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Adaptive Control and the Avoidance of Cognitive Control Demands Across Development

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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, as well as a metacognitive signal guiding adaptive demand avoidance behavior 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.

Introduction

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).

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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, 5yo 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 10-17yo 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- and 11-12-year-old 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. Lastly, a subset of child participants also completed a motivational frameworks questionnaire to assess whether intelligence beliefs influenced control demand preferences.

Materials and Methods

Participants

Forty-seven 6-7-year-olds (M=6.41, SD=0.39, range: 5.59-7.34; 26 male), 48 11-12yo children (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.

Motivational Frameworks Questionnaire

After completing the DST, 6-7yo (N=22) and 11-12yo (N=31) participants completed a verbally administered Motivational Frameworks Questionnaire (Appendix A) adapted from Gunderson, Romero, Dweck, Goldin-Meadow, and Levine (2013) to assess a participant's fixed versus growth intelligence mindset. After 22 participants, the questionnaire was dropped from the 6-7yo protocol due to total session length commonly exceeding 1 hour. Participants responded verbally using a five-point thumbs scale (1-5) or by pointing at images of thumbs ranging in orientation from thumbs down ("I do not agree") to thumbs up ("I do agree") or by verbally responding yes or no when appropriate. Standardized z-scores were created for intelligence-domain items and socio-moral-domain items, and a composite measure was created by averaging the two standardized scores (11-12yo: M=0, SD=0.65; 6-7yo: M=0, SD=0.82). Open-ended questions were not scored, resulting in 12 intelligence-domain questions and 2 socio-moral-domain questions.

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 6-7yo and one 11-12yo 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); 6-7yo: 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, 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

Baseline switch costs in adults significantly correlated with low-demand deck preference (r=.346, p=.020, BF_{10}=2.89) (Figure 3A), 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). 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 3B). 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

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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).

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), where 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). The 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 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.

Motivational Frameworks and Demand Avoidance

We explored whether motivational frameworks negatively correlated with low-demand deck preference across child groups, reasoning that a child with a growth mindset motivational framework may intentionally select the high-demand deck. The standardized intelligence-domain score and composite score were not correlated with low-demand deck preference (intelligence domain: r=.07, p=.63; composite: r=.19, p=.18).

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.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- Adults and 11-12-year-olds avoided cognitive control demands but 6-7yo did not, despite all ages exhibiting evidence of demand signals.
- Adults and 11-12yo but not 6-7yo had subjective awareness of cognitive control demands.
- Older children may especially attend to external cues, such as feedback or accurate performance to ascertain demand differences, whereas adults may develop cognitive demand sensitivity from internal effort signals.

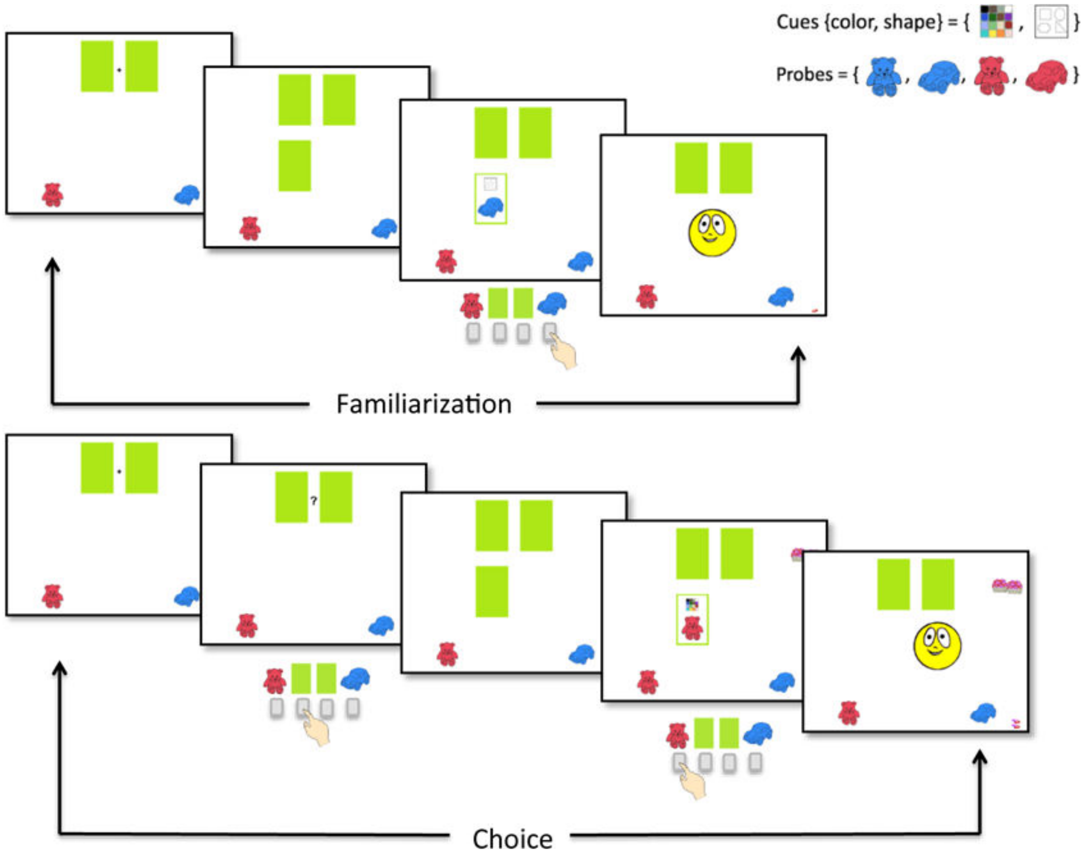

Figure 1.
Demand Selection Task Flow. Participants completed 40 familiarization trials (20/deck), 20 forced choice trials (10/deck), and then 102 free choice trials. Probes were presented at the bottom of the screen for answer reminders. The left and right green rectangles depict decks of toys; one deck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

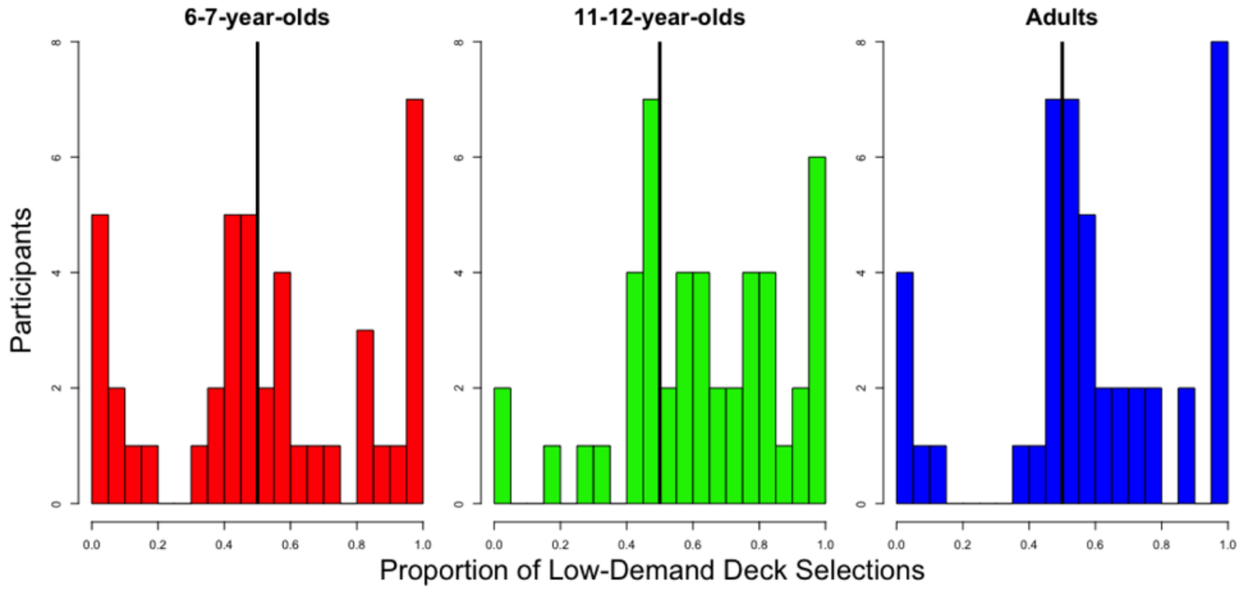

Figure 2.

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, $p<.05$).

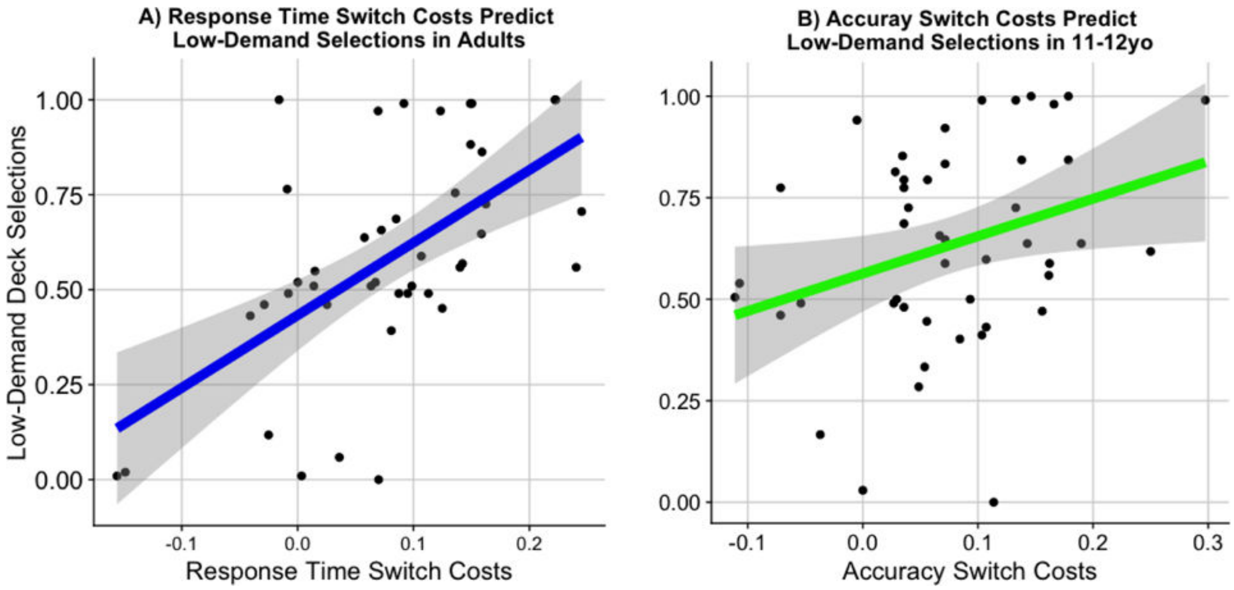

Figure 3.

A) Log response time switch costs predicted the proportion of low-demand deck selections in adults (r=.35; p=.020); B) Accuracy costs predicted the proportion of low-demand deck selections in older children (r=.32; p=.029).

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 $p<.01$.