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A Developmental Eye Tracking Investigation of Cued Task Switching Performance

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Children perform worse than adults on tests of cognitive flexibility, which is a component of executive function. To assess what aspects of a cognitive flexibility task (cued switching) children have difficulty with, investigators tested where eye gaze diverged over age. Eye-tracking was used as a proxy for attention during the preparatory period of each trial in 48 children ages 8–16 years and 51 adults ages 18–27 years. Children fixated more often and longer on the cued rule, and made more saccades between rule and response options. Behavioral performance correlated with gaze location and saccades. Mid-adolescents were similar to adults, supporting the slow maturation of cognitive flexibility. Lower preparatory control and associated lower cognitive flexibility task performance in development may particularly relate to rule processing.

At many points in any school day, a child is asked to change tasks, or to take in new information and adapt their actions to suit. Shifting between tasks and processing different instruction cues requires cognitive flexibility, an example of executive functioning. Executive functions (EFs) are regulatory cognitive processes that support goal-oriented behaviors (Diamond, 2013). EFs comprise multiple domains such as inhibition (intentionally overriding a prepared response), working memory and updating (temporarily storing and manipulating information in your mind), and cognitive flexibility (the ability to adjust to new information, or to switch between tasks) among others (Engelhardt, Briley, Mann, Harden, & Tucker-Drob, 2015; Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003; Miyake & Friedman, 2012). EFs are supported by a consistent set of fronto-parietal and cingulo-opercular brain regions that co-activate during cognitively demanding tasks (Dosenbach et al., 2006; Engelhardt, Harden, Tucker-Drob, & Church, 2019; McKenna, Rushe, & Woodcock, 2017) and correlate together at rest (Power & Petersen, 2013; Reineberg, Andrews-Hanna, Depue, Friedman, & Banich, 2016). Because EFs strongly relate to academic achievement (Best, Miller, & Naglieri, 2011; Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008; Espy, McDiarmid, Cwik, Stalets, & Senn, 2004) and predict long-term outcomes (Blair & Diamond, 2008; Diamond, 2013; Duckworth & Seligman, 2005), understanding the maturational time course of an EF aspect like cognitive flexibility could lend insight into better educational or treatment practices.

Cued task switching is used to investigate cognitive flexibility, as it requires the moment-to-moment adaptation to different tasks on a trial-by-trial basis. This type of task can be administered to a wide range of ages from preschool to old age (Cepeda, Kramer, & Sather, 2001; Logan & Gordon, 2001), making cued task switching an ideal tool for interrogating cognitive flexibility. Attending to the cued rule, and the loading and unloading of different task parameters to later apply the appropriate rule, are cognitive processes that could be occurring in preparation for any subsequent target stimuli. Adults remain better than children at cued task switching until children are around mid-adolescence (Anderson, 2002; Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Bauer,

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Martinez, Roe, & Church, 2017). The performance gap could result from children's less productive use of the cue period to prepare prior to the appearance of the target, as has been implicated through differences in control-related (e.g., fronto-parietal and/or cingulo-opercular) brain activity in children and adults (Church, Bunge, Petersen, & Schlaggar, 2017; Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006).

A motivating model within the cognitive flexibility literature is the Dual Mechanisms of Control (DMC) model. DMC posits that there are preparatory, or proactive task control mechanisms, and reactive, or in-the-moment control mechanisms, at play during any task (Braver, 2012; Braver, Paxton, Locke, Barch, & Edward, 2009). Cued task switching is a paradigm in which both proactive and reactive control processes are potentially at play, if the cue preparatory period is considered "proactive," whereas the target response period is considered "reactive." In development, young children have been shown to rely more on reactive task control, shifting to proactive control as they age (Cepeda et al., 2001; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Chevalier, Martis, Curran, & Munakata, 2015; Munakata, Snyder, & Chatham, 2012). However, young children do appear to have the capacity to use proactive control in some circumstances as early as ages 3–5 years (Brace, Morton, & Munakata, 2006; Chevalier et al., 2015; Diamond, Carlson, & Beck, 2005). Despite evidence of some use of proactive control abilities by middle childhood, performance gaps between children and adults in cued task switching persist into mid-adolescence, even with experimental manipulations in cue type (lexical or symbolic), amount of working memory demand, and number of cued features (Bauer et al., 2017; Martinez, Mack, Bauer, Roe, & Church, 2018).

Furthermore, cognitive flexibility within a cued task switching paradigm interacts with working memory abilities and can be informative of what other cognitive processes might be necessary to mature cognitive flexibility. Task manipulations can require the relevant rule and/or the appropriate response mappings for that rule to be maintained in working memory. Working memory, like other aspects of EFs, exhibits protracted development into adolescence, which may be mediated in part by increased processing speed (Fry & Hale, 1996; Kail, 2007; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Nettelbeck & Burns, 2010). Blackwell and colleagues demonstrated that increased working memory strength is predictive of greater cognitive flexibility in cued task switching (Blackwell, Cepeda, & Munakata, 2009). The authors posited that children who are successful switchers have stronger representations of the current rule allowing for top-down control of task-relevant information, whereas those who perseverate have weaker representations that are unable to overcome the conflict between the multiple dimensions present in cued task switching. Thus, successful preparatory task control in cued task switching may rely on both cognitive flexibility and working memory (among other factors such as processing speed). Varying working memory demand may manipulate the degree to which preparatory, proactive task control is engaged (Blackwell & Munakata, 2014; Braver, 2012).

Being able to temporally distinguish between proactive and reactive control may be critical to understanding the performance gap. Button-press responses allow limited insight, capturing only the endpoint of the decision-making process at the target response period. Slightly better are functional magnetic resonance imaging (fMRI) studies, which, using a catch-trial task design that allows separation of brain activity related to cue from that related to target presentation, can break trials into an anticipatory, proactive control period and a moment-to-moment, reactive control period. These data have indicated that children are engaging putative cognitive control (e.g., fronto-parietal, cingulo-opercular) networks less during the preparatory cue period relative to adults (Church et al., 2017). Similarly, electroencephalography studies have been able to divide the trials into an anticipatory cue and target period, demonstrating an anterior negativity/posterior positivity event-related potential (ERP) complex 400–600 ms (termed switch-positivity) after cue onset that reflects proactive control in rule remapping during switch trials (Karayanidis & Jamadar, 2014; Lavric, Mizon, & Monsell, 2008). There's also a fronto-central negativity ERP complex (termed switch-negativity) that appears 200 ms posttarget during switch trials that is theorized to reflect reactive control (Karayanidis & Jamadar, 2014). Children, relative to adults, exhibit delayed preparatory processing (Manzi, Nessler, Czernochowski, & Friedman, 2011). Furthermore, children who successfully task switch compared to those that perseverate exhibit a smaller amplitude in the N2 component, a negative fronto-central ERP signal 200–400 ms after stimulus presentation that is related to conflict monitoring and need for cognitive control (Espinet, Anderson, & Zelazo, 2012).

Behavioral measures combined with neural markers of proactive control indexed by fMRI and

ERP signals has allowed us to infer the broader spatiotemporal dynamics of cognitive control processing in children. However, the question that then arises is: What are children doing during the anticipatory cue period if not using the cue information to proactively prepare for target onset? Eye tracking offers a unique opportunity to measure moment-to-moment spatial attention during the task, using location and duration of eye fixations as a proxy for visual attentional focus. The duration of time a participant's eyes fixate on the cued rule, the possible response choices, or, later, on the target itself, may provide clues about the stage of cued task processing where children most differ from adults. These data can provide potential insight into what cognitive processes may be at play in driving developmental differences in cued task switching, and more broadly, in cognitive flexibility. Furthermore, we can then identify the age at which any fixation differences transition to adult-like patterns during the task, and test whether these eye movements significantly relate to the end of trial behavioral responses, that is, age-related improvements in accuracy rates and response times.

The maturation of eye movements is not simply an initial bottom-up orienting process that, driven by changes in the environment, matures into a goal-driven, top-down process. Instruction can modify eye patterns in even young children, indicating that top-down attentional control plays an important role in directing eye gaze during some tasks from very early in life (Lagattuta & Kramer, 2017). There is a growing number of developmental task-switching studies that have employed eye tracking, with particularly relevant work by Chevalier and colleagues. They have found that when the cue and target are presented simultaneously, young children focus earlier and more often on the target first, and then the cue, whereas older children and adults follow a more productive cue-then-target pattern of eye movements (Chevalier, Dauvier, & Blaye, 2018). Furthermore, when children are given an unlimited time to prepare for a trial before they proceed, and are allowed to trigger target onset themselves, older children performed better, suggesting more effective preparation abilities or at least better self-assessment of preparation readiness (Chevalier & Blaye, 2016). About one-third of trials in 6-year-olds had efficient eye trajectories, whereas about half of trials showed that pattern in 10-year-olds, demonstrating that even in 10-year-olds, there was variability at the individual and session level. These eye tracking and behavioral results combine to support mixed strategy use in children, and increased attempts over developmental age to use preparatory cognitive strategies (Chevalier & Blaye, 2016; Munakata et al., 2012).

However, it remains unclear how children, relative to adults, are dividing their eye movements between the rule and response options during the cue period when the target, and thus a behavioral response, is not yet available. More specifically, do children begin to differ from adults in their attentional focus in this preparatory period? Does maturation of eye movements precede or occur in step with behavioral changes in performance?

There were four primary goals for this experiment: (a) To test if children's eye fixations differed from those of adults during the anticipatory cue and delay periods; (b) To identify at what age children's eye movements became similar to adults' to see if this aligned with or preceded previously published behavioral results of ages 13–14 years for this task (Bauer et al., 2017; Martinez et al., 2018); and (c) To see if eye movements held relevance for the behavioral response recorded at the end of the trial by examining relationships between eye movements and task accuracy and response times. We predicted that: (a) Children's eye fixations would differ from adult eye fixations, particularly in viewing response choices; (b) Eye movement maturity would occur at the same age as we see behavioral improvement, reflecting more mature attention patterns; and (c) More mature eye patterns would correlate with better behavioral performance in task accuracy and response time above and beyond age. While we had clear initial hypotheses, we did not preregister our analysis, and thus this experiment should be considered mostly exploratory.

Method

Participants

All participants were typically developing children or adults with no known diagnosed psychiatric disorders or medications. All participants were native English speakers; 12 reported fluency in an additional language (8 adults, and 4 children). All had normal, uncorrected vision to facilitate eye tracking.

Fifty-four adults, ages 18–29 years, and 63 children, ages 6–16 years, were initially recruited for this study. Previous studies (Bauer et al., 2017; Martinez et al., 2018) utilizing a similar cued task-switching paradigm found reasonable effects at a similar sample size, motivating the sample size for this study. The age range for analysis was narrowed for adults to 18–27 years to overcome limited sampling in ages 28–29 years, and for children to 8–16 years to have complete neuropsychological assessments. One adult was dropped from analysis because of exceeding the age range, another due to poor performance on three levels, and another because of poor eye tracking data quality. Thus, 51 adults were left for final analysis (24 males, M = 22.08 years; Table 1A). Five children were excluded due to age (6–7 years), six were dropped for not meeting task accuracy thresholds (see below), one due to a clinical-level score on the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2001) and three because of poor eye tracking data quality; 48 children were left in the final analysis (28 males, M = 12.51 years).

Participants were administered the Wechsler Abbreviated Scale of Intelligence—Second Edition (WASI-II) Vocabulary and Matrix Reasoning [Wechsler, 2011], Digit Span (Wechsler Intelligence Scale for Children—Fourth Edition [WISC-IV] for children and Wechsler Adult Intelligence Scale—Fourth Edition [WAIS-IV] for adults; Wechsler, 2003; Wechsler, 2008), and D-KEFS Stroop and Trail-Making (Delis, Kaplan & Kramer, 2001). A parent/legal guardian completed the CBCL for any participating child. Legal guardians of children and adult participants completed questions about socioeconomic status, education, race, and ethnicity. For the reported sample of children, the IQ (estimated from the WASI-II Vocabulary and Matrix Reasoning scores) of the sample ranged from 96 to 142 with a mean of 115.58 and the IQ estimate for the reported adult sample ranged from 84 to 136 with a mean of 110.96. IQ estimates between the child and adult sample were not significantly different, although slightly elevated in the child sample (t = 1.92, p = .06). CBCL total T-scores for the child group ranged from 29 to 57 with a mean of 43.4. Most participants were White and/or Latino (Table 1B). Our participant sample's household income (for those who self-reported) ranged from \$21,000 to \$1 million, with a median household income of \$115,000. Participants came from a total of 43 zip codes from Austin, Texas, and the surrounding metropolitan area.

Table 1
(A) Breakdown of the Number of Female and Males in Each Age Group That Were Included in the Analysis. (B) Number of Participants That Identified With Any of These Ethnicities/Races

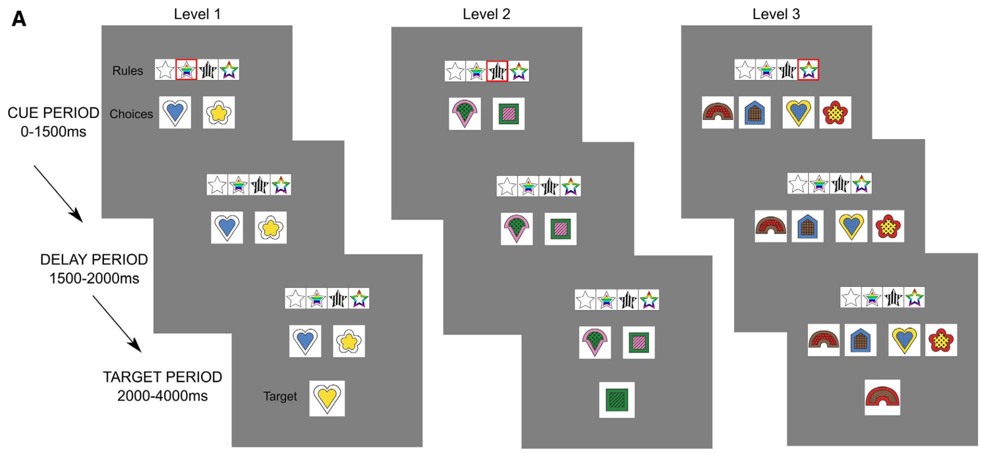
	Female (*N*)	Male (*N*)	Total (*N*)
(A)			
8–10 years	7	9	16
11–13 years	6	10	16
14–16 years	8	8	16
Adult	28	23	51
Total	49	50	99

Ethnicity/race	Number of participants
(B)	
White	68
Latino/Hispanic	19
African-American/Black	3
Asian	10

Experimental Task: Cued Task Switching

This experiment was modeled after Bauer et al. (2017). For the experimental task, participants were asked to choose which response matched a "target" object based on a cued feature or "rule" (i.e., shape, inner color, outer color, or pattern) that changed ("switch" trials) or repeated ("repeat" trials) on a trial-by-trial basis (Figure 1A). The number of possible response options or "choices" ranged between two and four. Half of all trials within the two-choice levels were switch trials, with the rest being repeat trials (Figure 1B). The four-rule levels (2, 3 and 5, 6) had 42%–43% repeat trials. Repeat and switch trials were not blocked; rather, trials could be either repeat or switch from trial-to-trial. We defined "congruent" trials to be ones where the correct response choice matched the target 100% on all possible features, whereas "incongruent" trials were ones where the correct response choice did not match the target on all features. Around 20% of all trials were congruent within a level; the exact number of congruent and incongruent trials per level are specified in Figure 1B. As the focus of this study is on the effect of task switching in children during the cue and delay periods, incongruency effects are discussed in Supporting Information. Testing for differences in congruency effects between groups for accuracy and response times can be found in Tables S3 and S4, respectively. Congruency effects between age bins for accuracy and response time can be found in Tables S5 and S6.

Within each 4,000 ms compound trial, the first 1,500 ms (the cue period) highlighted the relevant rule with a red box outline, and displayed the possible response choices in the middle of the screen. Response choices differed from trial-to-trial; therefore, the response mappings could not be memorized as the task proceeded. The red cue outline then disappeared, but the rule bar and possible



B

Level	# of Rules	# of Choices	# Repeat | Switch	# Congruent| Incongruent	# of Trials
1/4	2	2	22 | 23	9 | 37	46
2/5	4	2	22 | 30	11 | 42	53
3/6	4	4	23 | 29	11 | 42	53

Figure 1. Experimental setup where (A) demonstrates the stimuli presentation during the task and (B) the manipulations within the experimental levels. (A) The cue period lasted 1,500 ms with a red box indicating the rule for that particular trial (here, "inner color" for Level 1, "pattern" for Level 2, and "outer color" for Level 3), and the rule bar and response choices were displayed on the screen (black text is added to Level 1 for identification of eye movement interest areas for this figure only). Then there was a 500 ms delay period, where the red box disappeared, but the rest of the visual information stayed on screen. The delay period was followed by a 2,000 ms target period when the target stimulus was displayed and the participant was to respond. The response choices and target changed from trial-to-trial; the highlighted rule would either change (switch trials) or remain the same (repeat trials). Levels 1–3 were considered lower working memory demand as the rules and the choices remained on the screen during the target period (as shown in A). Not depicted here are Levels 4–6, which were considered higher working memory demand as the target stimulus was displayed alone on the screen during the target period. (B) The experimental session consisted of six levels: Three lower working memory (WM) demand and three higher WM demand. The table gives the number of rules and choices, along with number of repeat (vs. switch) and congruent (vs. incongruent) trials for Levels 1–3. Experimental parameters for Levels 4–6 were the same as Levels 1–3 respectively. [Color figure can be viewed at wileyonlinelibrary.com]

response choices remained onscreen during a 500 ms delay period before target onset (the delay period). In the last 2,000 ms (the target period), the target appeared on the screen, prompting participants to indicate their response choice using a button box (Figure 1A). Participants were instructed to choose as quickly as they could while still maintaining accuracy.

Participants were familiarized to the task demands by engaging in a practice session of four trials that were self-paced, and then six practice trials that followed the experimental timing before starting the experiment. To ensure that all participants understood the experimental task demands, the researchers were able to explain to the participants as many times as needed how to complete the task during the practice session before proceeding with the experimental trials. Furthermore, practice trials were monitored by the researchers to ensure participants were responding correctly and any questions participants may have had were clarified before proceeding.

The experimental session had six task levels: The first three had a lower working memory demand and the last three a higher one. The lower working memory demand levels (1–3) were designed so that the response choices remained on the screen simultaneously with target presentation during the target period. The last three levels had a higher working memory demand, as the target was displayed alone on the screen, and thus participants had to memorize the cued rule as well as the relevant response choice mappings prior to seeing the target. Another practice session preceded the last three levels, consisting of two self-paced trials and three trials mimicking the experimental timing. Given that working memory demands proceeded from lower to higher for all participants, we were unable to disentangle the effects of practice or task experience from working memory demands. Therefore, the primary focus of our analysis and interpretation in this study does not include working memory effects. However, analyses and associated figures related to working memory effects can be found in Supporting Information (Tables S1, S2, S9 and S10).

The first and second half of the experiment had the same three levels of increasing difficulty: The first level for each working memory demand condition consisted of two button response choices and two possible cued rules (shape, inside color; 46 trials each, Levels 1 and 4). The second level still had two button response choices but four possible cued rules (shape, inside color, pattern, outside color; 53 trials each, Levels 2 and 5). The third level was the hardest manipulation and asked the participant to choose from four possible response choices while trials switched among the same four possible cued rules (53 trials each, Levels 3 and 6). See Figure 1B for a summary.

Eye Tracking

An Eyelink 1000 Plus (SR Research Ltd., Ottawa, Canada) tracked participants' eye movements throughout the trials. All participants used a chin rest throughout the experiment to help stabilize head motion. Participant head height was adjusted via seat cushions to be equivalent across participants. The eye tracker was (re)calibrated to the participants' eyes before the start of each level. The Eyelink Data Viewer software calculated participants' fixation time on each predefined interest area (Rules, Choices, Target). Fixations had to last at least 50 ms. Interest areas were created based on the location of stimulus presentation with an approximately 30-pixel extension past the borders and at least a 20-pixel buffer zone between all Interest Areas. Fixation dwell times were estimated for each interest area across three interest time periods: cue, delay, and target. Saccades between the Rules and Choices were counted for each interest period as well. Only eye movements during correct trials were analyzed. The results discussed in this article will primarily focus on the cue and delay periods as the period of interest that principally reflects proactive or preparatory control processes. Nonetheless, analyses and associated figures related to the target period can be found in Supporting Information. Statistical tests of significance for the predictors of the group and age bin models for the target period can be found in Table S11. Figure S2A demonstrates the amount of visual fixation on the Rules and Choices Interest Areas between children and adults for the target period. Figure S2B shows fixation times on each interest area for each age bin for the target period.

Exclusion Criteria

Participants had to perform above 60% accuracy on the first and fourth levels (i.e., the easiest levels of each working memory demand category), and above chance on at least three of the six levels. To ensure the data quality of the behavioral and eye tracking data, entire trials were dropped from analysis if the response time was faster than 200 ms or if there were more than three blinks in the trial, which left little to no eye tracking data within the trial. If more than 21 trials (38.9% in Levels 2, 3, 5, or 6; 44.7% in Levels 1 or 4) were removed for a level due to poor eye tracking, the entire level was excluded. If more than three levels were dropped for a participant, the participant was excluded from analysis completely.

Analysis Methods

All statistical analyses were conducted in R (R Core Team, 2017). Linear mixed effects models were run using the lme4 package (Bates et al., 2015) for both the behavioral and eye tracking analysis (outlined below). F tests with Satterthwaite approximation for degrees of freedom were used to calculate the significance of model predictors. Estimated p-values of the predictors were calculated using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2016). Post hoc comparisons for significant main effects or interaction effects were conducted with the lsmeans package (Lenth, 2016). Estimated means and standard errors were calculated with the same package. All p-values of post hoc contrasts reported have been adjusted for multiplicity with the "mvt" (multivariate t) method from the same package. Partial correlations, controlling for age, between fixations and behavioral performance were run using the psych package with p-values adjusted for multiple comparisons using the Holm method (Revelle, 2017).

Behavioral Analysis: Accuracy and Response Time

Accuracy was calculated for each level separately. Participant median response time for each level was calculated from correct trials. Separate linear mixed effects models were run for accuracy or response time as the dependent variable, Group (Child, Adult), Rule Switching (Repeat, Switch), and Level (1–6) as the predictors. There were varying intercepts for Participant. The child group was then subdivided into three age bins to examine age effects. The same models were rerun by replacing the Group predictor with Age Bins (8–10 years, 11–13 years, 14–16 years, and Adult).

Eye tracking Analysis: Cue and Delay Periods

For correct trials, the fixation time in each Interest Area (Rules, Choices, Target) was calculated for the cue and delay periods. We ran separate linear mixed effects models for each Interest Period with Interest Area, Group (Child, Adult), Rule Switching (Repeat, Switch), and Level (1–6) as the predictors, and Fixation Time as the dependent variable. We also included varying intercepts for Participants and Trials as random effects. The models were also rerun with Age bins instead of Group as a predictor.

Time Course

To examine eye movements over smaller time epochs than our broader interest periods, we divided up trials from Level 2 into 100 ms sections. We then calculated the average proportion of time spent fixating on each interest area (Rules, Choices, Target) during each 100 ms time bin. We then used a linear mixed effects model to predict the ratio of Choices:Rules fixation with our smaller Age Bins (8–10 years, 11–13 years, 14–16 years, and adults) and Time (100 ms intervals) as predictors and varying intercepts for Participants during the cue and delay periods (excluding the target period). Post hoc contrasts compared each of the child age bins against the adults for every time bin with *p*-values adjusted for multiple comparisons.

Correlations Between Eye Fixations, Saccades and Performance

To relate eye gaze patterns with behavioral measures of task performance, partial correlations, controlling for participants' age, were run between averaged task accuracy/response times and averaged eye fixation times in Interest Areas and saccades between the Rules and Choices Interest Areas during the cue and delay periods across all six levels with *p*-values adjusted for multiple comparisons.

Results

Behavior: Accuracy and Response Time

Group Model

There was a significant main effect of Group (F(1, 101.01) = 62.98, $p < .001$) and a significant interaction effect of Group × Level (F(5, 1,105.29) = 31.45, $p < .001$) for accuracy (Table 2A). Post hoc pairwise comparisons of the two-way interaction effect revealed that children were less accurate than adults across all six levels, with the accuracy gap the largest on the most difficult levels (3 and 6; Figure 2A). There was also a significant main effect of group (F(1, 101.17) = 39.16, $p < .001$) for response time, but with no interaction of Level (Table 2B). Post hoc analysis demonstrated that children are generally slower than adults across all six levels, consistent with prior findings with a previous version of this task (Figure 2B, (Bauer et al., 2017)).

Switching. When examining the effect of Repeat versus Switch trials on task accuracy (Table 2A), there was a significant main effect of Rule Switching (F(1, 1,105.01) = 33.60, $p < .001$) and an interaction effect of Rule Switching × Group (F(1, 1,105.01) = 5.53, $p = .02$). Broken down by Adult versus Child groups, we found that the accuracy difference in Repeat versus Switch trials in adults was not significant (Repeat-Switch = 1.51%, $t = 2.45$, $p = .11$), whereas it was in children (Repeat-Switch = 3.57%, $t = 5.72$, $p < .001$). We did not find significant Rule Switching effects on response times, although the interaction effect of Rule Switching × Group was moderate but not significant (F(1, 1,105.48) = 3.75, $p = .05$; Table 2B).

Age Bin Model

The same models for accuracy and response time were rerun with the Group predictor replaced by Age Bins (8–10 years, 11–13 years, 14–16 years, and Adult). Statistical tests of predictors can be found in Tables S1 and S2. We found a significant main effect of Age Bin (F(3, 101.29) = 56.76, $p < .001$) and an interaction effect of Age Bin × Level (F(15, 1,105.82) = 21.54, $p < .001$) on accuracy (Table S1). Post hoc analysis showed that averaged across levels, 8- to 10-year-olds (8–10 years–adults = −22.82%, $t = -12.38$, $p < .001$) and 11- to 13-year-olds (11–13 years–adults = −12.25%, $t = -6.82$, $p < .001$) were significantly less accurate than adults, whereas 14- to 16-year-olds were not significantly different (14–16 years–adults = −4.66%, $t = -2.60$, $p = .15$; Figure 3A). Furthermore, all the Child Age Bins (8–10 years vs. 11–13 years vs. 14–16 years) were also all significantly different from one another (Figure 3A). When broken down by level, both 8- to 10-year-olds' and 11- to 13-year-olds' accuracy rates were significantly different from adults across all six levels, but 14- to 16-year-olds' accuracy rates were

Table 2
Significance Testing of the Predictors From the (A) Accuracy Group Model and (B) Response Time Group Model

	Sum Sq	Mean Sq	NumDF	DenDF	*F* value	*Pr*(> *F*)
(A)						
Rule switching	1,945	1,945	1	1,105.01	33.595	< .001***
Group	3,646	3,646.1	1	101.01	62.979	< .001***
Level	86,363	17,272.7	5	1,105.29	298.349	< .001***
Rule switching:group	320	320	1	1,105.01	5.528	.01889*
Rule switching:level	390	78	5	1,105.01	1.348	.24161*n.s.*
Group:level	9,392	1,878.4	5	1,105.29	32.445	< .001***
Rule switching:group:level	94	18.8	5	1,105.01	0.324	.8987*n.s.*
	Sum Sq	Mean Sq	NumDF	DenDF	*F* value	*Pr*(> *F*)
(B)						
Rule switching	13	13	1	1,105.4	0	.97014*n.s.*
Group	370,417	370,417	1	101.09	39.95	< .001***
Level	14,872,190	2,974,438	5	1,105.72	320.78	<.001***
Rule switching:group	34,814	34,814	1	1,105.48	3.75	.05292*n.s.*
Rule switching:level	8,215	1,643	5	1,105.48	0.18	.97117*n.s.*
Group:level	135,813	27,163	5	1,105.72	2.93	.01236*
Rule switching:group:level	31,156	6,231	5	1,105.48	0.67	.64475*n.s.*

n.s. $p > .05$.
*$p < .05$. **$p < .01$. ***$p < .001$.

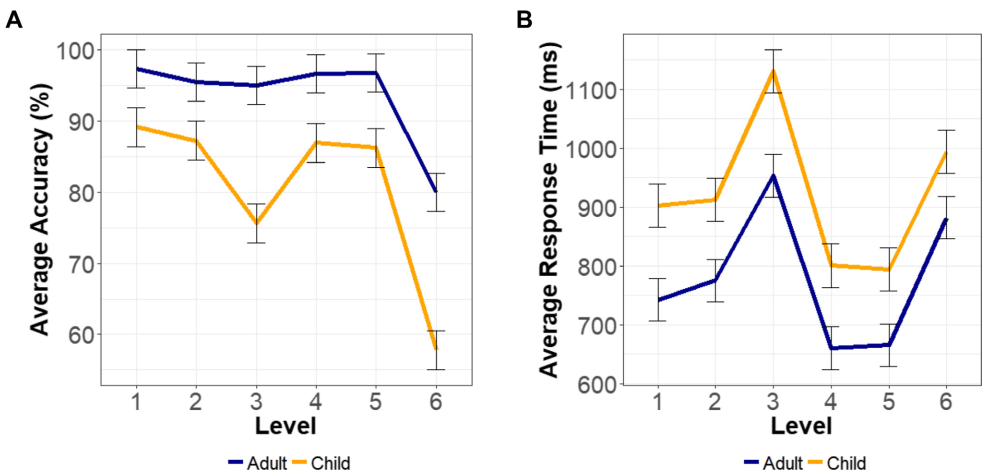


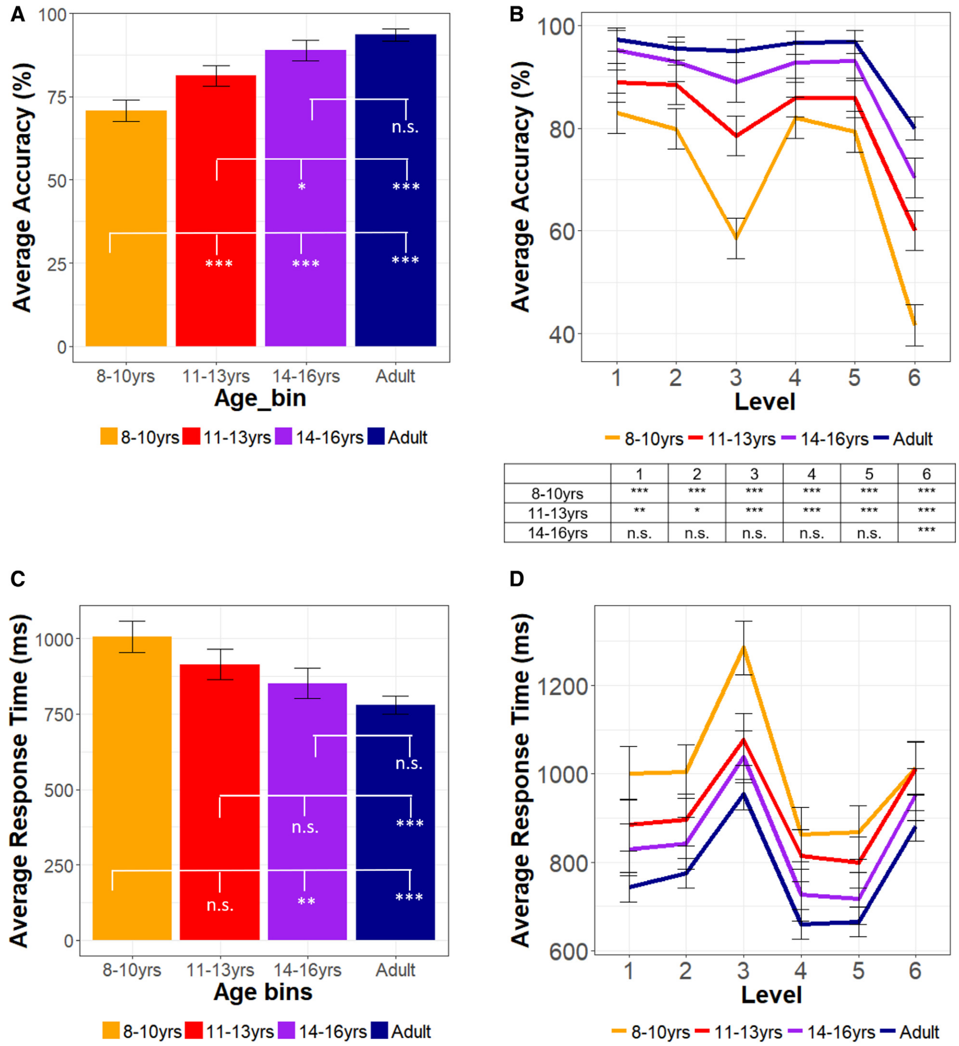
Figure 2. Estimated group child and adult mean (A) accuracy and (B) response time ±2 *SE* for each level. Post hoc contrasts revealed that children were significantly less accurate and slower to respond than adults on every level. All post hoc contrasts were corrected for multiple comparisons.
n.s. $p > .05$. *$p < .05$. **$p < .01$. ***$p < .001$. [Color figure can be viewed at wileyonlinelibrary.com]

not significantly different from adults' for the first five levels (Figure 3B). Overall, accuracy increased over age within the child group.

For response times (Table S2), we also found there was a significant main effect of Age Bin (F(3, 101.16) = 21.69, $p < .001$) and interaction effect of Age Bin × Level (F(15, 1,106.14) = 4.64, $p < .001$). Again, we found that 8- to 10-year-olds and 11- to 13-year-olds were significantly slower than adults (8–10 years–adult = 225.74 ms, $t = 7.55$, $p < .001$; 11–13 years–adult = 134.06 ms, $t = 4.60$; $p < .001$), whereas 14- to 16-year-olds were not (14–16 years–adult = 71.21 ms, $t = 2.44$, $p = .22$); this was true when averaged across the six levels (Figure 3C) and when looking at the levels individually (Figure 3D). Furthermore, while 8- to 10-year-olds' and 11- to 13-year-olds' response times were not significantly different from the next oldest Age bin (8–10 years–

11–13 years = 91.68 ms, $t = 2.52$, $p = .19$; 11–13 years–14–16 years = 62.85 ms, $t = 1.76$, $p = .67$), they were significantly different from the older Age Bins (e.g., 8–10 years–14–16 years = 154.53 ms, $t = 4.25$, $p = .001$; Figure 3C). These results suggested faster response times in older age groups compared to younger ages that is incremental in nature, and visually this appeared to be the case (Figure 3D).

Switching. We found only a trending interaction effect of Rule Switching × Age Bins on accuracy ($F(3, 1{,}105.16) = 2.46$, $p = .06$; Table S1), and no effect of Rule Switching × Age Bin for response times ($F(3, 1{,}105.68) = 1.43$, $p = .23$; Table S2).



	1	2	3	4	5	6
8-10yrs	***	***	***	***	***	***
11-13yrs	**	*	***	***	***	***
14-16yrs	n.s.	n.s.	n.s.	n.s.	n.s.	***

	1	2	3	4	5	6
8-10yrs	***	***	***	***	***	**
11-13yrs	**	**	**	***	**	**
14-16yrs	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Figure 3. (A) Accuracy rates averaged across the six levels ±2 *SE*s broken down by age bins. (B) Accuracy rates ±2 *SE*s for each of the six levels broken down by age bins. (C) Mean response times averaged across the six levels ±2 *SE*s broken down by age bins. (D) Estimated response times ±2 *SE*s for each of the six levels broken down by age bins. Due to the complexity of Levels 3 and 6 (i.e., 4 features and 4 response choices), accuracy rates were lower and response times were slower compared to other levels. Level 6 was the most difficult given the higher working memory demand, that is, choices were not present at the target presentation. The legend at the bottom of (B) and (D) indicates if each of the child age bins were significantly different from the adults at every level. All post hoc contrasts were corrected for multiple comparisons.
n.s. $p > .05$. *$p < .05$. **$p < .01$. ***$p < .001$.

Eye Tracking Results: Cue Period (0–1,500 ms)

Group Model

There were significant interaction effects of Interest Area × Group ($F(1, 38{,}628) = 904.76$, $p < .001$) and Interest Area × Group × Level ($F(5, 38{,}628) = 6.41$, $p < .001$; Table 3). Post hoc comparisons for the two-way interaction effect revealed that children spent more time fixating on the cued Rules Interest Area compared to adults (Adult–Child = −81.63 ms, $t = -11.44$, $p < .001$), whereas adults fixated more on the Choices Interest Area (Adult–Child = 90.67 ms, $t = 12.71$, $p < .001$). Post hoc contrasts for the three-way interaction indicated that child and Adult differences in gaze fixation patterns held across all six levels. Figure 4A,B demonstrates that both groups tended to fixate less on the Rules Interest Area and more on the Choices Interest Area over time as the levels proceed.

Switching. Examining trials in which the cued rule repeated versus switched, there was a significant two-way interaction of Interest Area × Rule Switching ($F(1, 38{,}628) = 82.22$, $p < .001$), but not a significant three-way interaction of Interest Area × Group × Rule Switching ($F(1, 38{,}628) = 0.01$, $p = .94$; Table 3). Post hoc contrasts revealed that individuals fixated more on the cued Rules Interest Area during Switch trials compared to Repeat trials (Repeat-Switch = −27.51 ms, $t = -6.77$, $p < .001$) and less on the Choices Interest Area (Repeat-Switch = 24.57 ms, $t = 6.05$, $p < .001$).

Age Model

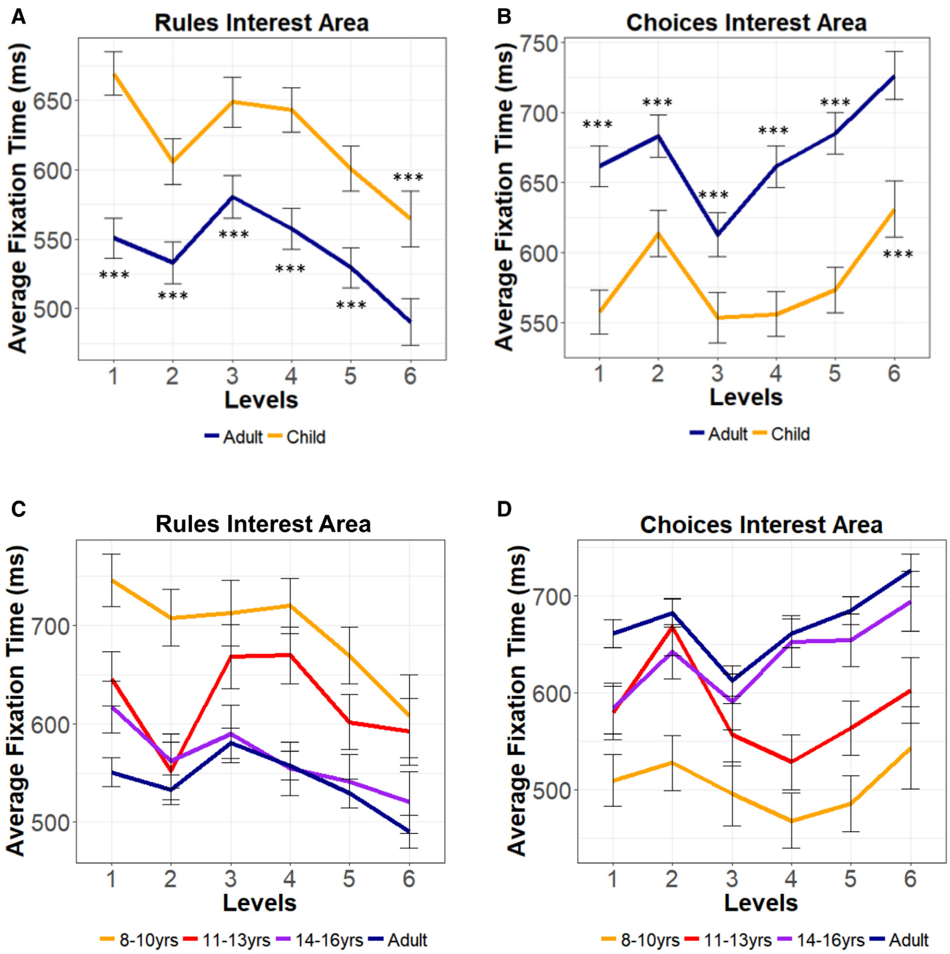
We tested the Age bin model for fixation times during the cue period (Table S7) and found a significant two-way interaction effect of Interest Area × Age Bin ($F(3, 38{,}541) = 489.41$, $p < .001$) and a three-way interaction of Interest Area × Age Bin × Level ($F(15, 38{,}541) = 8.75$, $p < .001$). Post hoc contrasts of the two-way interaction indicated that there was a significant difference between the younger child age bins (8–10 years and 11–13 years) and adults (8–10 years–adult = 153.63 ms, $t = 14.76$, $p < .001$; 11–13 years–adult = 81.32 ms, $t = 7.78$, $p < .001$), but no significant difference between 14- to 16-year-olds compared to adults (23.89 ms, $t = 2.34$, $p = .58$) in Rules Interest Area fixation time (Figure S1A). All child age bins, including 14- to 16-year-olds, fixated significantly less on the Choices Interest Area compared to adults (e.g., 8–10 years–adult = −166.53 ms, $t = -16.00$, $p < .001$; Figure S1A).

Furthermore, all child Age Bins were significantly different from each other with regard to Rules Interest Area fixation time (e.g., 11–13 years–14–16 years = 57.43 ms, $t = 4.47$, $p = .001$), and all Age Bins (including adults) were significantly different from one another with respect to Choices Interest Area fixation time (e.g., 11–13 years–14–16 years = −53.51 ms, $t = -4.16$, $p = .003$; Figure S1A). When broken down by levels, we found that although 8- to 10-year-olds

Table 3
Significance Testing of the Predictors From the Cue Period (0–1,500 ms) Group Model of Eye Fixations

	Sum Sq	Mean Sq	NumDF	DenDF	*F* value	*Pr*(> *F*)
Interest area	19,482,849	19,482,849	1	38,628	263.35	< .001***
Group	35,337	35,337	1	84	0.48	.4914*n.s.*
Rule switching	19,392	19,392	1	38,651	0.26	.60867*n.s.*
Level	872,622	174,524	5	38,734	2.36	.03773***
Interest area:group	66,935,391	66,935,391	1	38,628	904.76	< .001***
Interest area: rule switching	6,082,615	6,082,615	1	38,628	82.22	< .001***
Group:rule switching	182	182	1	38,649	0	.96043*n.s.*
Interest area:level	30,671,913	6,134,383	5	38,628	82.92	< .001***
Group:level	935,078	187,016	5	38,732	2.53	.02702***
Rule switching:level	140,819	28,164	5	38,657	0.38	.86234*n.s.*
Interest area:group:rule switching	441	441	1	38,628	0.01	.93843*n.s.*
Interest area:group:level	2,371,200	474,240	5	38,628	6.41	< .001***
Interest area:rulerep:level	5,263,160	1,052,632	5	38,628	14.23	< .001***

Note. Age bin model for the cue period is found in Table S7.
n.s. $p > .05$.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.



	1	2	3	4	5	6
8-10 yrs	***	***	***	***	***	***
11-13 yrs	***	n.s.	***	***	***	***
14-16 yrs	***	n.s.	n.s.	n.s.	n.s.	n.s.

	1	2	3	4	5	6
8-10 yrs	***	***	***	***	***	***
11-13 yrs	***	n.s.	n.s.	***	***	***
14-16 yrs	***	n.s.	n.s.	n.s.	n.s.	n.s.

Figure 4. Cue period (0–1,500 ms). Estimated average fixation times ±2 *SE*s on the (A) Rules and the (B) Choices Interest Areas during the cue period (0–1,500 ms) for each of the six levels for the Adult and Child groups. (C, D) are the estimated average fixation times for the (C) Rules and (D) Choices Interest Areas broken down by Age bins. Post hoc contrasts revealed that children, particularly the 8- to 10-year-olds, fixated more on the Rules and less on the Choices Interest Areas compared to adults during the cue period. The legend at the bottom of each graph (C, D) indicates if the Child Age bins were significantly different from the Adult Age bin at each level. All post hoc contrasts were corrected for multiple comparisons.
n.s. $p > .05$. *$p < .05$. **$p < .01$. ***$p < .001$.

were significantly different from adults across all six levels in Rules and Choices Interest Area fixation time, older child Age bins (i.e., 11–13 years and 14–16 years) were more variable (Figure 4C,D).

Switching. In examining Repeat versus Switch trials, we did not find a significant interaction of Interest Area × Age bins × Rule Switching (F(3, 38,541) = 0.10, p = .86; Table S7), indicating that differences in fixation patterns between Repeat and Switch trials did not vary by age.

Eye Tracking Results: Delay Period (1,500–2,000 ms)

Group Model

There was a significant interaction effect of Interest Area × Group (F(1, 41,041) = 984, p < .001) and Interest Area × Group × Level (F(5, 40,991) = 17, p < .001; Table 4). Post hoc contrasts of the two-way interaction of Interest Area × Group revealed that averaged across levels, children continued to spend more fixation time on the Rules Interest Area relative to adults (Adult-Child = −34.62 ms,

Table 4
Significance Testing of the Predictors From the Delay Period (1,500–2,000 ms) Group Model of Eye Fixations

	Sum Sq	Mean Sq	NumDF	DenDF	*F* value	*Pr*(> *F*)
Interest area	9.84E+08	9.84E+08	1	41,041	68,453	< 2e-16***
Group	27,648	27,648	1	106	2	.16837*ns*
Rule switching	35,233	35,233	1	41,005	2	.11743*ns*
Level	2,931,826	586,365	5	41,013	41	< 2e-16***
Interest area:group	14,139,656	14,139,656	1	41,041	984	< 2e-16***
Interest area:rule switching	1,898	1,898	1	40,983	0	.71633*ns*
Group:rule switching	633	633	1	41,005	0	.83381*ns*
Interest area:level	26,064,686	5,212,937	5	40,991	363	< 2e-16***
Group:level	142,548	28,510	5	41,013	2	.07762*ns*
Interest area:group:rule switching	1,309	1,309	1	40,983	0	.76279*ns*
Interest area:group:level	1,239,341	247,868	5	40,991	17	< 2e-16***

Note. Age bin model for the delay period is found in Table S8. Group and Age bin models for the target period are found in Table S11.
ns $p > .05$.
*$p < .05$. **$p < .01$. ***$p < .001$.

$t = -13.28$, $p < .001$), whereas, adults fixated more on the Choices Interest Area compared to children (Adult–Child = 41.15 ms, $t = 15.33$, $p < .001$). However, overall, adults and children fixated mostly on the Choices Interest Area compared to the Rules Interest Area. Adults on average spent 353.87 ms ($t = 220.02$, $p < .001$) more time fixating on the Choices Interest Area compared to the Rules Interest Area, whereas children fixated 228.10 ms ($t = 154.32$ ms, $p < .001$) more on the Choices Interest Area than the Rules Interest Area (out of 500 ms total).

Post hoc contrasts of the three-way interaction of Interest Area × Group × Level suggested that these fixation pattern differences between adults and children were consistent across all six levels, although generally, Rules Interest Area fixation time decreased, whereas Choices Interest Area fixation time increased as the levels increased (Figure 5A,B).

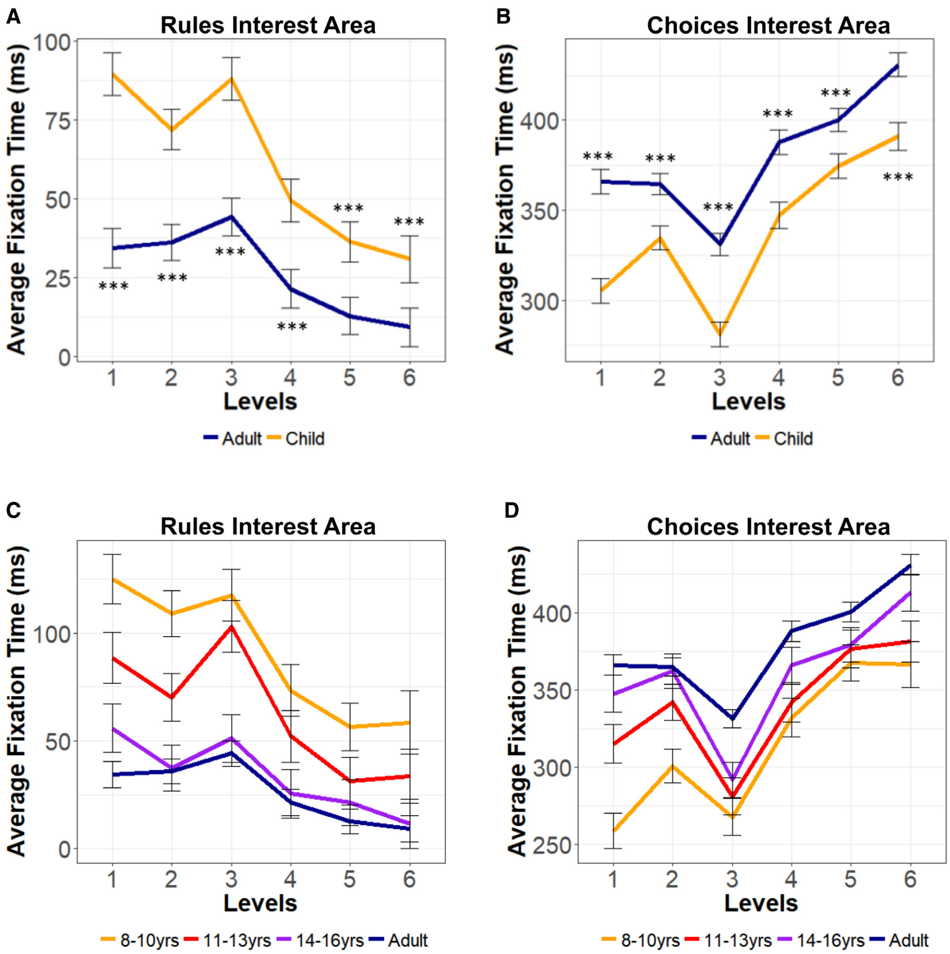
Age Bin Model

There were significant interaction effects of Interest Area × Age Bins ($F(3, 41{,}044) = 500$, $p < .001$) and Interest Area × Age Bins × Level ($F(15, 41{,}001) = 11$, $p < .001$; Table S8). Post hoc contrasts of the two-way interaction revealed that when averaging across levels, whereas the younger child Age Bins (8–10 years–adult = 63.66 ms, $t = 17.15$, $p < .001$; 11–13 years–adult = 36.84 ms, $t = 9.82$, $p < .001$) spent significantly longer looking at the Rules Interest Area relative to adults, 14- to 16-year-olds were not significantly different from adults (14–16 years–adult = 7.53 ms, $t = 2.06$, $p = .81$; Figure S1B). The child Age Bins were also significantly different from each other in Rules Interest Area fixation time. All three of the child Age Bins were significantly different from adults, as well as each other, for fixation times on the Choices Interest Area (e.g., 14–16 years–adult = −20.35 ms, $t = -5.41$, $p < .001$; Figure S1B).

Post hoc analysis of the three-way interaction further indicated that while 14- to 16-year-olds were not significantly different from adults in fixation time on the Rules and Choices Interest Areas during many levels (e.g., Level 5 or 6), they were significantly different in Choices Interest Area fixation at one of the hardest levels, Level 3. On the other hand, both the younger child groups (8–10 years old and 11–13 years old) were significantly different from adults in both Rules and Choices Interest Areas fixation time across all levels (Figure 5C,D).

Time Course Analysis

Consistent with our prior fixation dwell time analyses, our finer-grained time course analysis of Level 2 demonstrated that children, relative to adults, fixated more on the Rules Interest Area than the Choices during the time period before target onset. Primarily, the effect was driven by the youngest age group (8- to 10-year-olds) during the end of the cue period and the majority of the delay period (1,400–1,900 ms; Figure 6). This youngest age group's proportion of Rules:Choices fixation



	1	2	3	4	5	6
8-10 yrs	***	***	***	***	***	***
11-13 yrs	***	***	***	***	n.s.	*
14-16 yrs	*	n.s.	n.s.	n.s.	n.s.	n.s.

	1	2	3	4	5	6
8-10 yrs	***	***	***	***	***	***
11-13 yrs	***	*	***	***	*	***
14-16 yrs	n.s.	n.s.	***	n.s.	n.s.	n.s.

Figure 5. Delay period (1,5000–2,000 ms). Estimated average fixation times ±2 *SE*s on the (A) Rules and the (B) Choices Interest Areas during the delay period (1,500–2,000 ms) for each of the six levels for the adult and child groups. (C, D) are the estimated average fixation times for the (C) Rules and (D) Choices Interest Areas broken down by Age bins. Post hoc contrasts revealed that the trend of children, particularly the 8–10 years olds, fixating more on the Rules and less on the Choices Interest Areas compared to adults continues from the cue period into the delay period. The legend at the bottom of each graph (C, D) indicates if the Child Age bins were significantly different from the Adult Age bin at each level. All post hoc contrasts were corrected for multiple comparisons. Average fixation time for the target period is found in Figure S3.
ns $p > .05$. *$p < .05$. **$p < .01$. ***$p < .001$.

time is significantly different from adults during this cue-delay period. Less response choice fixation before target onset may have initiated a consistent lag in choice and target processing throughout the rest of the trial in children. This cascading effect possibly accounts for children's overall slower response times and lower accuracy. We directly tested the association between task performance, fixation patterns, and saccades in the following analyses.

Relationship Between Task Performance and Fixation Patterns During Cue and Delay periods

After controlling for the effect of age, increased fixation times in the Choices interest area ($r = .28$, $p = .03$) during the cue period were related to increased task-switching accuracy, but not response times (Figure S3).

The association between fixation patterns and task performance were more notable during the delay

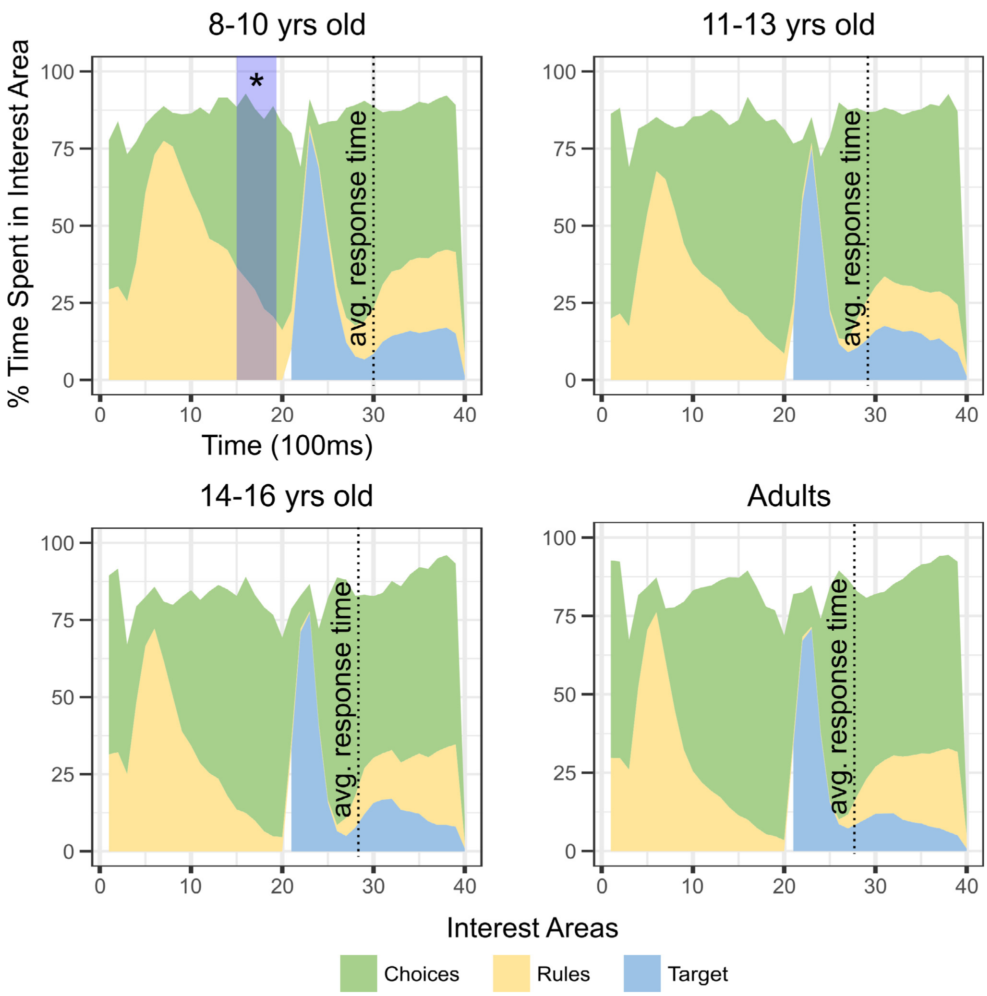


Figure 6. Proportion of time spent fixating on each Interest Area for Child age bins and adults during Level 2. The time course is divided up into 100 ms time bins. The average response time for each age bin is indicated by the dotted line. The average 8- to 10-year old response time (RT) is after 3,000 ms; 11- to 13-year old is after 2,900 ms; 14- to 16-year old is after 2,800 ms; and Adult RT is after 2,700 ms. The time spent in the three Interest Areas does not total 100% because of portions of time spent outside the Interest Areas or completing saccades. We tested for significant differences in the ratio of time spent on the Choices versus Rules Interest Areas between the Child age bins and the adults during the cue and delay periods. Indicated time bins in purple reflect a significant difference from adults (1,400–1,900 ms; *$p < .05$, corrected for multiple comparisons).

period, as suggested by the prior time course analysis. Partial correlations, controlling for age, between fixation times and accuracy/response time for the delay period are shown in Figure 7. We found that decreased fixation on Rules ($r = .71$, $p < .001$) and increased fixation on Choices ($r = .56$, $p < .001$) were associated with greater task-switching accuracy. Similarly, decreased fixation on Rules was related to faster response times ($r = .36$, $p < .001$).

Saccades During Cue and Delay Periods: Association Between Saccades and Task Performance

While child participants fixated longer on the Rules Interest Area during both the cue and delay periods, relative to adults, we also wanted to see if children differed in the number of saccades between interest periods in those times. During the cue period, children and adults did not significantly differ in their eye movements between the Rules and Choices Interest Areas (Figure 8A). During the delay period, children made significantly more average saccades between the Rules and Choices than adults ($t = -5.65$, $p < .001$; Figure 8B).

In order to test if saccades were also associated with task performance, we ran partial correlations between the average number of saccades between the Rules and Choices and accuracy/response time. After controlling for the effect of age, we found that more saccades were associated with poorer

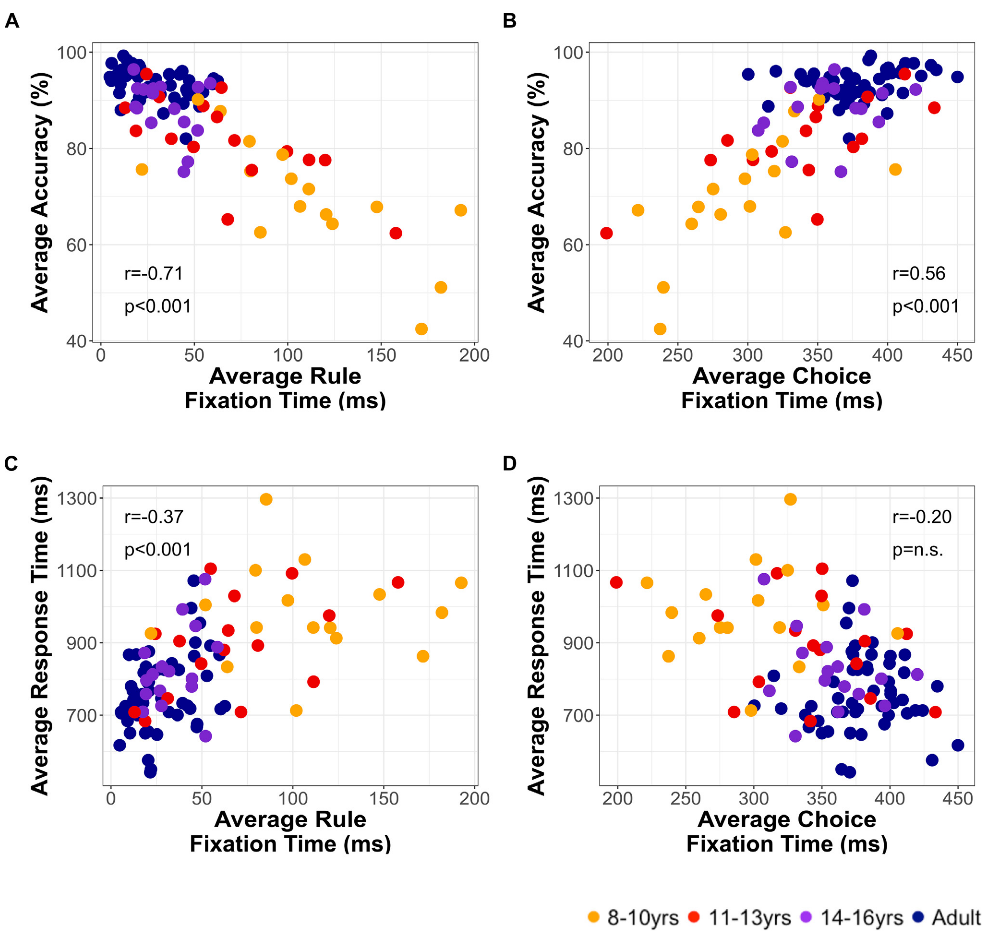


Figure 7. Delay period (1,5000–2,000 ms). Partial correlations, controlling for participants' age, between average accuracy and average (A) Rules and (B) Choices fixation time; average response time and average (C) Rules and (D) Choices fixation times. The partial correlation strength *r* and its corresponding *p*-value (with the effect of age partialed out) are indicated on each figure. Correlations for the cue period are shown in Figure S4.

accuracy ($r = -.54$, $p < .001$) and slower response times ($r = .45$, $p < .001$; Figure 9A,B). Furthermore, saccades between Rules and Choices during the delay period were also associated with an initial suboptimal fixation pattern during the cue period—namely, greater fixation on the Rules during the cue period related to more saccades during the delay period between Rules and Choices (r= .36, p = .01; Figure 9C,D). On the other hand, greater fixation on the Choices during the cue period related to fewer saccades during the delay ($r = -.44$, $p < .001$; Figure 9C,D).

Discussion

We used eye-tracking to gain insight into how child cued-switching performance lags behind adults at a finer temporal grain than either behavior or fMRI could provide. In particular, we used eye tracking as a proximal measure of visual attention during key aspects of the trial that do not have a behavioral response (i.e., the cue and delay periods). We found evidence that children differ from adults from the very beginning of a trial, spending more time fixating on the cued rule, rather than on response choices. This early processing difference related to more frequent later saccades between rule and response choices, and subsequent poorer behavioral performance.

Children Were Most Different From Adults During Rule Processing

Throughout all six levels of cued task switching, children were less accurate and slower to respond than our adult group, replicating our previous work (Bauer et al., 2017). Across the cue period (0–1,500 ms), our child group fixated more on the rules, and less on the response choices, than young adults.

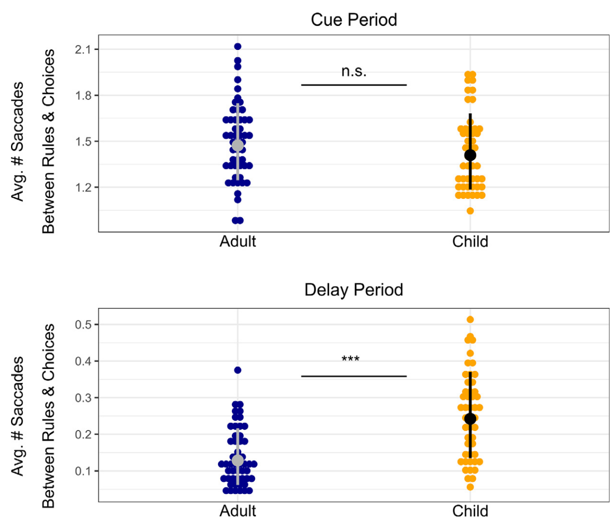


Figure 8. Average number of saccades between the Rules and Choices Interest Areas during the (A) cue and (B) delay periods. *t*-tests for differences between adults and children in the number of saccades made are indicated by ***$p < .001$; *nsp* > .05. [Color figure can be viewed at wileyonlinelibrary.com]

The greater fixations on the cued rule persisted across six levels of experience with the task (310 total trials), indicating that this fixation pattern was not a temporary lack-of-familiarity effect in children. In fact, the gap between child and adult fixation patterns remained relatively constant across all six levels. Our main result is consistent with another developmental eye tracking study of task switching (Chevalier, Blaye, Dufau, & Lucenet, 2010), which found that much younger children also fixated more on the cued dimension rather than the response choices in a similar but simpler task. However, in that study, the response options remained the same throughout the task; perhaps the increased rule processing was due to the low need to focus on response choices in that case. Here, we show that developmental gaze stickiness on the rule persisted throughout the cue and delay periods in older children for a far more complex task. This pattern held despite the response choices changing for each trial, which ought to have served as competition for visual attention.

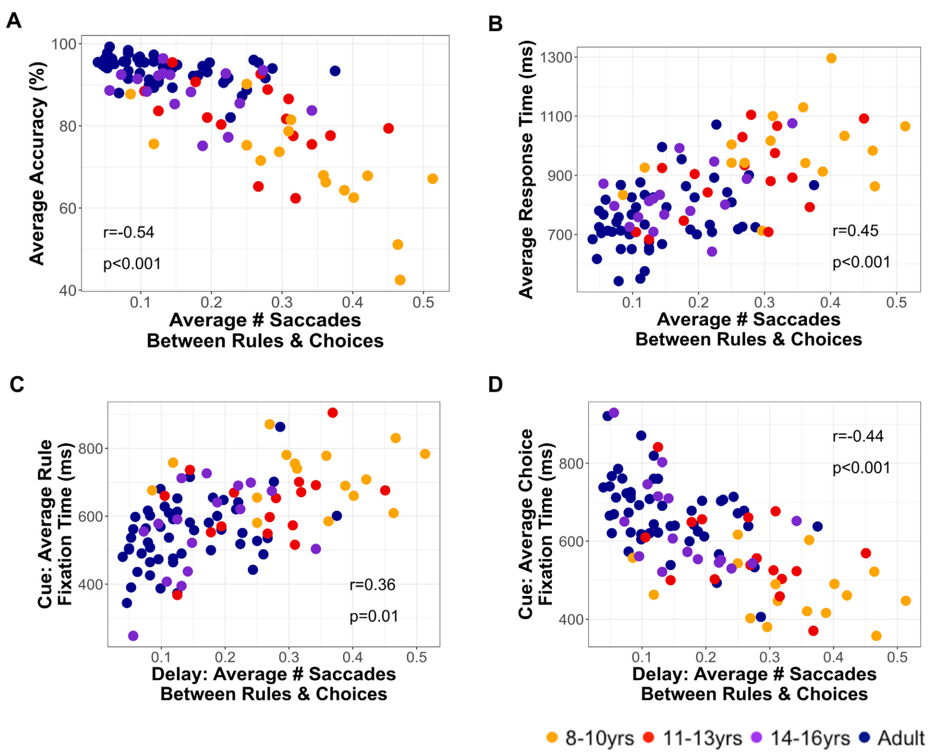


Figure 9. Delay period (1,5000–2,000 ms). Partial correlations, controlling for age, between the average number of saccades between the Rules and Choices Interest Areas and (A) accuracy, (B) response time, (C) average cue period fixation on the Rules and (D) average cue period fixation on the Choices across the six levels. Individuals who made more saccades between Rules and Choices Interest Areas during the delay period had poorer performance, and there was a correlation between the number of saccades in the delay period and time spent fixating in the Rules or Choices Interest Areas during the cue period.

Our results lend evidence toward a lack of preparatory control and efficient rule processing in children, relative to young adults, even in a task where greater fixation on response choices strongly correlated with better behavioral outcomes. This developmental difference in eye fixations (and by proxy, attention) perhaps accounts for the relatively robust performance decrement observed across versions of cued task switching in children and young adolescents relative to young adults (Bauer et al., 2017; Church et al., 2017).

The greater fixation times on the rules during the cue and delay periods could reflect two different processes. First, rule fixation could relate to slower loading of task-set parameters during the trial: the children could quickly understand the rule, but could be slow to load or apply the relevant attention processes for that rule. Second, children could be slow at interpreting what rule the star symbol represents (decoding or memory difficulty). Two pieces of evidence lead us to believe that loading of rule processes, rather than rule interpretation, may be more likely. First, similar performance gaps and age effects were seen in a related cued task-switching design using a lexical (word) cue that did not require translation like our current symbolic cue (Church et al., 2017). Second, practice with the task, and high levels of accuracy did not diminish the finding of increased fixations on the rule observed in children. Despite six different exposures to the task, this relatively greater time commitment on rule fixation seen in children relative to adults did not decrease over time, even though total fixation time declined for both groups overall with practice.

Certainly, other studies have found that cue processing difficulties account for part of the task-switching effects in both adults and children (Holt & Deák, 2015; Schneider & Logan, 2007). Cue transparency or the rule decoding aspect has also been studied by others with evidence toward decoding playing a role in children's performance as well (Chevalier & Blaye, 2009; Chevalier, Huber, Wiebe, & Andrews, 2013). Future research could directly test whether other cue formats (e.g., auditory, or multiple modality) in older child and adolescent samples could speed rule processing via easier decoding, or whether there is a continued lag in rule processing in children related to rule implementation.

Children's Task-Switching Performance Improves With Age

We do see substantial age-related improvements in our tested age range, such that by age 14 years, children are more adult-like in both behavior and eye movements. The 14- to 16-year-old group was not significantly different from adults in their accuracy across the first five levels and in their response times across all six levels. This result was largely consistent with what has been found behaviorally with versions of this task—that adult-like performance is seen around age 14 years (Bauer et al., 2017; Martinez et al., 2018). It is intriguing to speculate, however, that ages 11–13 years may be in a transitional period where fixation patterns begin to change prior to behavioral performance; 11- to 13-year-olds for some task levels (e.g., Level 2 during the cue period) had equivalent fixation times to adults. Thus, there are some tentative signs that eye movement pattern maturation may slightly precede endpoint decision-making maturation. Overall, however, across the three trial epochs, we largely find that eye gaze patterns change in step with changes in traditional behavioral measures of response times and accuracy, rather than preceding them, at least at the age resolution of our sample.

Children's Eye Gaze Behavior is Consistent With Lower Preparatory Control Engagement

Our time course analysis and fixation data support the finding of children being delayed in rule processing relative to older adolescents and adults. This result is consistent with and extends previous fMRI results that found decreased activity in control-related brain regions during the cue period in children relative to adults (Church et al., 2017). Longer visual attention on the rule itself may sufficiently delay loading of response options and other possible task operations that would allow for greater preparatory control engagement. Future studies could combine eye tracking with imaging to see if individuals who have particularly long rule fixation times are those with the least amount of cue-related brain control network activity. Our result is also consistent with other proactive and reactive control research and provides a possible explanation for why children rely on a more reactive strategy in these task paradigms (Blackwell, 2014; Chevalier et al., 2018; Munakata et al., 2012).

Fixation and Saccades Were Linked to Behavioral Outcomes

The eye fixation patterns we observed seem strongly linked to behavioral outcomes. Fixation on the rule and response options before target onset was strongly and inversely correlated with behavioral performance, even after accounting for the influence of age. Longer Rule fixation during the delay period predicted slower response and lower accuracy. Furthermore, fewer saccades between the rules and choices during the delay period were also associated with more choice fixation during the cue period, and greater accuracy and faster response time.

Working memory acts to support cued task switching (and cognitive flexibility) as the task requires flexible updating and maintenance of rules and stimulus properties and other task-relevant information on a trial-by-trial basis (Amso, Haas, Mcshane, & Badre, 2014; Blackwell et al., 2009; Blackwell & Munakata, 2014). Our saccade results during the delay period suggest that children were struggling to maintain the cued rule in working memory in addition to taking longer at the rule processing stage during the cue and delay periods. Interestingly, while confounded with task order, increasing working memory load at the target epoch in Levels 4–6 did not have a strong influence on eye gaze patterns. This is possibly consistent with Zelazo and colleagues' work in younger children (Zelazo et al., 2003) and across the life span (Zelazo, Craik, & Booth, 2004), which found switch costs could not be attributed to memory capacity limitations alone. We believe our work highlights the impact of difficulty engaging control and working memory processes in the early epochs (cue, delay) of the compound trial, (which were constant across levels) relative to the manipulation of the target epoch in Levels 4–6. Our results are consistent with the supposition that stronger rule representation allows for greater preparatory control, and that this interaction of working memory and cognitive flexibility matures over development (e.g., Blackwell & Munakata, 2014; Cepeda & Munakata, 2007).

As a whole, these results indicate that the level to which a child's eye fixations favored the adult pattern (less time spent on rule fixation, more time spent on choice fixation, fewer saccades during the delay period), the better they performed on the task. As a group, eye patterns and cued task-switching behavior were consistent with the adult pattern around mid-adolescence.

Limitations and Future Directions

Our experiment looked only at undiagnosed children with low clinical burden—future eye tracking work in different developmental diagnoses could provide a sensitive way for detecting differences in cognitive flexibility and rule processing. Deficits in EFs are often present in many neurodevelopmental disorders, such as attention deficit hyperactivity disorder or Autism Spectrum Disorder (Corbett, Constantine, Hendren, Rocke, & Ozonoff, 2009; Hill, 2004). Eye tracking may provide a more sensitive, reliable measure of cognitive flexibility deficits than overt behavioral measures that have thus far yielded inconsistent conclusions.

In addition, while this study broke down our child group into sub-group bins based on chronological age, these groups were small and did not account for pubertal differences. Thus, our study provides only broad markers toward potential differences between middle childhood and middle adolescence in eye fixations during cued task switching. Future work can investigate if pubertal status, rather than chronological age, is a more effective predictor of this transition from child-like to adult-like eye movement patterns in a cued task-switching paradigm. Being able to disentangle the effects of chronological age versus pubertal status during adolescence when EFs are maturing will be important in understanding the mechanisms underlying (a)typical development, as well as the opportunities for developmental trajectories to be altered during this critical developmental stage (Blakemore, Burnett, & Dahl, 2010; Sisk & Foster, 2004).

While this study generates many additional questions, it adds to the sparse eye tracking literature regarding the development of cognitive flexibility as measured by cued task switching. We provide additional insights into previous reports of less proactive, preparatory control in children and differences in cognitive flexibility performance over development.

Conclusions

Eye tracking has revealed that children may be more likely to show less preparatory control processing during cued task switching due to prolonged visual attention on rule processing. Eye fixation differences from the very beginning of the trial set children up for a delay in processing relative to adults that culminates in more numerous late saccades, slower response times and lower accuracy rates. Eye movements become consistently more adult-like over adolescence, in line with more similar behavioral performance on the task, suggesting that abstract rule processing also matures in that time frame, allowing more effective, preparatory control processing and greater cognitive flexibility.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Supplemental Analyses