($B=-0.179$, $t=-6.694$, $p<.001$), and a trial number by task order interaction was observed

(B=0.080, t=2.113, p=.046), suggesting that participants task decision times decreased across trials faster when performing the standard VTS first (Figure 4A). No main effect of counterbalance order was observed (p=.752). In the short preparation time condition, log response time decreased with trials (B=-0.364, t=-10.430, p<.001), and a significant trial number by task order interaction was observed (B=0.176, t=3.521, p<.001), suggesting that participants response times decreased across trials faster when performing the standard VTS first (Figure 4B). A marginal main effect of counterbalance order was observed (B=-0.297, t=-1.982, p=.0536).

Prior Task Experience Influences Task Switching Frequency

In the long preparation condition, the probability of switching tasks did not decrease with trial number (B=-0.006, z=-0.142, p=.887) or significantly differ with counterbalance order (B=-0.279, z=-1.465, p=.143), and no order by trial number interaction was observed (B=-0.032, z=-0.562, p=.574), suggesting that prior task experience did not influence the probability of task switching (Figure 5A). The analysis also suggests that task switching frequency did not decrease overall when task decision time was long. In the short preparation condition, the probability of switching tasks marginally decreased with trial number (B=-0.094, z=-1.833, p=.067), and a significant main effect of task order was observed (B=-0.405, z=-1.974, p=.048) (Figure 5B). No significant interaction was observed (B=-0.010, z=-0.133, p=.896). These results suggest that participants switched less frequently when preparation time was short if they performed the experimental VTS first. Overall, however, these results are suggestive of macro-level changes in task switching frequency based on prior task experience.

To further examine changes in task switching frequency based on counterbalance order, we averaged participants switch frequency, and conducted linear models predicting mean task switching frequency with counterbalance order and preparation time condition. A significant main effect of counterbalance order ($B=0.07$, $t=2.285$, $p=.026$) and marginal main effect of preparation time were observed ($B=-0.063$, $t=-1.868$, $p=.067$). These results are consistent with increased avoidance of task switching across time, as participants were less likely to switch overall if they had previously performed an experimentally manipulated VTS paradigm.

Discussion

In Study 1, we analyzed an adult dataset to independently replicate prior changes in performance and task switching frequency across a VTS task. Response times decreased, and accuracy remained high and stable, suggesting that participants improved with practice and remained engaged throughout the task. Task switching frequency decreased across trials, suggesting increased avoidance of mental effort over time. The decrease in switch frequency was notably smaller in this sample than in prior analyses (e.g., Orr & Imburgio, 2021), and exploratory analyses indicated that the decrease was more driven by participants with less time to prepare for task selection. Notably, response time costs for task switching were considerably smaller in this VTS paradigm compared with paradigms incorporating typical cognitive control tasks, such as Stroop stimuli (e.g., Braem, 2017; Orr & Imburgio, 2021). Participants took consistently longer to repeat tasks when given more time to select tasks. Thus, the desire to avoid switch costs over time may be attenuated in this version, especially when provided more time to prepare for task selection.

Participants also switched tasks less frequently overall if they had already performed a manipulated VTS task first, providing further support for that task switching in the VTS is effortful and aversive over time. Participants with prior task experience responded more quickly and maintained high accuracy; thus, it is unlikely that decreased switch rates are due to task disengagement or fatigue.

These results also demonstrate that performance and task decision changes across the VTS in adults in ways that are consistent with practice effects and mental effort avoidance. Because behavioral changes across trials differed according to task preparation time and prior task experience, participants may be improving or learning to perform the task at different rates based on distinct task characteristics.

Study 2

In Study 2, we analyzed a publicly available dataset originally examined in de Bruin, Samuel, and Duñabeitia (2020) that included two studies using both cued and voluntary task switching paradigm: one study in older and younger adults and one in older children. The original study was designed to examine differences in bilingual task switching across the lifespan. Data were obtained from the project's Open Science Framework (osf.io/qmxk5/). Trial exclusion criteria matched the original analysis; response times from incorrect trials and response times greater or less than 2.5 SD of the participant mean were excluded.

All participants completed the cued task-switching picture-naming task in one session and the voluntary picture-naming task in a separate session. All sessions also included rule familiarization and blocked rule practice. Session order was counterbalanced across participants but not available in the current data.

We analyzed only the child data from the voluntary task switching paradigm for two reasons. First, the two task options differed in difficulty for the child groups but were equally difficult for both adult groups due to age cohort effects of bilingualism within Spain, indicating that task dynamics differed across age. Second, we sought to specifically test developmental patterns of behavioral change within the VTS in childhood.

Method

Participants were 7-9-year-olds (N=20, M_{age}=8.15) and 11-12-year-olds (N=27, M_{age}=11.89), resulting in a total sample size of 47 children (M_{age}=10.30, SD=1.93). Age was coded in years. We combined child groups for our analyses due to the low sample sizes in each group and then included age a predictor in all models. All participants had at least intermediary proficiency at both Spanish and Basque, and participants attended a trilingual school with 60% of classes taught in Basque, 20% in Spanish, and 20% in English (de Bruin et al., 2020) but primarily spoke Spanish at home. Included participants scored at least 40 on a 65-item Basque picture-naming task. Both child groups scored significantly higher on Spanish (7-9yo: M=64.7, SD=0.7; 11-12yo: M=64.7, SD=0.5) than Basque (7-9yo: M=52.7, SD=8.1; 11-12yo: M=52.5, SD=5.6) on the picture-naming task.

Paradigm

Participants completed single-registration VTS paradigm, in which participants were instructed to name pictures aloud in either Spanish or Basque. Thirty picture stimuli matched on word length and frequency were used. The task consisted of 360 voluntary selection trials comprising 6 trial blocks. Participants were instructed in both Spanish and Basque as follows: “In the following part, you can name the pictures in Spanish or Basque. You are free to switch between languages whenever you want. Try to use the word that comes to mind first, but don't use the same language throughout the whole task” (de Bruin et al., 2020). Thus, participants were not explicitly instructed to choose tasks equally often and randomly.

Trials began with a 500 ms fixation cross, followed by stimuli presentation for 2500 ms. Responses were voice-recorded, and stimuli remained on screen for 2500 ms, regardless of participant responses. Thus, participants could not finish the task more quickly by preferentially choosing the task with faster response times. Prior to performing voluntary task switching blocks, participants completed 4 practice trials in each language condition and 8 mixed language trials.

Analyses

The available dataset included 90.34% of all possible trials for analyses. Trials were only included if a vocal response prior to the response deadline (2500 ms) was recorded; without a vocal response, classification as a trial switch or trial repeat was not possible. Further, for all analyses, the initial trial of each block was removed. For analyses of voluntary task switching frequency and responses times, trials response time 2.5 standard deviations from the participant mean were removed, as in de Bruin et al. (2020). To improve model convergence, trial number was centered and scale for all analyses. Further, error trials and trials following errors also removed for analysis of task switching frequency and response time. Because children have shown a response time benefit for picture naming in Basque over Spanish during cued task switching (de Bruin et al., 2018), we first tested for differences between language type during the VTS to determine if the Basque naming task was significantly easier than the Spanish naming task. For analyses with language, Basque was coded as -0.5, and Spanish was coded as 0.5. Trial type was dummy coded (switch: 1; repeat: 0). We then reproduce the primary analyses as conducted in Study 1.

Results

Response Time Advantage for the Basque Task

To test for changes in response time over trials according to language selected (Basque or Spanish), log response time was predicted with trial number, language, age, and all interactions. No significant interactions between any predictor and trial number were observed. Thus, we removed all interactions terms and predicted log response time with trial number, language, and participant age. Significant mains effects of language ($B=.006$, $t=13.698$, $p<.001$) and age ($B=-.004$, $t=-3.538$, $p<.001$) but not trial number ($B=-0.007$, $t=-1.409$, $p=.166$) were observed (Figure 7A), indicating that older children responded faster than younger children and that responses in Basque were faster than responses in Spanish.

Response Time Decreased Across Trials

To test for changes in response time over trials, we predicted log response time with trial number, trial type (switch vs. repeat), age, and all interactions. No significant trial number by trial type interaction was observed ($B=0.019$; $t=0.607$, $p=.546$), suggesting that response time switch costs remained consistent across the task. Further, no significant three-way interaction with age was observed ($B=-0.002$, $t=-0.856$, $p=.392$), suggesting that switch costs were consistent across ages across the VTS. Thus, we removed all interaction terms and predicted log RT with trial number, age, trial type. Significant main effects of trial type ($B=0.074$, $t=14.747$, $p<.001$) and age ($B=-.041$, $t=-3.748$, $p<.001$) were observed but no main effect of trial number ($B=-0.007$, $t=-1.445$, $p=.156$) (Figure 7B), indicating that participants responded more quickly with age and on repeat than switch trials but that response time remained relatively stable.

Accuracy Remains Stable Across Trials

No interaction between trial type and trial number predicting accuracy was observed (B=0.056, z=0.380, p=.704), suggesting no change in accuracy switch costs across the task. We removed the interaction term and found a significant main effect of trial type (B=-0.398, z=-2.67, p=.008) but not trial number (B= -0.023, z=-0.316, p=0.752) (Figure 2C), indicating that participants were less accurate on switch trials than repeat trials but that accuracy remained stable across the task. Accuracy was near ceiling throughout task. These results are consistent with task engagement across the task.

Switch Frequency

Trial number predicted trial type (B=-0.095, z=-3.969, p<.001), indicating that participants increasingly chose to repeat tasks across trials (Figure 8A), consistent with increased mental effort avoidance across time in older children. We next conducted two exploratory models. First, we predicted trial type with trial number, participant age, and their interaction to determine whether the frequency of switching trials differed by age and across trials. Marginal main effects of trial number (B=-0.237, z=-1.794, p=.073) and age (B=0.043, z=1.760, p=.078) were observed but no significant age by trial number interaction (B=0.014, z=1.098, p=.272), suggesting that the tendency to avoid switching across trials did not differ by age. Second, we predicted trial type with trial number, language, and their interaction to determine whether the increases in task repetitions were driven by repeating specific tasks (i.e., Basque or Spanish). We observed significant main effects of trial number (B=-0.075, t=-

4.344, p<.001) and language (B=0.314, t=8.937, p<.001), and a significant trial number by task type interaction (B=0.152, t=4.428, p<.001) (Figure 8B). These results indicate that participants were more likely to repeat Basque trials than Spanish across the task. Given that responding in Spanish came at a response time cost, these results are consistent with participants increasingly avoiding mental effort; however, these data are not well suited for distinguishing between avoiding task switching costs, avoiding the more effortful task, or both as trials increased.

Discussion

In Study 2, we conducted the first analysis of changes in child performance and switch frequency across a VTS task. Response times and accuracy remained stable across the task, suggesting that participants remained engaged throughout the task and did not experience fatigue or practice effects.

Children increasingly repeated tasks across trials, and this decrease did not vary by participant age, suggesting that participants aged 7 to 12 years similarly decreased switch frequency across the task. The decreased frequency in switching tasks was driven by participants increasingly deciding to respond in Basque instead of Spanish. Notably, responding in Spanish took consistently longer than responding in Basque, despite children's primary language being Spanish and scoring significantly better on a Spanish than Basque picture-naming task. Thus, participants increasingly chose to avoid the more difficult task and repeat the same easier task across trials. These results are consistent with increased mental effort avoidance across time in older children.

Study 3

In Study 3, we analyzed a dataset originally examined in Frick, Brandimonte, and Chevalier (2019). This dataset was obtained via personal communication with permission from the authors for this analysis. In this study, 5-6-year-olds, 9-10-year-olds, and adults completed a single-registration VTS paradigm in which participants sorted bi-valent pictures by their shape or color. The original study was designed to assess the effects of within-participant manipulations of task preparation time on subsequent decisions to switch or repeat tasks in children and adults.

This dataset provides an opportunity to replicate the patterns observed in Study 2 using a VTS task that includes fewer trials, fewer participants within each age group, and manipulations of preparation time within participants. Given that Study 1 found that decreased task switching primarily occurred when preparation time was short, we specifically sought to examine how different preparation times and prior task experience influence patterns of voluntary task switching and repeating. Further, given that we found that prior task experience influences subsequent changes in the VTS, we also investigated changes in performance and task switching based on condition counterbalancing order. With this dataset, we can extend analyses to children younger than 7 years, who we predict will not increasingly avoid switching across the task.

Method

Adults (N=31, M=21.80 years), 9-10-year-olds (N=31, M=10.05 years), and 5-6-year-olds (N=29, M=6.11 years) completed the VTS paradigm. Child participants were recruited from local schools and received a small prize for participating. Adult participants were recruited from the

University of Edinburgh and received course credit or £5 for participating. Children were tested individually at school, and adults were tested in the lab.

Paradigm

Participants completed a child-friendly, single-registration voluntary task switching paradigm, in which bi-valent stimuli (e.g., blue or red cars or bears) were sorted according to either their color or shape. Participants were instructed that they were going to play the "Santa Claus and Mitch the Bad Elf Game." In this game, participants helped Santa Claus sort toys into two toy bags (the color and shape bags) for Christmas. Participants were instructed to put about as many toys in each bag and that they needed to pick between sorting toys into the two bags randomly, mirroring adult instructions to select tasks randomly but equally often. To reinforce instructions for randomness, participants were introduced to Mitch the Bad Elf, who would appear and steal toys if he could predict which bag the participants would select to fill or if one bag contained too many more toys than the other bag.

Each trial began with a fixation cross, and the color and shape bags were also presented on either side of the computer screen (a blue and red patch under the color bag and a car and bear under the shape bag). Task preparation time was manipulated within participants. In the long preparation condition, the fixation cross remained on screen for 1500 ms; in the short preparation condition, the fixation cross remained on screen for 100 ms. After the fixation cross disappeared, the target remained on screen until the participant responded by pressing one of four keys, two for the color bag and two for the shape bag, to sort the target. Then, a present box replaced the target for 250 ms, and the target was moved into the selected bag across 250 ms.

If a predictable strategy was detected, Mitch the Bad Elf appeared alongside a small version of the target and an open present box for 250 ms. Task switching strategies (for Task A or Task B) triggering the appearance of Mitch the Bad Elf and disappearance of a toy are as follows:

Repetitions: A, A, A, A, A, A, A

Switches: A, B, A, B, A, B, A

Repetition/Switch: A, A, B, B, A, A, B, B, A

Two repetitions/Switch: A, A, A, B, B, B, A, A, A, B, B

Three repetitions/Switch: A, A, A, A, B, B, B, B, A, A, A, A, B

For each condition (short or long preparation time), participants first completed two single-task practice blocks (shape and color) of 16 trials each. An experimenter then demonstrated voluntary task-switching trials, including demonstrating predictable switching patterns triggering the appearance of Mitch the Bad Elf. Participants then independently completed a 16-trial voluntary task switching block in which they were instructed to fill each bag equally and trick Mitch by selecting tasks randomly. Then, participants completed 2 blocks of 40 voluntary task switching trials in each respective preparation condition, with short breaks between condition. Condition order was counterbalanced across participants. Feedback (accuracy, relative distribution of toys in each bag, and number of toys stolen by Mitch) was provided after each block.

Analysis

We contrast-coded preparation condition (short: -.5; long: .5). Age group was included as a linear predictor (1: 5-6-year-olds; 2: 9-10-year-olds; 3: adults). Trial type was dummy coded (switch: 1; repeat: 0). We first replicated our prior analysis, except that age group was included as a covariate with all possible interactions. Multilevel models were conducted for each primary trial-level outcome variable, with trial number and age group as the key predictor variables and with random intercepts and slopes for participants. Trial number was centered and scaled across the entire task and within each condition for exploratory analyses.

Results

Response Time Decreased Across Trials

To assess changes in response time, we predicted log response time with trial number, trial type, and age group, as well as all interactions. We found a significant trial number by trial type interaction ($B=-0.070$, $t=-3.717$, $p<.001$), as well as a three-way interaction with age group ($B=0.020$, $t=2.371$, $p=.018$). These results suggest that response time switch costs significantly decreased across trials and that switch costs decreased across trials more for younger age groups. Further, significant main effects of age group ($B=-0.479$, $t=-13.902$, $p<.001$) and trial type ($B=0.302$, $t= 16.189$, $p<.001$) were observed, indicating that older participants responded faster than younger participants and that participants responded slower on switch trials than repeat trials. In the full model with all interactions, no main effect of trial number was observed ($B=0.023$, $t=1.009$, $p=.315$), suggesting that participants maintained similar response times across the task.

We conducted two follow-up exploratory models predicting log response time. First, we included a contrast code for preparation time condition, as well as all possible interactions. No significant two-way interactions with trial number were observed (all $p>.526$), suggesting that condition did not influence changes in response time with increasing trials. Second, we include both contrast codes for condition and counterbalance order (long-preparation-first or short-preparation-first). No significant two-way interactions with trial number were observed (all $p>.12$). A significant two-way interaction between counterbalance order and condition was observed ($B=-.338$, $t=-3.744$, $p<.001$), suggesting that participants who performed the long preparation condition first responded significantly faster with short preparation time than those who performed the short preparation condition first (Figure 9). Collectively, these results indicate that response time remained stable across the task, response time decreased with age, and switch costs were present in all groups but decreased in magnitude across trials, especially in the younger groups. These exploratory models also suggest that counterbalance order led to differences in response time. Specifically, participants responded faster with the short preparation time if they already had practice responding with long preparation time. Although significant interactions with trial number were not observed, performance may differentially change over trials based on different tasks parameters.

Accuracy Increased Across Trials

No significant two-way interactions between trial number and trial type or age were observed predicting accuracy, suggesting that accuracy switch costs remained similar across trials. When the interaction terms were removed, significant main effects of trial number ($B=0.150$, $t= 2.366$, $p=.018$) and age group ($B=0.614$, $t=4.857$, $p<.001$) were observed but not trial type ($B=-0.041$, $t=-0.497$, $p=.619$) (Figure 10). These results indicate that there were not significant accuracy switch costs across the task but that participants improved in accuracy across trials and that older age groups performed better than younger age groups. An exploratory model including counterbalance order and condition, as well as all possible interactions, did not reveal significant interactions with trial number or counterbalance order. Overall, accuracy improved with trials, consistent with practice effects.

Task Switch Frequency Does Not Change Across Trials

We first predicted the probability of switching tasks with trial number, age group, and their interaction. No main effects of trial number (B=-0.046, z=-0.580, p=.562) or age group (B= 0.036, t=0.593, p=.553) or interaction (B=0.003, z=0.084, p=0.933) were observed, suggesting that participants did not increasingly repeat tasks across trials and that switch frequency was similar across age groups. A follow-up model with the interaction term removed also showed no main effects of trial number (B=-0.001, z= 1.361, p=.174) or age group (B=0.036, z=.593, p=.553) (Figure 11).

Next, models including counterbalance order and condition predicting trial switches were included, along with all possible interactions. No significant interactions with trial number were observed (all p>.429); however, a significant counterbalance order by condition interaction was observed (B=-0.746, z=-1.979, p=.048), indicating that participants who performed the long preparation condition first switch trials significantly more often in the long preparation condition than those who performed the short condition first (Figure 12).

To further investigate potential differences due to counterbalance order, we next calculated participant's mean switch frequency within each preparation time condition. We then conducted an exploratory linear regression predicting participants average switch frequency with age group, counterbalance order, and their interaction for each condition. For the short preparation condition, a significant main effect of counterbalance order (B=-0.157, t=-2.120, p=.037), no significant main effect of age group (t=1.520, p=.132), and a marginal age group by task order interaction were observed (B=-0.061, t=-1.801, p=.075) (Figure 13; top panel). Adults and 9-10-year-olds had similar switch frequencies with short preparation time, regardless of whether they had prior experience with long preparation time trials. However, 5-6-year-olds had marginally bigger difference in switch frequency with short preparation time, switching more often when performing the trials with short preparation time first. For the long preparation condition, no significant main effects of counterbalance order (B=-0.113, t=-1.523, p=.131) or age group (B=-0.004, t=-0.177, p=.860) but a marginal interaction with age group and counterbalance order (B=0.063, t=1.850, p=.067) were observed (Figure 13; bottom panel).

Adults and 9-10-year-olds had lower switch frequencies with long preparation time if they had performed the trials with short preparation time first, whereas 5-6-year-olds had marginally higher switch frequencies with long preparation time if they performed trials with short preparation time first. Although the interaction effects are marginal, these results are partially consistent with effort avoidance in adults and 9-10-year-olds, who switched tasks less often on easier trials after performing more difficult trials first, but not 5-6-year-olds, who switched tasks more often on easier trials after performing more difficult trials first.

Discussion

In Study 3, we sought to replicate patterns of performance change and changes in task switching frequency observed in Study 2 within another VTS task performed by younger and older children and adults. Performance changed across trials consistent with practice effects and continued task engagement: response time remained consistent across the task, response time switch costs were reduced, as has been sometimes observed in cued task-switching paradigms (e.g., Koch et al., 2018), and accuracy improved across trials.

In contrast to Study 1 in adults and Study 2 in older children, switch frequency did not decrease across trials, suggesting that children and adults did not choose to avoid the mental effort associated with task switching. The relatively small number of trials (80/condition; 160 total) could have decreased statistical power to detect changes across time, especially because the task parameters changed after 80 trials, in addition to the relatively low number of participants in each age group. Feedback was also given between blocks if one toy bag contained more trials than another (>62.5%). Although the relative frequency of selecting each task can be independent of switch rate, reminders to select tasks randomly through Mitch the Bad Elf paired with this feedback could have increased frequency more than instructions in other paradigms.

Exploratory models suggested that counterbalancing the order of different preparation time conditions influenced the overall rates of task switching in each condition, and these differences also varied according to age, although these effects were marginal. Overall, adults and older children switched less often with long preparation time if they had previously performed trials with short preparation time. This pattern suggests that older children and adults avoided switching tasks after performing the more difficult switching trials, which is partially consistent with increased effort avoidance over time. Transitioning to trials with short preparation time after performing trials with long preparation time did not change overall switch frequencies in older children and adults compared with those who performed trials with short preparation time first. Younger children appeared to struggle with task switching when given long preparation time. Specifically, younger children switched marginally less often with long preparation time if they had performed these trials first but switched more often on trials with long preparation time if they had performed trials with short preparation time first. Conversely, younger children switched more often when performing trials with short preparation time first, and the decreased switch frequency with long preparation time carried over into short preparation trials. Such results suggest that these younger children may lack capacity to adapt control appropriately to task demands when provided more time to prepare to use control (Chevalier, 2015).

Overall, this pattern of results in older children and adults supports some avoidance of task switching at the condition level due to task order effects. However, these results should be interpreted with caution, given both the exploratory analyses and small cell sizes for each condition and counterbalance order (N=13-16/cell).

General Discussion

The current studies sought to examine evidence of mental effort avoidance within the voluntary task switching (VTS) paradigm in adult and children by examining performance changes and changes in task switching frequency across trials. Across three independent datasets, we found consistent effects of practice: Response times decreased throughout the task in Studies 1 and 2 while accuracy remained high, and accuracy increased throughout the task in Study 3 while response times remained consistent. In Study 3, response time switch costs decreased across the task, which has been observed in some cued task-switching paradigms (Karayanidis et al., 2003; Koch et al., 2018; Rogers & Monsell, 1995). Importantly, task switching frequency decreased in adults in Study 1 and in older children in Study 2, consistent with increasing effort avoidance across trials. These results corroborate evidence from demand selection tasks, which are aimed at assessing sensitivity and adaptations to cognitive demands, finding that older children and adults avoid unnecessary cognitive demands (Kool et al., 2010; Niebaum et al., 2019). As in those paradigms, adults and older children adapted their behavior across the voluntary task switching paradigms to reduce their mental effort and avoid unnecessary switching costs.

No changes in switch frequency with trials were observed in Experiment 3 in either children or adults. Notably, this task included substantially fewer trials (160) compared with the other studies (504 in Study 1 and 360 in Study 2), which may have been insufficient to detect changes in switch frequency, especially because task parameters also changed within participants. Thus, it is unclear whether younger children do not increasingly avoid mental effort or whether this paradigm was unable to capture changes in switch frequency. Young children also did not increase switch frequency across the task, which may have been predicted due to attempts to alleviate boredom or an increased desire to explore different tasks. To better assess behavioral changes across the VTS in children, future work must include more trials with consistent task parameters. However, older children and adults marginally decreased their overall switch frequency on easier trials after performing harder trials first compared with older children and adults who started performing the easier trials, providing some suggestive evidence of effort avoidance for these age groups.

Interestingly, the decreasing switch frequency in Study 1 was driven by adults with shorter preparation time, which also slowed response time. The decreasing switch frequency in Study 2 was driven by children preferentially selecting the easier task. These results suggest that effort avoidance within the VTS may only occur when the task is sufficiently hard or when one task option is significantly easier than the other. This pattern of results could also be due to adaptations to maximize accuracy or compensate for fatigue. The current analyses are not well-suited to directly distinguish between these potential explanations; however, given that performance typically improved over time, even in conditions in which switch frequency did not change across trials, these possibilities are still consistent overall with increased effort avoidance throughout the task.

The performance and behavioral changes within the VTS task and differences in performance changes according to specific task parameters observed here hold important implications for future analyses and designs using the VTS. Most research studies provide ample practice with selecting each task (e.g., 8 single-language trials in Study 2; 32 single-task trials in Study 3) and with switching between tasks (8 mixed-language trials in Study 2; 16 trials mixed trials in Study 3). However, despite extensive practice, performance still systematically changed throughout the VTS, suggesting that task learning occurs after practice and may vary between individuals, between task conditions, and across age groups. Differences in learning could systematically influence group or participant analyses in ways that are masked by averaging. Although the current analysis was not aimed at assessing individual differences, these patterns of change could also be an interesting source of meaningful variance in VTS data. For example, task-switching decreases within the VTS positively correlated with scores on the Behavioral Inhibition System subscale in adults (Carver & White, 1994; Orr & Imburgio, 2021), which has previously been theorized to correlate with mental effort avoidance (Kool et al., 2010) and predicted greater mental effort aversion in adults (Storbeck et al., 2015). In contrast, average switch frequency did not correlate with BIS scores. Thus, assessing changes across the task may provide information about participant learning and mental effort avoidance or enable investigations into factors that engender more mental effort in voluntary task switching.

Where possible, we also analyzed changes in performance due to prior task switching experience. Specifically, we examined performance changes due to completing a separate VTS task first in adults and completing different variations of VTS trial blocks in children and adults. In Study 1, task switching frequency was lower in adults after performing a prior VTS task compared with adults performing a VTS task first. In Study 3, adults and older children switched marginally less often on trials with long preparation time after performing trials with short preparation time compared with adults and older children beginning with trials with long preparation time, consistent with effort avoidance. Further, response time changed differently across trials based on prior task experience. Thus, counterbalance order systematically and meaningfully changed group averages and differentially influenced group performance changes across the task, which could alter other analyses. Condition counterbalancing is frequent within the VTS literature (e.g., Arrington & Yates, 2009; Chen & Hsieh, 2013; Demanet et al., 2010; Mittelstadt et al., 2018a); however, analyses of counterbalancing effects are rare (e.g., Arrington & Logan, 2005). Future work using counterbalanced designs using the VTS must anticipate, analyze, and account for potential order effects.

Children's sensitivity to cognitive task demands appears to emerge across late childhood. Like adults, older children avoid cognitive demands, preferring to take on easier tasks over hard tasks. Using the voluntary task switching paradigm, we found further evidence that older children were sensitive to cognitive task demands, instantiated with task switching, and increasingly avoided cognitive demands. Understanding the developmental trajectories of these sensitivities and preferences to avoid cognitive demands will provide insight into children's decision-making, especially as they age and gain increasing agency in deciding for themselves what tasks to take on or avoid.

Conclusions

The present analyses assessed changes within different versions of the voluntary task switching paradigm in children and adults to assess performance changes and changes in task switch frequency throughout the task. We observed performance improvements across trials, consistent with practice effects with more time on task. In two of the three studies included here, we observed evidence of decreased task switching frequency across trials, consistent with mental effort avoidance. Performance and task choice behavior also changed based on prior task order and experience, suggesting new avenues for investigating factors that influence performance improvements with practice and that influence decisions to switch or repeat tasks over time. Such changes across the task could also be a fruitful source for understanding individual differences in learning and effort avoidance. Assessing performance and behavior across trials within voluntary switching tasks is needed to understand individuals' preferences for avoiding cognitive demands and factors that influence the avoidance of cognitive demands across development.

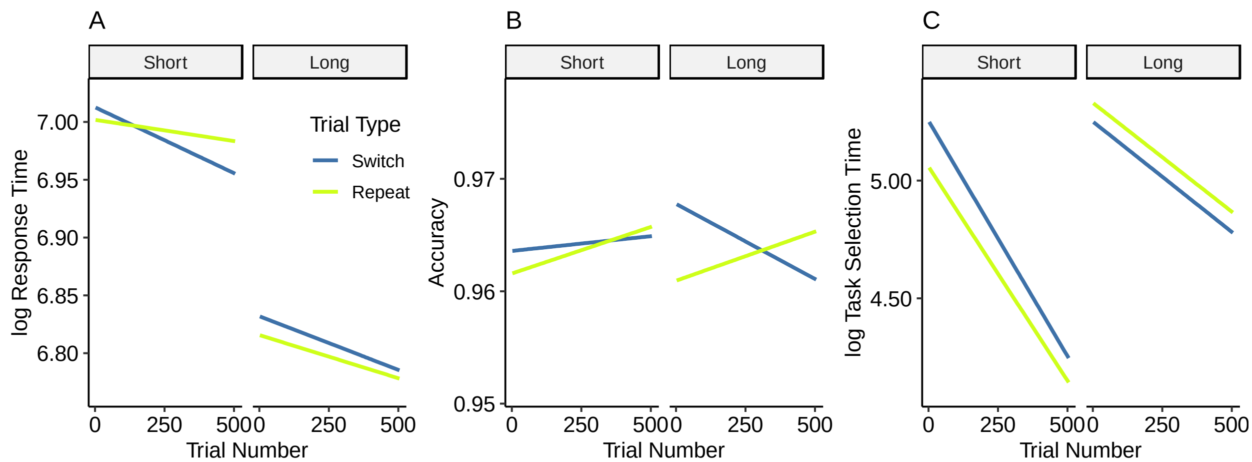
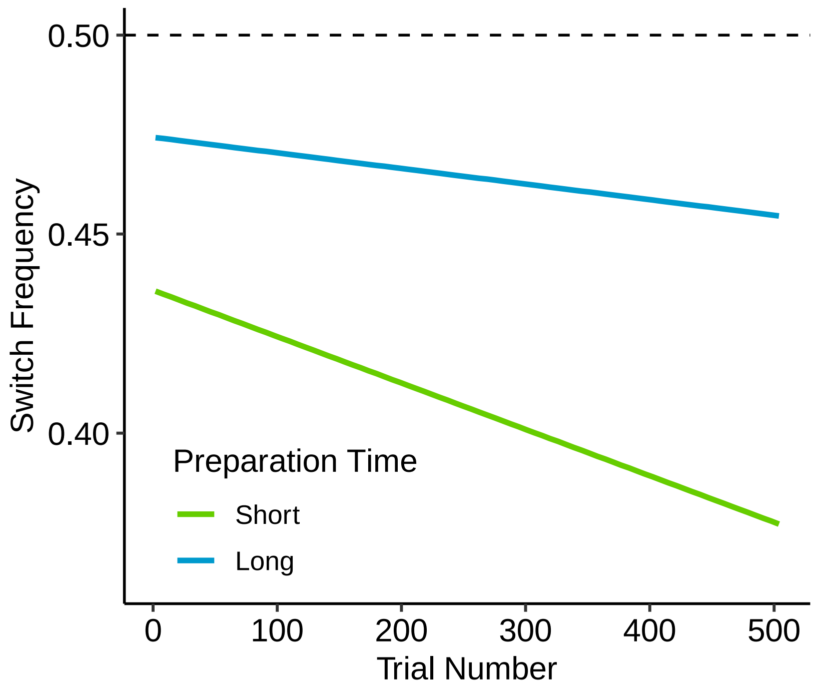
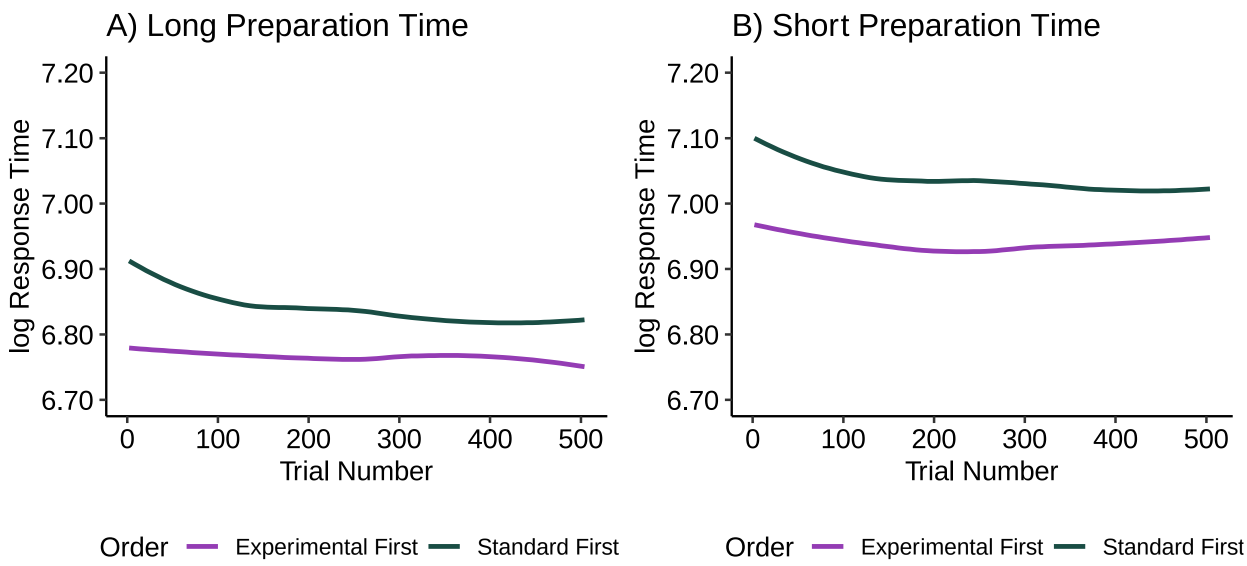


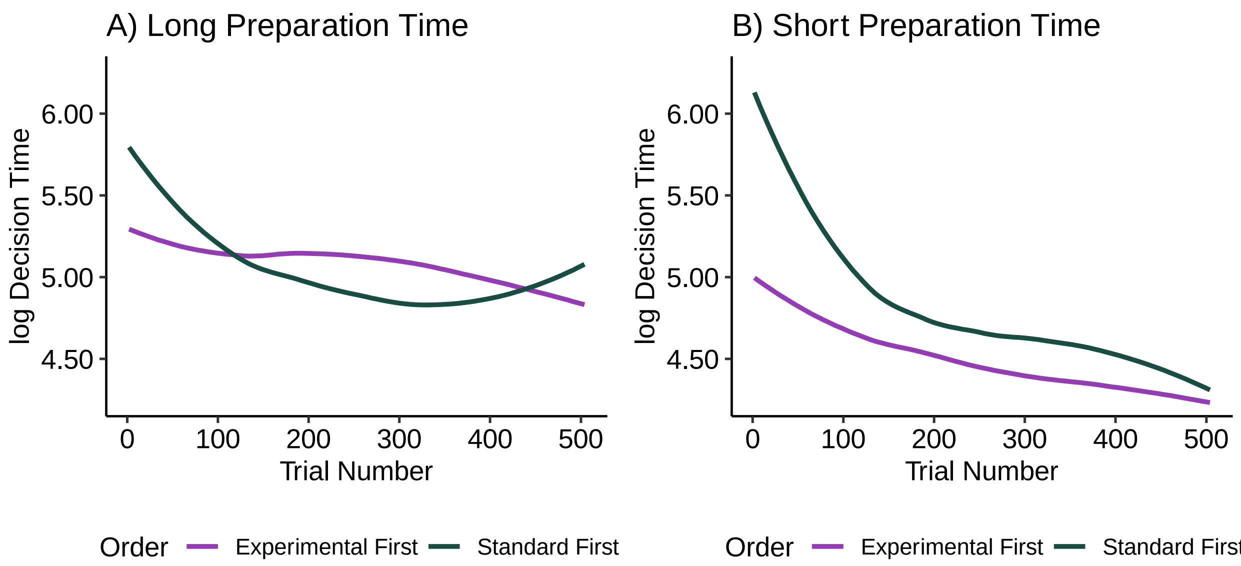
Figure 1. Group-level changes in log response time (A), accuracy (B), and log task selection time (C) by trial type (switch vs. repeat) and task preparation time (short = 100 ms vs. long = 500 ms) across trials. Log response time and log decision time significantly decreased across trials. Shaded regions represent standard error. Surprisingly, response time costs and decision time costs differed across trials, driven primarily by preparation time, with response time switch costs diminishing over time and an overall repeat decision time cost occurring in the short preparation condition.



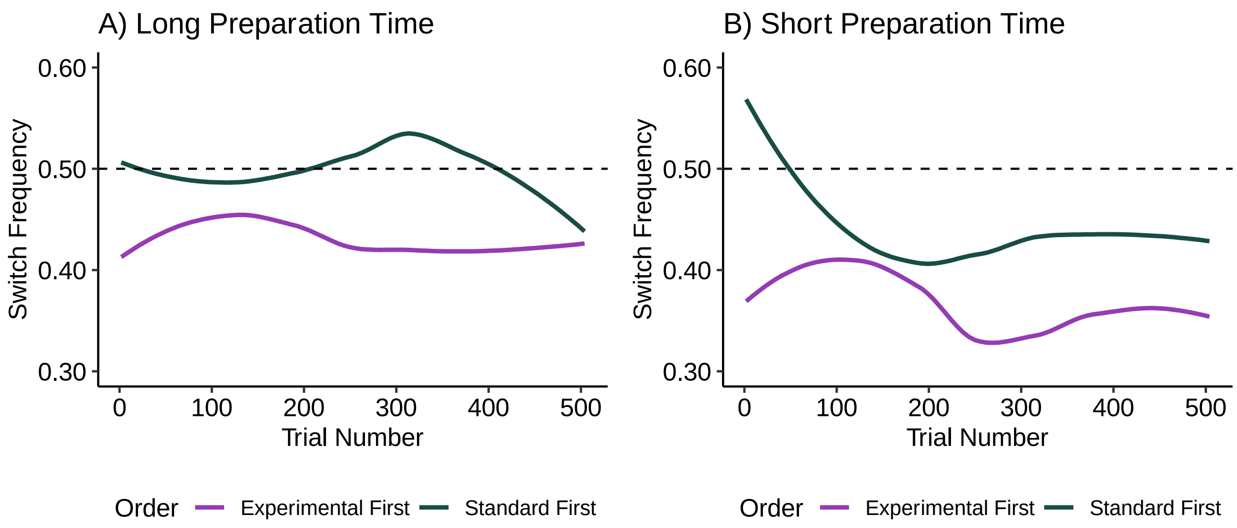
<u>Figure 2</u>. Frequency of voluntary task switching across trials according to task preparation time (short = 100 ms; long = 500 ms). The dashed line depicts a 50% switch rate. Overall, switch frequency decreased across trials.



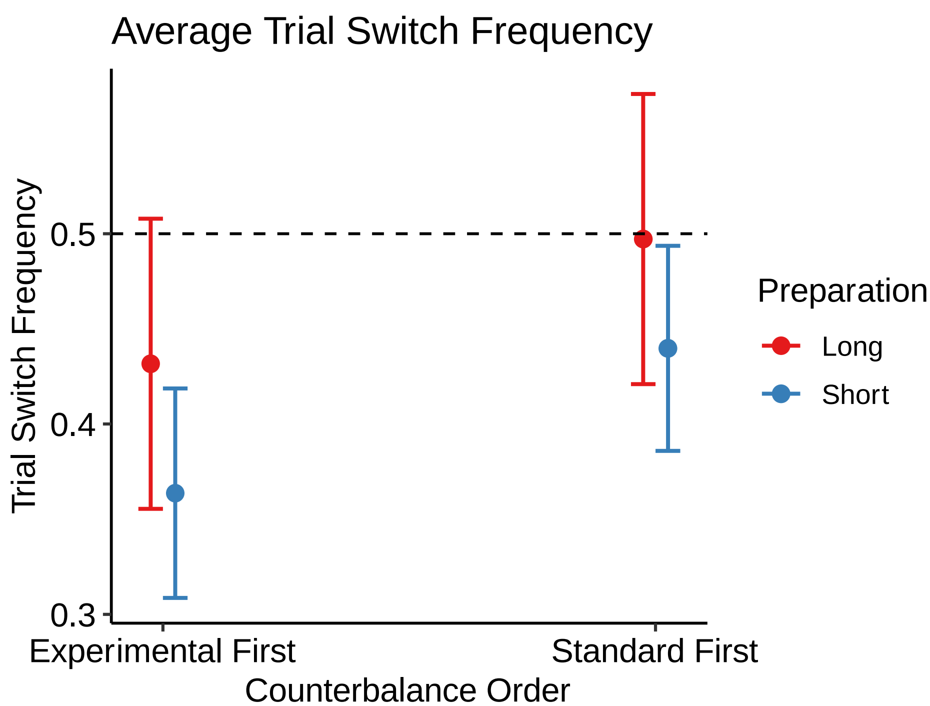
<u>Figure 3</u>. Changes in response time according to task order across trials across the (A) long task preparation and (B) short preparation time conditions. Response times decreased overall with trial number and decreased marginally faster for participants who performed the standard VST task first.



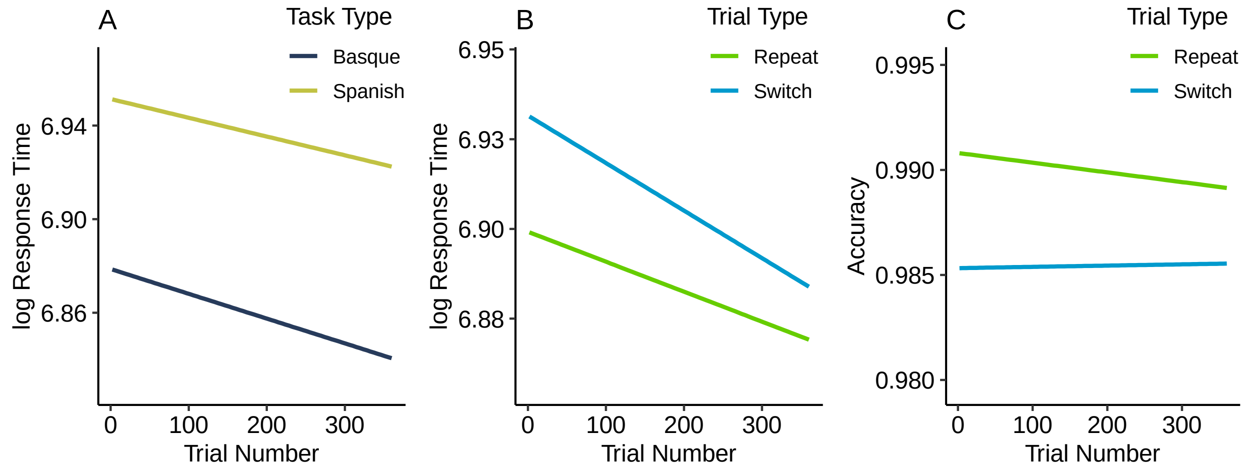
<u>Figure 4</u>. Changes in task decision time according to task order across trials across the (A) long task preparation and (B) short preparation time conditions. Task decision times decreased overall with trial number and decreased faster for participants who performed the standard VST task first.



<u>Figure 5</u>. Changes in task switching frequency according to task order across trials across the (A) long task preparation and (B) short preparation time conditions. Task switching frequency decreased primarily when preparation time was short and was marginally higher when performing the standard VTS first.



<u>Figure 6</u>. Average switch frequency according to task order and preparation time condition. Participants switched tasks significantly less after completing a separate VTS task prior to completing a standard VTS compared with those who completed the standard VTS first.



<u>Figure 7</u>. A) Log response time decreased across trials and was faster in Basque than Spanish. B) Log response time decreased across trials and was faster on repeat than switch trials. C) Accuracy remained stable across trials and was higher on repeat than switch trials.

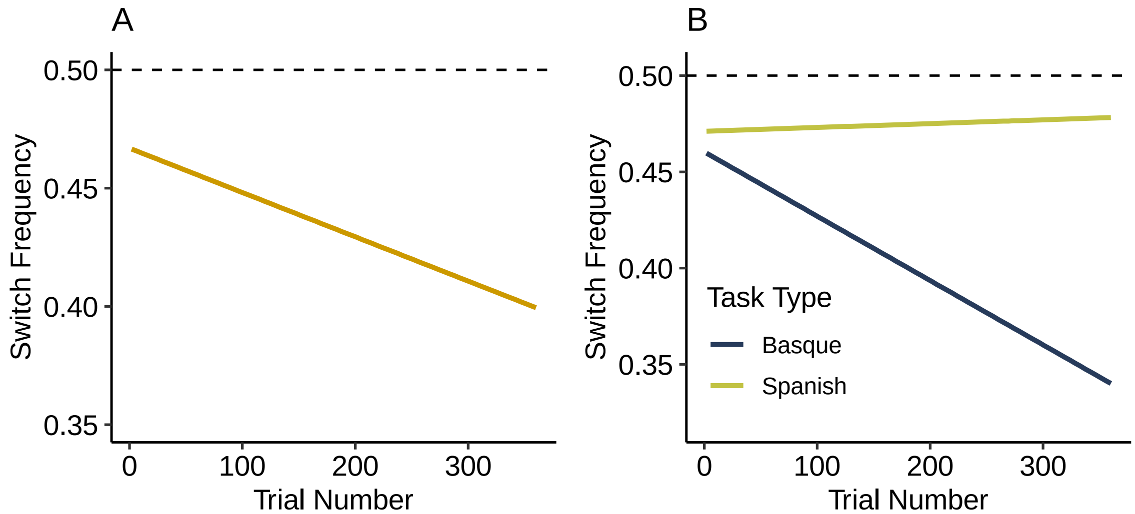
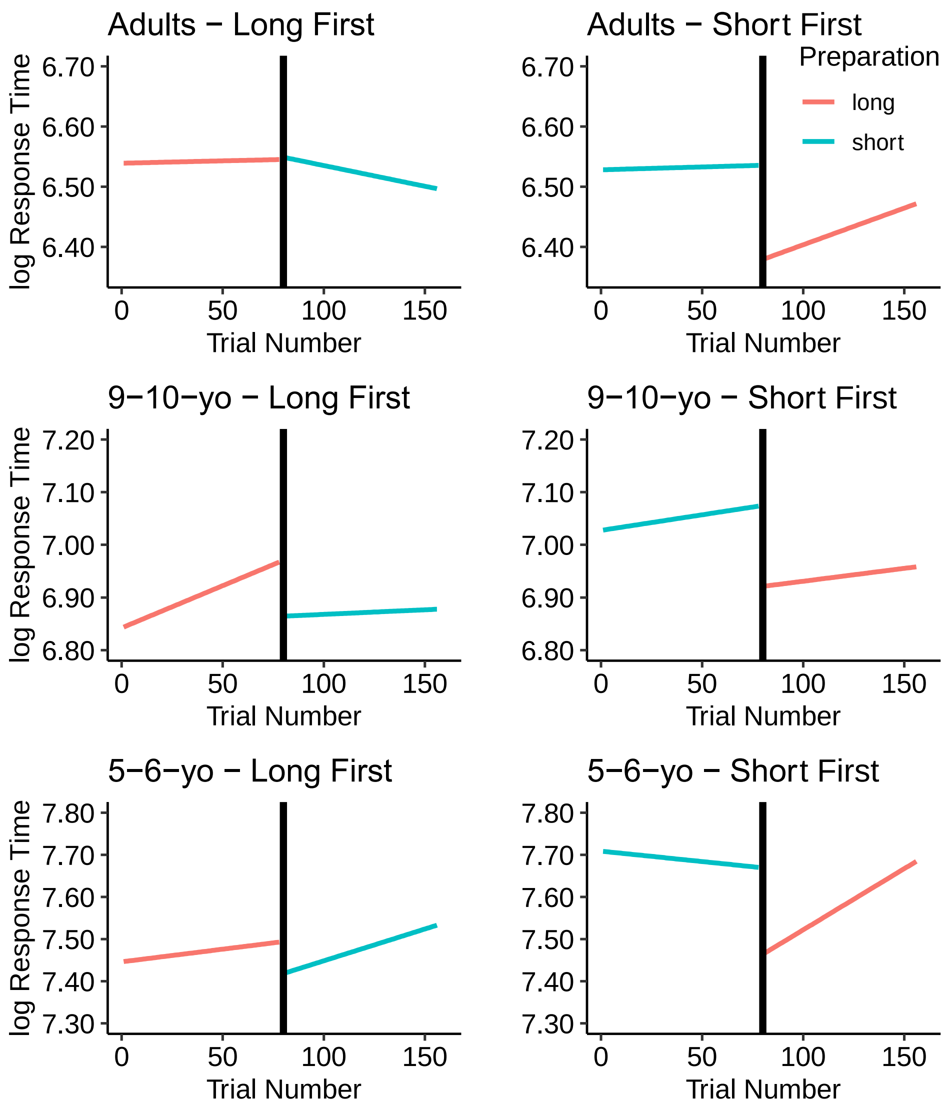
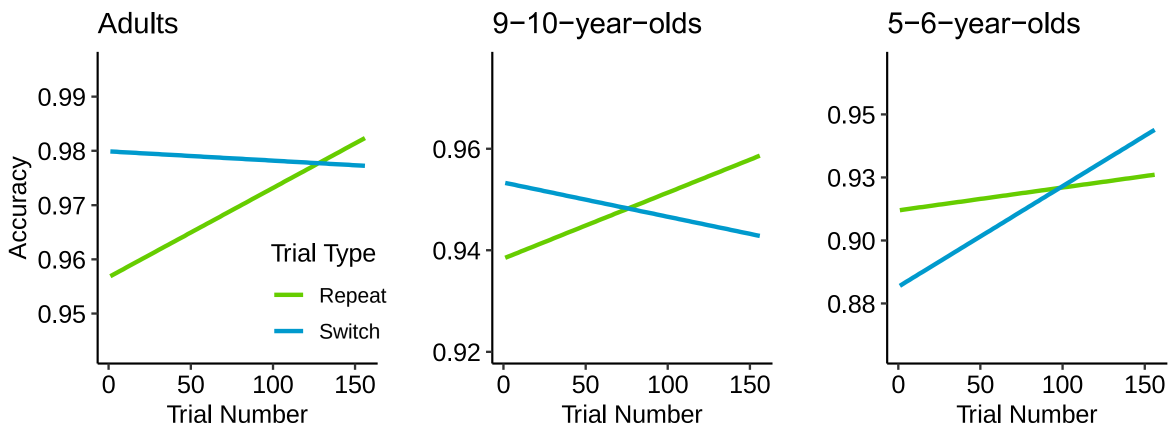


Figure 8. A) Decrease in task switching frequency across trials in 7- to 12-year-old children, showing significant decreases in switch frequency across trials. B) Decreases in task switching frequency across trials according to task type, showing that Basque trials were significantly less likely to be switch trials over time.



<u>Figure 9</u>. Changes in log response time according to trial number, counterbalance order, age group, and preparation time condition. Exploratory analyses indicated that participants who performed the long preparation condition first responded more quickly when preparation time was short compared with participants who performed the short preparation condition first.



<u>Figure 10</u>. Accuracy across trials according to trial type for each group. Accuracy improved across trials overall, and no significant differences between trial types were observed.

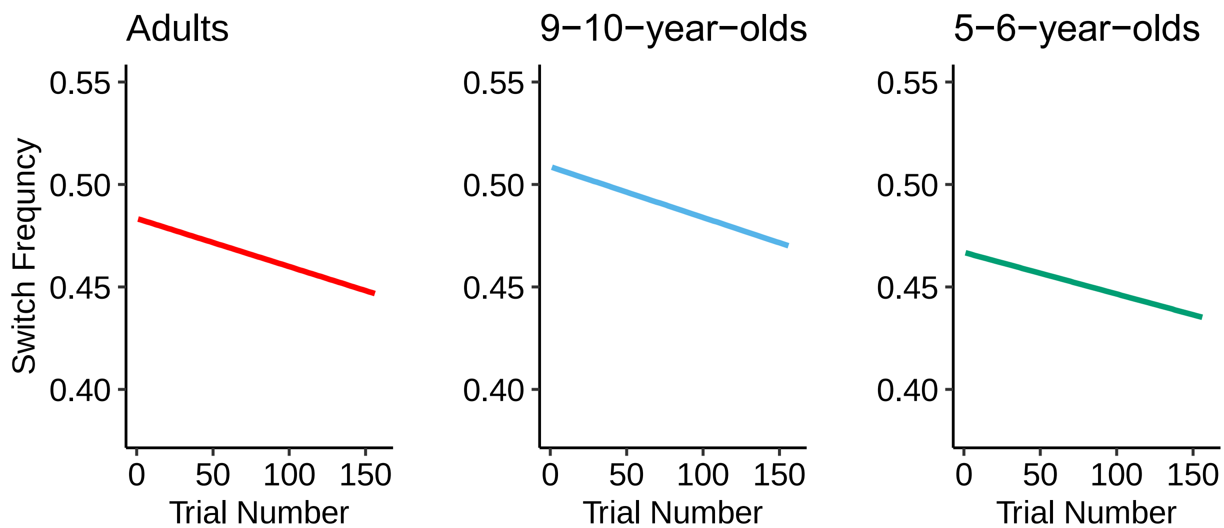


Figure 11. Trial switch frequency across trials in each age group. Switch frequency did not significantly decrease across trials overall.

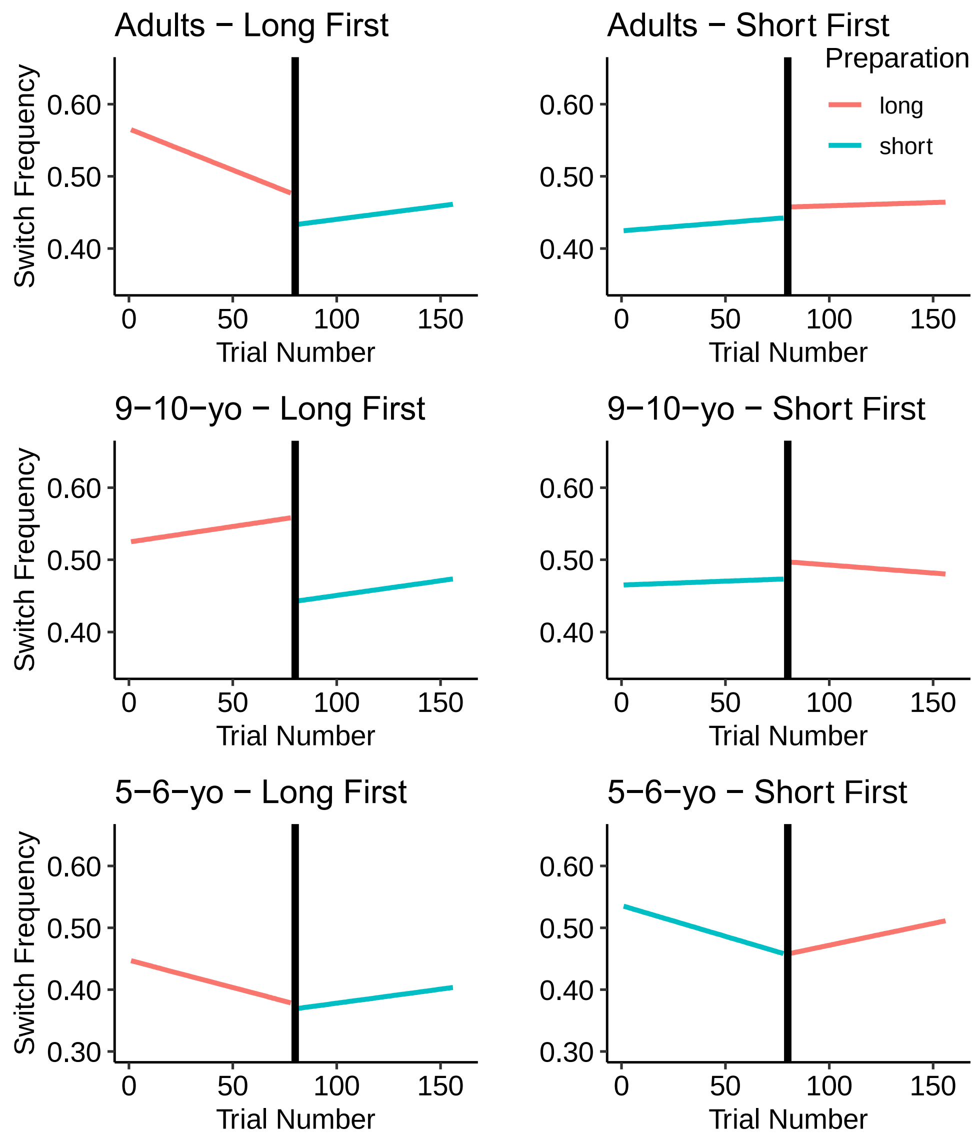


Figure 12. Changes in trial switch frequency across trials according to age group, counterbalance order, and preparation condition. Exploratory analyses suggested that participants who performed the long preparation condition first switched more frequently on long condition than those who performed the short condition first.

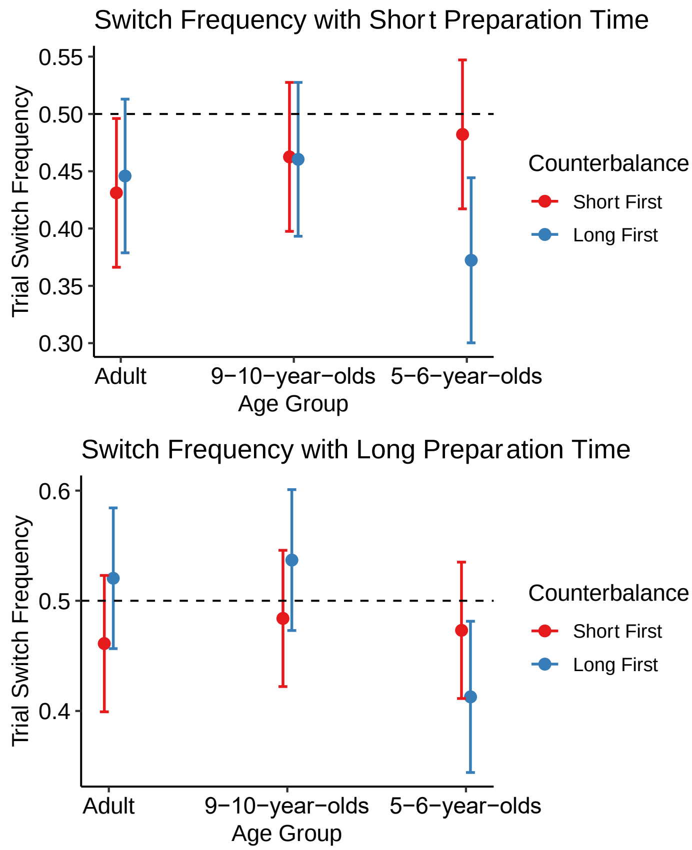


Figure 13. Top Panel: Average trial switch frequency in the short preparation condition within each age group according to counterbalance order. **Lower Panel:** Average trial switch frequency in the long preparation condition within each age group according to counterbalance order. The changes in task switching frequency based on prior task are partially consistent with effort avoidance in adults and older children but not younger children.

Conclusions

Cognitive demands are a core aspect of everyday living. Adults are sensitive to cognitive task demands and use this sensitivity to calibrate their mental effort and take courses of action that reduce demands on their cognition. When does this sensitivity arise, and when do children develop preferences for avoiding cognitive demands? As children grow up, begin schooling, and decide for themselves which tasks to take on or avoid, understanding when and how cognitive demands guide children's decisions will be crucial for understanding cognitive development and children's behavior more broadly.

The research presented herein suggests that the sensitivity to cognitive demands and preferences for avoiding cognitive demands arise across late childhood, particularly after 5-6 years of age. Chapter 2 showed that children at this age neglected relative differences in cognitive demands between tasks, and in turn, these children did not preferentially select to play the less cognitively demanding task. Chapter 3 showed that 5-year-old children also generally neglected differences between tasks when they differed in when cognitive control was required. Chapter 4 suggested that 5-year-old children did not increasingly avoid more cognitively demanding decisions over time. In contrast, Chapters 3 and 4 showed that children aged 10-11 years were adept at monitoring relative cognitive task demands, similar to adults, and used signals of relative demands to adaptatively coordinate their behavior to select easier tasks for themselves, especially when selecting a particular task led to accuracy benefits. Chapter 4 found that older children, similarly to adults, increasingly avoided more cognitively demanding task choices over time, indicating that older children may also adapt their behavior within tasks to increasingly reduce cognitive demands.

Cognitive demands influence children’s decision-making differently across childhood. Older children, like adults, prefer avoiding cognitive demands when possible, using relative cognitive demands as a factor in deciding which tasks to take on or how to coordinate behavior while completing cognitively demanding tasks. Younger children, in contrast, generally do not monitor relative task demands when deciding which tasks to take on. Thus, understanding the relative cognitive demands of different tasks is necessary for understanding children’s decisions and behavior as they develop. Children’s monitoring and preferences for demand likely gain increasing importance as children begin formal schooling and gain independence in deciding which tasks are worth taking on or avoiding. Older children’s emerging sensitivity to cognitive tasks demands and preferences to reduce such demands may help these children allocate their mental effort more efficiently. However, older children’s (and adults’) preferences for avoiding the costs of cognitive demands may also lead to them avoid challenging activities that may have long-term benefits for learning or positive life outcomes. Future work should endeavor to uncover the neural, cognitive, and social mechanisms underlying this developmental transition and investigate how a sensitivity to cognitive demand and preferences for avoiding or exerting mental effort predict children’s everyday behaviors and key outcomes like academic achievement and success in life.

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