

## Proactive control in early and middle childhood: An ERP study

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### ABSTRACT

Children experience important cognitive control improvements in the transition to school. This study examined 4–5-year-olds' ( $n = 17$ ) and 7–8-year-olds' ( $n = 22$ ) ability to proactively deploy cognitive control. Children performed a cued task-switching paradigm presenting them with a cue indicating which attribute, color or shape, they should use to sort the upcoming stimulus. Following both cue and stimulus, we analyzed two event-related potentials: the P2 and P3, positive peaks reflecting sensory and attentional components of cognitive control, respectively. Following the cue, we also analyzed a positive slow-wave, indexing working memory engagement. We predicted that on switch trials, which required switching tasks, proactive control would result in larger cue-P3 amplitudes, reflecting recognition of the need to switch, and larger slow-wave amplitudes, reflecting maintenance of the new task-sets over the post-cue delay. This pattern was observed in both age groups. At the stimulus, in switch trials, both age groups had shorter stimulus-P2 latencies, consistent with processing facilitation. These results suggest that both 4–5- and 7–8-year-olds engaged cognitive control proactively. Older children, however, demonstrated better performance and larger cue-P2 amplitudes, suggesting more effective proactive control engagement in middle childhood.

Set-shifting is the ability to flexibly switch between modes of behavior. As children transition to school, their ability to set-shift is increasingly required. In some situations, children can use environmental cues to anticipate the need to switch modes, for example to use their “indoor” rather than “outdoor” voices. In this study, we used event-related potentials (ERPs) to investigate how children of different ages use cue information to recruit cognitive control in set-shifting.

Braver's Dual Mechanisms of Control model has been used to frame cognitive control development (Braver, 2012; Braver et al., 2007). Preschool children (3-year-olds) are limited to reactive control (Chatham et al., 2009). School-age children transition from using proactive control only when required (5-year-olds) to using proactive control reliably whenever possible (8 years and up; Chatham et al., 2009; Chevalier et al., 2015). In adults both kinds of cognitive control engagement depend on the prefrontal cortex (Braver et al., 2007; Stuphorn and Emeric, 2012), which develops rapidly in childhood (Huttenlocher and Dabholkar, 1997), so developmental differences in proactive control are unsurprising.

Cued task-switching paradigms are ideal for examining proactive control. In these paradigms, participants sort stimuli on multiple dimensions, often color and shape (Chevalier et al., 2015; Zelazo, 2006). Participants are presented with a cue indicating the task rule (e.g., sort by color) and a stimulus that could be sorted by either rule. When cue and stimulus are presented simultaneously, only reactive

control is possible, but when they are temporally separated, proactive control is required (Chevalier et al., 2015). In the latter configuration, proactive control affects ERPs at both phases of a trial, due to increased processing load at the cue and reduced cognitive demands at the stimulus.

ERPs following the cue provide the most direct indication of proactive control processes. There is some evidence that the cue-P2 is sensitive to task-switching requirements, but results are mixed (Finke et al., 2012; Kieffaber and Hetrick, 2005). There are more consistent findings regarding the cue-P3, which is attributed to updating stimulus and response sets (Barceló et al., 2002; Jost et al., 2008). The P3 is generated in the period between stimulus perception and response selection, linking perception and action (Kok, 2001; Verleger et al., 2005). P3 amplitude is associated with many processes, including context updating (Donchin, 1981), attentional engagement (Isreal et al., 1980; Kok, 2001), stimulus habituation (Polich, 1989), and recognition of familiar stimuli (McEvoy et al., 2001). P3 latency is proportional to the speed of stimulus classification and attentional allocation (Houlihan et al., 1998; Kutas et al., 1977) and is slowed by response conflict (McCarthy and Donchin, 1981). P3 latency decreases across childhood (Polich et al., 1990). In cued task-switching, the cue-P3 has larger amplitudes in switch trials (when the task changes) than in stay trials (when the task is repeated; Barceló et al., 2006; Jost et al., 2008). In development, cue-P3 amplitudes are sensitive to cognitive

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control modes: 10-year-olds show larger cue-P3 amplitudes when engaging with cues proactively (Chevalier et al., 2015).

When cue and stimulus are temporally separated, cue information must be maintained over a delay, resulting in a sustained slow-wave positivity (cue slow-wave; Manzi et al., 2011). The cue slow-wave is larger in switch trials than stay trials in adults (Astle et al., 2008; Nicholson et al., 2006) and the magnitude of this difference is associated with switching success (Lavric et al., 2008). Although the cue slow-wave is present in 9-10-year-old children, Manzi et al. (2011) found it was insensitive to task-switching.

Fewer studies have examined ERPs to the stimulus, but these are also informative about proactive control. If task-set reconfiguration was engaged proactively, stimulus processing should be less demanding. Both the stimulus-P2 (Kieffaber and Hetrick, 2005) and the stimulus-P3 are smaller in switch trials than stay trials (Gajewski and Falkenstein, 2011; Ikeda and Hasegawa, 2012).

The goal of the present study was to examine age differences in children's proactive control using ERPs with a cued task-switching paradigm. We tested children in two age groups (Early Childhood: 4- and 5-year-olds; Middle Childhood: 7- and 8-year-olds). These age groups border the transition to school, when children must increasingly deploy the proactive control demanded by classrooms (Hughes et al., 2010).

Previous studies examining age differences in proactive control have used a wider age span than we did (Chatham et al., 2009; Chevalier et al., 2015). By using age groups that more closely bracket the transition towards the reliable use of proactive control, we expected quantitative rather than qualitative differences. Because the cue-P2 has been associated with switch-unspecific processes (Adrover-Roig and Barceló, 2010), we did not expect the cue-P2 to demonstrate switch-stay differences. We expected the cue-P2 to describe general age differences in stimulus processing, with older children having larger cue-P2 amplitudes than younger children. We expected the Middle Childhood group to use a proactive strategy reliably, resulting in larger cue-P3 amplitudes on switch trials. In contrast, we expected that the Early Childhood group would engage fewer processes proactively, resulting in smaller differences between switch and stay trials at cue presentation, shorter cue-P2 and -P3 latencies, longer response times, lower accuracy performance, and more perseverative errors than the Middle Childhood group. If children were able to hold cue information in mind over the cue-stimulus interval, we expected them to demonstrate a cue slow-wave, which would be larger in switch trials than in stay trials, reflecting switch-related working memory processes, and larger in the Middle Childhood group than in the Early Childhood group, reflecting greater working memory engagement. Upon stimulus presentation, we expected that the Middle Childhood group, having engaged with the cue more deeply, would show facilitation of stimulus processing, resulting in smaller amplitude and shorter latency stimulus-P2s and -P3s on switch trials.

## 1. Methods

### 1.1. Participants

The sample included 39 children in two age groups: 17 in the Early Childhood group (9 girls;  $M = 5$  years 4 months; range: 4;8–5;11) and 22 in the Middle Childhood group (11 girls;  $M = 7$  years 6 months; range: 7;0–8;6). Participants were recruited through fliers and online advertising. Exclusionary criteria included low birth weight ( $< 2500$  g), preterm birth ( $< 37$  weeks gestation), and diagnosed neurological or psychiatric conditions. Children were from middle- to upper-middle class backgrounds: Parents reported a median of 16 years of education and median annual family income of \$100,000. The sample was ethnically diverse, with 51% of parents reporting their child's ethnicity as European-Canadian. Children had an average IQ of 112, based on the Peabody Picture Vocabulary Test (PPVT; Dunn and Dunn, 2007). IQ data from 1 participant was missing

due to technical difficulties. Twenty-one additional children visited the lab but their data was excluded due to excessive artifact in the EEG data ( $n = 6$ ), refusal of the EEG net ( $n = 5$ ), technical difficulties ( $n = 4$ ), refusal to perform the task ( $n = 3$ ), or early task discontinuation ( $n = 3$ ). The IQs of children whose data were excluded did not differ from those included in the final sample ( $t(50) = 0.26, p = .92$ ).

### 1.2. Procedure

Procedures were approved by the university Human Research Ethics Board. Children and parents came to the lab for a single 2-h session. After study procedures were explained, parents provided written informed consent and children provided verbal assent. During the session, children participated in four tasks in the following order: a working memory task, the Ocean Sort set-shifting task, an emotion regulation task, and the PPVT. The working memory and emotion regulation tasks were unrelated to the present study. Parents filled out questionnaires while their child participated. Child participants received a toy or book and parents received a gift card.

#### 1.2.1. Tasks

**1.2.1.1. Peabody picture vocabulary test (PPVT-4).** This standardized test measures receptive vocabulary, and a computerized version was used to provide an estimate of general intelligence (Dunn and Dunn, 2007). On each trial, children were presented with an array of four images and were asked to point to the image representing a given vocabulary word. The PPVT-4 has been normed with a large, representative sample of American children and adults and has demonstrated validity and high internal consistency ( $\alpha = .94$ ; Dunn and Dunn, 2008).

**1.2.1.2. Ocean sort task.** Children completed a cued task-switching paradigm (Fig. 1) while their electroencephalogram (EEG) was recorded. The task was performed in a soundproofed, electrically shielded room and a research assistant stayed with the child. The task was presented using E-prime 2.0.8.74 (Psychological Software Tools, Pittsburgh, PA) on a Dell 20-inch LCD monitor (43.5 cm by 31 cm) with a 60 Hz refresh rate and equipped with a Magic Touch touchscreen adapter. Children sat approximately 42 cm away from the monitor. Cues and stimuli were approximately 5 cm by 5 cm.

Children were told that Mrs. Crab's class was doing an art project and two of her students needed help sorting seashells and starfish: Daisy Dolphin was interested in shape and Ollie Octopus was interested in color. Each trial began with a ready screen, indicating that children could initiate the trial by pressing and holding the rightmost and leftmost buttons on a four-button EGI response pad. Following a 250 ms delay, a cue appeared, signaling which task children should perform on the upcoming trial, along with four response buttons along the periphery of the display. The cue was either a plain grey dolphin (shape) or a colorful octopus (color). Response options were purple and green paint swatches (color), and grey seashells and starfish (shape). We chose to use univalent (e.g., purple for color, starfish for shape) rather than bivalent (e.g., purple starfish) response options to differentiate perseverative errors, where children respond to the incorrect stimulus attribute, from random errors. Response locations were counterbalanced between participants in four conditions, with the constraint that both response options for a single task were on the same side. This meant that after cue presentation, children could anticipate the upcoming response side and orient their attention accordingly. The cue was displayed for 1000 ms, followed by a fixation cross for a random interval between 400 and 600 ms. The response options remained on the screen over this delay. Next, the stimulus was presented, a green or purple seashell or starfish. Children responded according to the cue within 3000 ms by pressing one of the on-screen response buttons, using their left hand for the left side and their right hand for the right side. Feedback was provided by a happy crab image

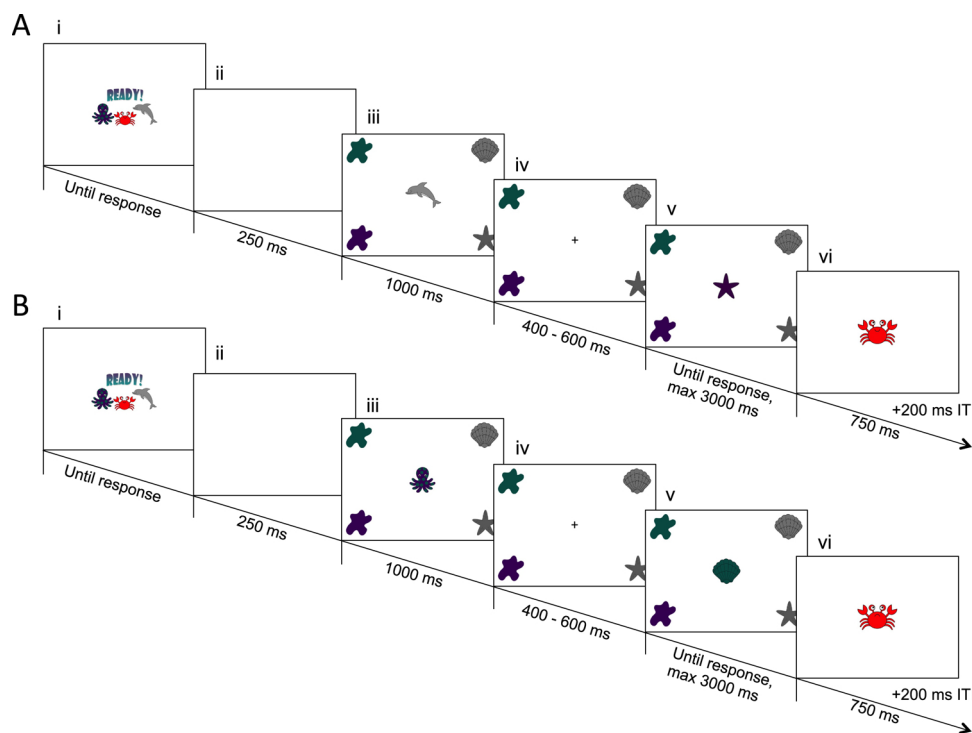


Fig. 1. Schematic depicting a correct shape trial (A) and an incorrect color trial (B). i) Ready screen, terminates when participants press and hold the left-most and right-most buttons on a four-button response pad. ii) A short delay. iii) Task cue and response options. iv) Cue-stimulus interval. v) Stimulus. vi) Visual and auditory feedback contingent on response accuracy.

and a pleasant bubbling sound for correct responses, or a sad crab image with a cartoonish “uh-oh” sound for incorrect responses. Feedback was displayed for 750 ms followed by a 200 ms intertrial interval with a blank screen.

The task began with a training phase where children were familiarized with the cues, stimuli, and sequence of events within each trial. Children completed a practice block including 8–48 trials, terminating after the child correctly completed six consecutive trials or achieved 75% accuracy. The test phase included five blocks of 31 trials, separated by short breaks when children received a sticker. The first trial of each block was discarded from analysis; of the remaining trials, two-thirds were stay trials (100 trials), where children completed the same task as in the previous trial, and the remaining third were switch trials (50 trials), where children completed the other task. Trials were presented in the same pseudo-random order across participants, constrained such that all stimuli and cues were presented with equal frequency, the same stimulus was not presented on two consecutive trials, and two switch trials were never presented consecutively.

Dependent measures included RT, accuracy, and perseverative error rate. Trials with RTs shorter than 200 ms were excluded. Trials occurring after an error were excluded because the switch-stay distinction was only valid following accurate trials. Perseverative errors were responses that matched the incorrect stimulus attribute. Perseverative error rate was the number of perseverative errors over the number of valid trials. For RT analyses, only correct trials were considered, and RTs greater than three standard deviations above the mean were trimmed.

### 1.2.2. Electroencephalography

EEG was recorded using NetStation 4.4.2 (EGI Software, Eugene, OR), an EGI NetAmps 300 amplifier with a 24-bit analog-to-digital converter, and a 128-channel HydroCel Geodesic sensor net. Impedances were maintained below 50 k $\Omega$ . Data was sampled at 250 Hz and referenced to the vertex. Recordings lasted an average of 20 min.

EEG analyses were conducted using EEGLab (Delorme and Makeig, 2004) in MATLAB (The Mathworks Inc., Natick, MA, 2013). A 0.1–30 Hz bandpass filter was applied. Event latencies were adjusted to account for a 7 ms presentation delay and a 36 ms delay introduced by the amplifier, and epochs were generated by segmenting the interval 200 ms before and 3600 ms after the cue event, encompassing the presentation of the cue and stimulus. Movement and eye-blink artifact was cleaned from the data. First, bad channels and epochs were rejected by visual inspection. An average of 9 channels ( $SE = 0.7$ , range: 2–23) were removed per participant. Channels with high amplitude ( $> 100 \mu V$ ), that deviated greatly from their neighbors, or that contained substantial oscillatory noise were removed. Second, independent components analysis (ICA) was applied to remove noise attributable to eye, muscle, and line-noise artifacts (Jung et al., 2000). Reliable ICA components that were computed across ICA calculations on the full dataset and two half-datasets were determined using the method described by Groppe et al., 2009. These reliable components were visually inspected and removed from the dataset. Third, removed channels were spherically interpolated, and the data were re-referenced to the average of all channels.

Epochs were divided into two, the first encompassing cue processing, extending from 200 ms before the cue to 1400 ms after the cue, and the second encompassing stimulus processing, extending from 200 ms before to 1400 ms after the stimulus. Epochs were baseline corrected using their respective 200 ms pre-event baselines. Epochs containing blinks, uneven baselines, or excessive noise were removed based on visual inspection. Finally, average waveforms were computed for each condition and participant, and data were extracted from MATLAB. An average of 36 ( $SD = 5.9$ ) stay trials and 16 ( $SD = 3.6$ ) switch trials contributed to cue average ERPs, and an average of 36 ( $SD = 6.3$ ) stay trials and 17 ( $SD = 3.2$ ) switch trials contributed to stimulus average ERPs. The number of epochs contributing to the subject averages did not significantly differ between the age groups or tasks for either the cue or the stimulus ( $p > .05$ ).

ERPs were analyzed during cue and stimulus epochs, at seven

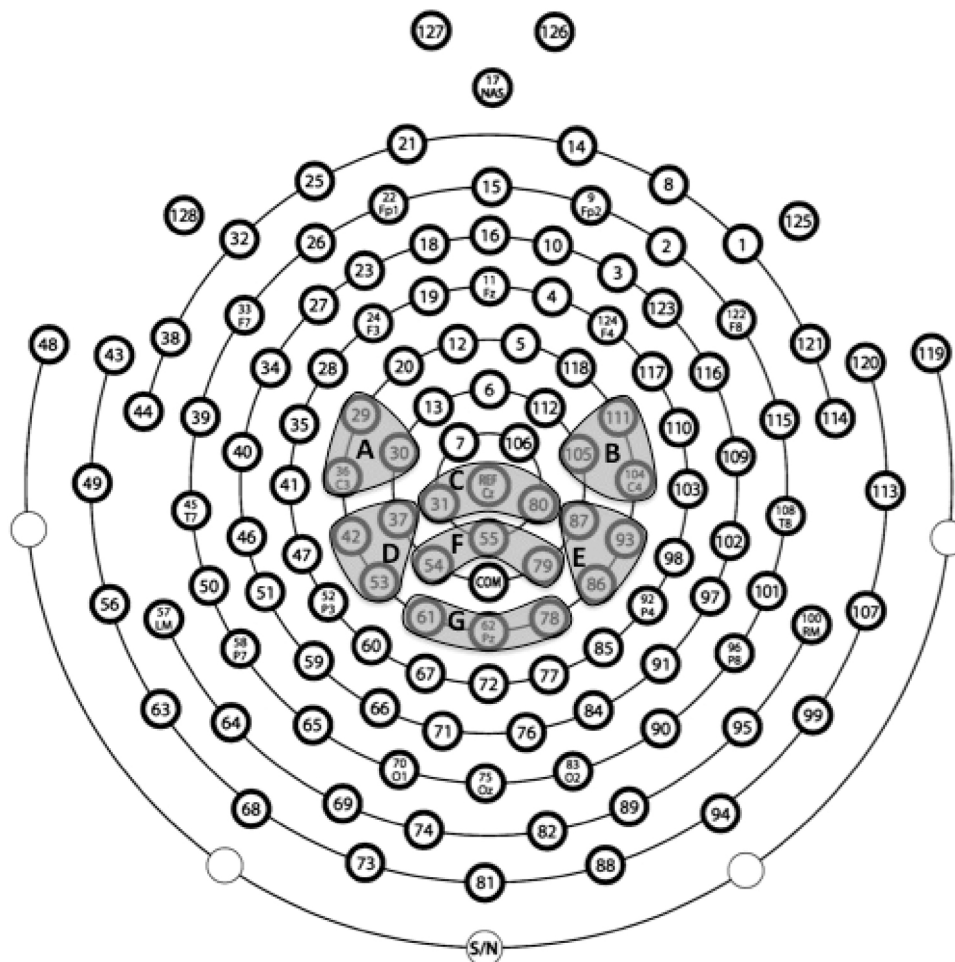


Fig. 2. The electrode montage for the EGI 129 channel HydroCel Geodesic sensor net with the electrode clusters used in this study. A) Left frontocentral electrode cluster. B) Right frontocentral electrode cluster. C) Midline central electrode cluster. D) Left parietocentral electrode cluster. E) Right parietocentral electrode cluster. F) Midline parietocentral electrode cluster. G) Midline parietal electrode cluster.

electrode clusters, shown in Fig. 2. Peak latency and amplitude were extracted from within-subject averaged waveforms for each condition. P2 peaks were determined as the maximum point 175–400 ms following cue or stimulus presentation. P3 peaks were determined as the maximum point 350–600 ms following cue or stimulus presentation. Peaks were visually inspected to ensure they represented the P2 or P3, and were adjusted to capture local rather than absolute maxima when necessary (Luck, 2014). Slow-wave amplitude was calculated as the sum of all positive area under the curve between 600 and 1400 ms after cue presentation. Signed area under the curve measurements are sensitive to noise levels but are useful for quantifying ERPs for which the latency window is poorly defined (Luck, 2014).

### 1.3. Statistical methods

Behavioral and ERP statistics were extracted using the pandas library (McKinney, 2011) in IPython Notebook (Pérez and Granger, 2007). Descriptive statistics were generated using the ezStats function from the ez package. Dependent measures included RT, accuracy, perseverative error rate, cue- and stimulus-P2 and P3 amplitudes and latencies, and cue slow-wave amplitude.

Pearson correlations between all behavioral measures and ERP amplitude and latency averaged across electrode clusters, were calculated using the corr.test function from the psych package in R (R Core Team, Vienna, Austria, 2014). Correlations controlling for age were calculated using the partial.r and corr.p functions from the psych package. Correlation *p*-values were corrected using false discovery rate

(Glickman et al., 2014). For behavioral measures, switch costs were generated by subtracting switch trial accuracy from stay trial accuracy and subtracting stay trial RT or perseverative error rate from switch trial RT or perseverative error rate, such that higher values represented greater costs.

Analyses of variance (ANOVAs) were conducted using general linear models (GLM; Field et al., 2012) using the lme function from the nlme package in R (R Core Team, Vienna, Austria, 2014). Models contained switch condition (switch, stay), task (color, shape), response side (left, right), and electrode cluster (left frontocentral, right frontocentral, midline central, midline parietocentral, left parietocentral, right parietocentral, midline parietal) as within-subject factors and age group (Early Childhood, Middle Childhood) as a between-subject factor. The response side factor was the side of the screen where the correct response option appeared. Interactions were interpreted by running follow-up models testing simple effects. Follow-up models that accounted for the most variance were interpreted. However, if interactions included electrode cluster, follow-up tests examined effects at each of the electrode clusters independently regardless of effect size, as electrode clusters were not comparable in a meaningful way. Likewise, main effects of electrode cluster were not interpreted. Effect sizes are reported using marginal and conditional  $R^2$  statistics, as recommended for mixed-effect GLM (Nakagawa and Schielzeth, 2013).  $R^2_{\text{marginal}}$  describes the proportion of variance explained by fixed factors alone, while  $R^2_{\text{conditional}}$  describes the proportion of variance explained by fixed and random factors. Age group, switch condition, task, response side, and electrode cluster were modeled as fixed effects, and participant was



modeled as a random effect. Effects were deemed significant using  $\alpha = .05$ .

## 2. Results

### 2.1. Descriptive statistics

Means and standard deviations for study variables, by age and switch condition, are presented in Table 1. Correlations among behavioural measures and among ERP measures are presented in Tables 2 and 3, respectively. Correlations between behavioural and ERP measures were also calculated, but are not presented because none were significant after correction for multiple comparisons.

Children’s age was negatively correlated with response times and positively correlated with accuracy in the Ocean Sort task, but not correlated with their perseverative error rate, contrary to our expectations. All significant correlations among behavioural measures remained significant after controlling for age. Age was not correlated with any ERP measures, including switch trial cue-P3 amplitude, switch trial cue slow-wave amplitude, or cue-P2 amplitude, as suggested by our hypotheses. PPVT scores were not correlated with age or with any behavioural measures on the Ocean Sort task. Correlations between behavioural and ERP measures were also calculated, but are not presented because none were significant after correction for multiple comparisons (all  $r_s > .40$ ).

**Table 1**

Means and standard deviations of all behavioral and electrophysiological dependent measures, by age group and switch condition.

Dependent Measure	Early Childhood ( $n = 17$ )		Middle Childhood ( $n = 22$ )	
	Stay trials $M \pm SD$	Switch trials $M \pm SD$	Stay trials $M \pm SD$	Switch trials $M \pm SD$
<b>Behavioral Measures</b>				
Accuracy (%)	85 $\pm$ 7.7	78 $\pm$ 7.4	91 $\pm$ 5.0	84 $\pm$ 9.9
Response Time (ms)	1361 $\pm$ 200.0	1399 $\pm$ 200.0	1201 $\pm$ 196.4	1258 $\pm$ 206.2
Perseverative Errors (%)	6 $\pm$ 3.2	14 $\pm$ 3.8	5 $\pm$ 3.3	11 $\pm$ 8.0
<b>Cue ERPs</b>				
P2 Amplitude ( $\mu$ V)	2.69 $\pm$ 2.819	2.75 $\pm$ 2.745	3.24 $\pm$ 1.952	4.12 $\pm$ 2.367
P2 Latency (ms)	297 $\pm$ 24.7	297 $\pm$ 28.5	300 $\pm$ 26.3	304 $\pm$ 33.7
P3 Amplitude ( $\mu$ V)	5.24 $\pm$ 3.340	5.60 $\pm$ 5.103	5.24 $\pm$ 2.769	7.10 $\pm$ 4.478
P3 Latency (ms)	579 $\pm$ 28.9	578 $\pm$ 33.5	567 $\pm$ 22.6	570 $\pm$ 27.3
Slow-wave Amplitude ( $\mu$ V*ms)	1058 $\pm$ 630.8	1321 $\pm$ 870.7	935 $\pm$ 488.4	1305 $\pm$ 782.1
<b>Stimulus ERPs</b>				
P2 Amplitude ( $\mu$ V)	4.06 $\pm$ 3.851	2.78 $\pm$ 3.341	3.08 $\pm$ 1.526	3.96 $\pm$ 2.187
P2 Latency (ms)	233 $\pm$ 29.0	223 $\pm$ 25.2	238 $\pm$ 28.7	236 $\pm$ 24.4
P3 Amplitude ( $\mu$ V)	3.63 $\pm$ 4.288	3.64 $\pm$ 5.631	4.06 $\pm$ 3.054	4.32 $\pm$ 3.895
P3 Latency (ms)	551 $\pm$ 30.4	535 $\pm$ 52.6	556 $\pm$ 29.9	540 $\pm$ 34.2

Note: ERP descriptive statistics are the average of all seven electrode clusters.

**Table 2**

Correlations among behavioural measures. Zero-order correlations are presented above the diagonal; correlations controlling for age are presented below the diagonal.

		2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
	1. Age	-.16	-.41*	-.43*	-.04	.43*	.42*	-.14	-.14	-.21	-.15
	2. PPVT <sup>a</sup>	-	.19	.16	-.07	-.05	.10	-.20	-.09	-.06	-.02
Response Time	3. Stay	.14	-	.90**	-.20	-.37	-.21	-.09	.20	.03	-.07
	4. Switch	.10	.88**	-	.24	-.32	-.26	.03	.15	.08	.01
	5. Switch cost	-.08	-.24	.24	-	.11	-.12	.29	-.11	.11	.18
Accuracy	6. Stay	.02	-.24	-.17	.14	-	.72**	.02	-.79**	-.50**	-.13
	7. Switch	.18	-.05	-.10	-.11	.66**	-	-.67**	-.57**	-.85**	-.62**
	8. Switch cost	-.22	-.17	-.03	.28	.09	-.68**	-	-.02	.69**	.77**
Perseverative Errors	9. Stay	-.12	.15	.09	-.12	-.82**	-.57**	-.04	-	.42*	-.008
	10. Switch	-.10	-.06	-.01	.11	-.47*	-.86**	.68**	.40*	-	.87**
	11. Switch cost	-.04	-.15	-.06	.18	-.07	-.62**	.76**	-.11	.87**	-

\*  $p < .05$ ; \*\*  $p < .01$ ; <sup>a</sup> $n = 38$ ; PPVT = Peabody Picture Vocabulary Test.

Generally, RT, accuracy, and perseverative error rate were correlated across switch and stay trials. Switch trial accuracy was also negatively correlated with switch trial perseverative error rate, suggesting that perseverative errors made up a substantial portion of children’s errors on switch trials. Likewise, for ERP measures amplitude and latency measures for each component were generally correlated across switch and stay trials.

### 2.2. ANOVAs

#### 2.2.1. Behavioral performance

**2.2.1.1. Accuracy.** Children were less accurate on switch trials than stay trials, reflecting a significant switch cost ( $\chi^2(1) = 32.95, p < .01, R^2_{\text{marginal}} = .10, R^2_{\text{conditional}} = .0001$ ; means in Table 1). Older children performed the task more accurately than younger children ( $\chi^2(1) = 7.67, p < .01, R^2_{\text{marginal}} = .10, R^2_{\text{conditional}} = .001$ ; means in Table 1). No other effects, including the predicted age group by switch condition interaction, were significant.

**2.2.1.2. Perseverative errors.** Switching also affected children’s perseverative error rate: Children made more perseverative errors on switch trials than stay trials ( $\chi^2(1) = 43.53, p < .01, R^2_{\text{marginal}} = .21, R^2_{\text{conditional}} = -.04$ ; means in Table 1). They also made more perseverative errors on left-side trials than right-side trials ( $M_{\text{LEFT}} = .10, SE_{\text{LEFT}} = .009, M_{\text{RIGHT}} = .08, SE_{\text{RIGHT}} = .008; \chi^2(1) = 3.95, p = .047$ ,

**Table 3**  
Correlations among ERP measures. Zero-order correlations are presented above the diagonal; correlations controlling for age are presented below the diagonal.

		2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.		
Cue	1. Age	-.16	.15	.25	-.02	-.02	-.01	.11	-.35	-.20	-.11	-.03	-.09	.16	.04	.19	.04	-.01	.06	.10		
	2. PPVT <sup>a</sup>	-	-.16	.06	.22	-.11	-.05	.07	-.14	-.09	-.05	-.44	-.35	.39	-.40	.00	-.41	.14	-.10	.08		
	P2 Amp	3. Stay	.09	-	.35	.12	.32	.72**	.24	.00	.30	.63**	.21	.45*	.35	.09	.16	-.21	-.01	-.22	.07	
		4. Switch	.22	.32	-	.13	.02	.46*	.83**	.21	.32	.37	.70**	.29	.13	-.03	-.11	-.23	-.08	.22	.03	
	P2 Lat	5. Stay	-.11	.12	.14	-	.56**	.21	.23	.13	.08	.06	.06	-.05	.20	.33	.16	.13	.13	-.14	-.02	
		6. Switch	-.12	.32	.02	.56**	-	.32	.11	.20	.29	.23	.00	.07	.31	.33	.27	.14	.11	-.23	.12	
	P3 Amp	7. Stay	.06	.73**	.48*	.21	.32	-	.59**	.29	.43	.88**	.53*	.37	.13	-.08	-.05	-.32	-.18	-.04	.30	
		8. Switch	-.15	.23	.83**	.24	.11	.60**	-	.21	.43	.46*	.89**	.16	.06	-.08	-.16	-.16	-.05	.16	.15	
	P3 Lat	9. Stay	-.09	.06	.33	.13	.21	.30	.27	-	.50*	.26	.14	.10	-.17	.07	.04	-.28	-.27	.07	.02	
		10. Switch	-.04	.34	.39	.08	.29	.43	.47*	.47*	-	.38	.40	.13	.01	.02	-.12	-.25	-.26	-.11	.00	
	Slow-wave	11. Stay	-.44	.66**	.42	.06	.23	.88**	.48*	.24	.37	-	.47*	.37	.04	-.25	-.16	-.30	-.13	-.18	.25	
	12. Switch	-.32	.22	.73**	.06	.00	.53*	.90**	.14	.40	.47*	-	.15	-.05	-.16	-.19	-.18	-.09	.06	.11		
Stimulus	P2 Amp	13. Stay	.39	.47*	.33	-.05	.07	.37	.17	.07	.12	.36	.15	-	.26	.08	-.10	-.11	-.03	-.09	.08	
		14. Switch	-.38	.34	.10	.20	.31	.14	.04	-.13	.04	.06	-.05	.28	-	.27	.29	.45*	.63**	.11	.06	
	P2 Lat	15. Stay	-.03	.08	-.04	.33	.34	-.08	-.08	.09	.02	.25	-.16	.08	.27	-	.70**	.38	.31	-.01	-.33	
		16. Switch	-.41	.13	-.17	.17	.28	-.05	-.18	.12	-.09	-.15	-.19	-.09	.26	.14	.07	.71**	-.37	.28	.03	-.31
	P3 Amp	17. Stay	.18	-.22	-.25	.16	.14	-.32	-.17	-.28	-.25	-.29	-.18	-.10	.45*	.38	.37	-	.80**	.19	.14	
		18. Switch	-.07	-.01	-.08	.13	.11	-.18	-.05	-.29	-.26	-.14	-.09	-.03	.64**	.31	.29	.80**	-	.08	.09	
	P3 Lat	19. Stay	.09	-.23	.21	-.14	-.23	-.03	.15	.10	-.09	-.18	.06	-.08	.10	-.01	.02	.19	.08	-	.28	
		20. Switch	-.04	.06	.01	-.02	.12	.30	.14	.06	.02	.26	.12	.09	.05	-.33	-.33	.14	.09	.28	-	

\*  $p < .05$ ; \*\*  $p < .01$ ; <sup>a</sup> $n = 38$ ; Amp = amplitude; Lat = latency; PPVT = Peabody Picture Vocabulary Test.

$R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = .005$ ). There were no other significant effects.

**2.2.1.3. Response time.** Switch costs were also found for response time: Children performed switch trials more slowly than stay trials ( $\chi^2(1) = 10.24$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .001$ ; means in Table 1). There were also main effects of age ( $\chi^2(1) = 5.58$ ,  $p = .02$ ,  $R^2_{\text{marginal}} = .11$ ,  $R^2_{\text{conditional}} = .0004$ ) and response side ( $\chi^2(1) = 5.76$ ,  $p = .02$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .001$ ), qualified by an interaction between the two factors ( $\chi^2(1) = 8.28$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .002$ ). On right-side trials, older children responded more quickly than younger children ( $M_{MC} = 1185$  ms,  $SE = 42.3$  ms;  $M_{EC} = 1386$  ms,  $SE = 47.9$  ms). There were no other significant effects.

**2.2.2. Cue-evoked ERPs**

After cue presentation, children could prepare to use the correct rule; moreover, because the response buttons for each rule were grouped together on the left or right side of the screen, children could prepare to orient their attention to one side of the screen and respond with the appropriate hand. Therefore, the amplitude and latency of ERPs to the cue are informative about children’s use of proactive control. Cue-ERPs by age group, switch condition, and electrode cluster are depicted in Fig. 3. Cue-ERPs featured a small N1, a clear P2 peak, a minimal N2, and a P3 peak most pronounced at the parietocentral electrode clusters. The P3 was followed by a sustained positivity over the cue-stimulus interval, consistent with the maintenance of cue information in working memory (Chevalier et al., 2015; Manzi et al., 2011).

**2.2.2.1. Cue-P2 amplitude.** There was a significant interaction between age group and electrode cluster ( $\chi^2(6) = 33.64$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = .002$ ). At right and midline parietocentral clusters, older children had larger cue-P2 amplitudes than younger children (right parietocentral:  $\chi^2(1) = 4.01$ ,  $p = .045$ ,  $R^2_{\text{marginal}} = .05$ ,  $R^2_{\text{conditional}} = .0002$ ;  $M_{MC} = 4.24$   $\mu\text{V}$ ,  $SE = 0.639$   $\mu\text{V}$ ,  $M_{EC} = 2.19$   $\mu\text{V}$ ,  $SE = 0.824$   $\mu\text{V}$ ; midline parietocentral:  $\chi^2(1) = 7.90$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .07$ ,  $R^2_{\text{conditional}} = .0004$ ;  $M_{MC} = 4.04$   $\mu\text{V}$ ,  $SE = 0.563$   $\mu\text{V}$ ,  $M_{EC} = 1.39$   $\mu\text{V}$ ,  $SE = 0.751$   $\mu\text{V}$ ). There was also a significant task by electrode cluster interaction ( $\chi^2(6) = 25.35$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = .002$ ), and an interaction between task, switch condition, and response side ( $\chi^2(1) = 3.90$ ,  $p = .048$ ,  $R^2_{\text{marginal}} = .007$ ,  $R^2_{\text{conditional}} = -.001$ ). However, the interpretations of task effects on

cue processing are ambiguous due to substantial perceptual differences between the two cues in our task. No other effects were significant.

**2.2.2.2. Cue-P2 latency.** There were significant interactions between electrode cluster and age ( $\chi^2(6) = 14.73$ ,  $p = .02$ ,  $R^2_{\text{marginal}} = .009$ ,  $R^2_{\text{conditional}} = .0007$ ) and response side, electrode cluster, and age ( $\chi^2(6) = 13.56$ ,  $p = .04$ ,  $R^2_{\text{marginal}} = .008$ ,  $R^2_{\text{conditional}} = .0006$ ). At the left parietocentral electrode cluster, on right-side trials, younger children had shorter cue-P2 latencies than older children ( $M_{EC} = 287$  ms,  $SE = 13.4$  ms,  $M_{MC} = 319$  ms,  $SE = 9.8$  ms;  $\chi^2(1) = 3.97$ ,  $p = .046$ ,  $R^2_{\text{marginal}} = .03$ ,  $R^2_{\text{conditional}} = .0005$ ).

**2.2.2.3. Cue-P3 amplitude.** Paralleling behavioral findings, cue-P3 amplitude varied by switch condition: switch trials were associated with larger cue-P3 amplitudes than stay trials (Fig. 4;  $\chi^2(1) = 4.98$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .007$ ,  $R^2_{\text{conditional}} = -.04$ ). There were also interactions between task and electrode cluster ( $\chi^2(6) = 16.13$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .006$ ,  $R^2_{\text{conditional}} = .0006$ ) and task, response side, and electrode cluster ( $\chi^2(6) = 22.49$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .000004$ ). At the right frontocentral electrode cluster, for right-side trials, color trials were associated with larger cue-P3 peaks than shape trials ( $M_{\text{COLOR}} = 9.56$   $\mu\text{V}$ ,  $SE = 2.003$   $\mu\text{V}$ ,  $M_{\text{SHAPE}} = 4.48$   $\mu\text{V}$ ,  $SE = 1.586$   $\mu\text{V}$ ;  $\chi^2(1) = 5.13$ ,  $p = .02$ ,  $R^2_{\text{marginal}} = 0.09$ ,  $R^2_{\text{conditional}} = 0.0006$ ). There were no effects of task for the other electrode clusters or for left-side trials. There was a significant electrode cluster by age interaction ( $\chi^2(6) = 21.60$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = -.0005$ ), but age differences were not significant at any electrode site. No other effects were significant.

**2.2.2.4. Cue-P3 latency.** Across all electrode clusters, cue-P3 latency differed by task: cue-P3 peaks reached their maxima with shorter latency to the shape cue than to the color cue ( $M_{\text{SHAPE}} = 564$  ms,  $SE = 5.0$  ms,  $M_{\text{COLOR}} = 582$  ms,  $SE = 4.1$  ms;  $\chi^2(1) = 12.13$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = .03$ ). There was also a significant interaction between switch condition, response side, and electrode site ( $\chi^2(6) = 4.72$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .006$ ,  $R^2_{\text{conditional}} = -.009$ ), but follow-up analyses revealed no significant effects. No other effects were significant.

**2.2.2.5. Cue slow-wave amplitude.** There was a significant main effect of

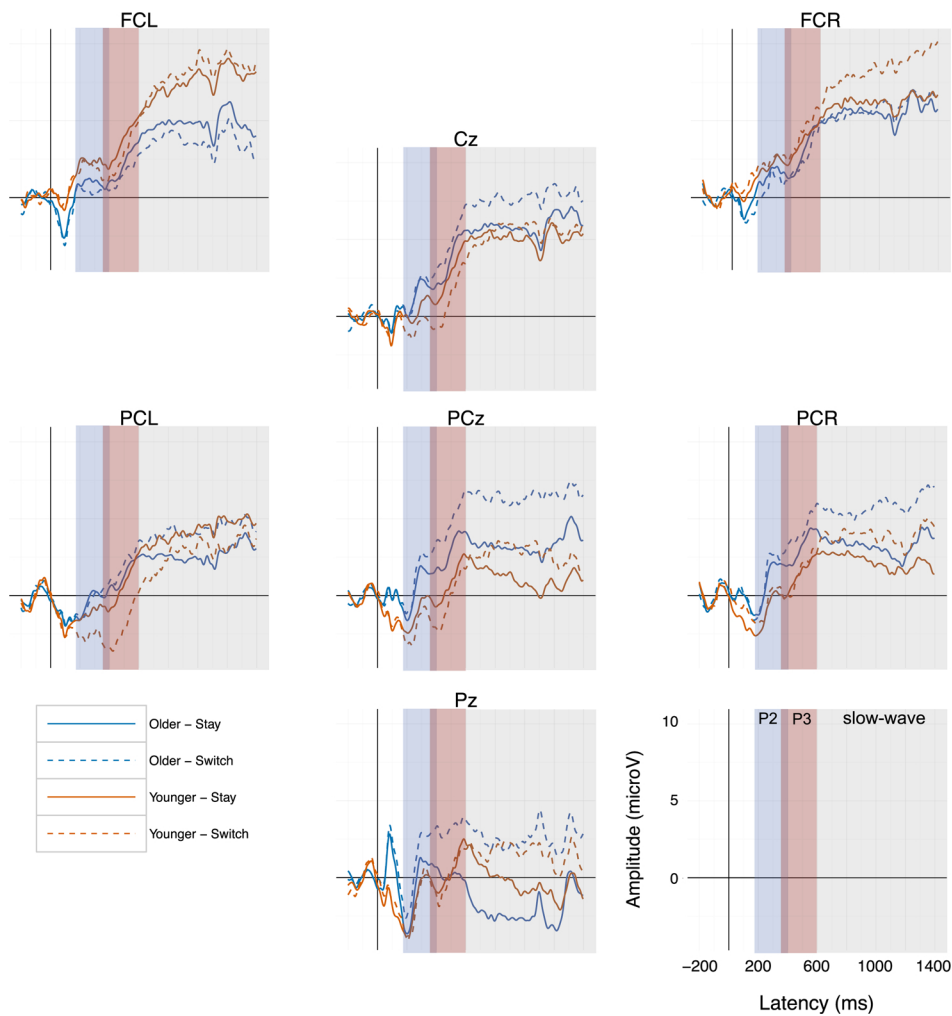


Fig. 3. Cue-evoked ERPs by electrode site, age group and switch condition. FCL: left frontocentral. FCR: right frontocentral. Cz: midline central. PCL: left parietocentral. PCR: right parietocentral. PCz: midline parietocentral. Pz: midline parietal.

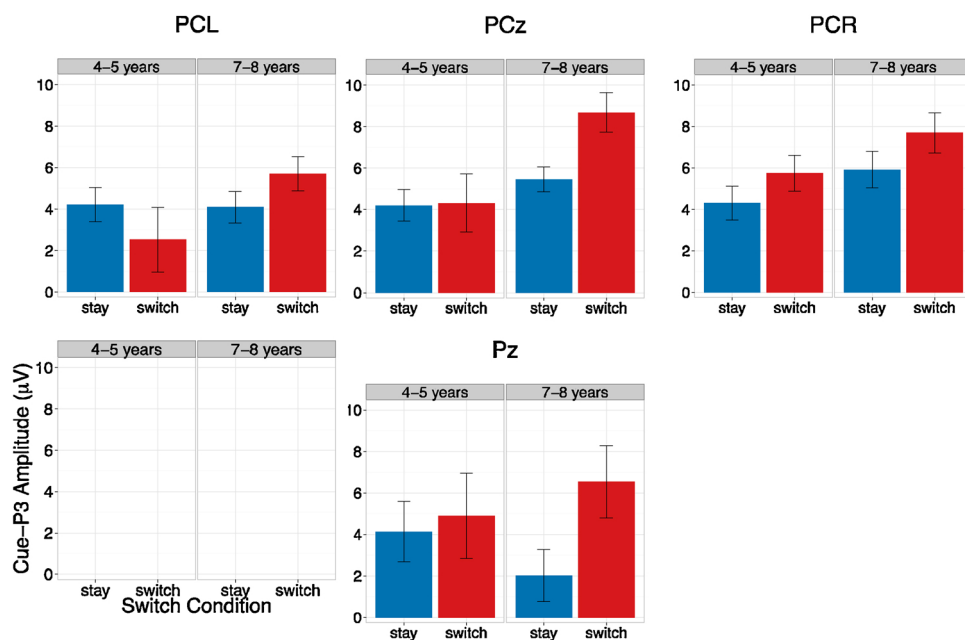


Fig. 4. Cue-P3 amplitude at posterior electrode clusters, by age group and switch condition. PCL: left parietocentral. PCR: right parietocentral. PCz: midline parietocentral. Pz: midline parietal. Main effect of switch condition is significant at all electrode sites.

switch condition ( $\chi^2(1) = 10.77$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = -.0003$ ), qualified by an interaction between switch condition and electrode cluster ( $\chi^2(6) = 13.52$ ,  $p = .04$ ,  $R^2_{\text{marginal}} = .007$ ,  $R^2_{\text{conditional}} = -.0005$ ). Switch trials had larger slow-wave amplitudes than stay trials at central ( $M_{\text{SWITCH}} = 1568 \mu\text{V}\cdot\text{ms}$ ,  $SE = 204.4 \mu\text{V}\cdot\text{ms}$ ;  $M_{\text{STAY}} = 1242 \mu\text{V}\cdot\text{ms}$ ,  $SE = 141.5 \mu\text{V}\cdot\text{ms}$ ;  $\chi^2(1) = 4.46$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = .00005$ ), parietocentral ( $M_{\text{SWITCH}} = 1302 \mu\text{V}\cdot\text{ms}$ ,  $SE = 188.6 \mu\text{V}\cdot\text{ms}$ ;  $M_{\text{STAY}} = 782 \mu\text{V}\cdot\text{ms}$ ,  $SE = 104.8 \mu\text{V}\cdot\text{ms}$ ;  $\chi^2(1) = 8.44$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .05$ ,  $R^2_{\text{conditional}} = .0002$ ), parietal ( $M_{\text{SWITCH}} = 1071 \mu\text{V}\cdot\text{ms}$ ,  $SE = 188.8 \mu\text{V}\cdot\text{ms}$ ;  $M_{\text{STAY}} = 473 \mu\text{V}\cdot\text{ms}$ ,  $SE = 96.3 \mu\text{V}\cdot\text{ms}$ ;  $\chi^2(1) = 11.77$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .07$ ,  $R^2_{\text{conditional}} = .0002$ ), and right parietocentral electrode clusters ( $M_{\text{SWITCH}} = 1280 \mu\text{V}\cdot\text{ms}$ ,  $SE = 167.1 \mu\text{V}\cdot\text{ms}$ ;  $M_{\text{STAY}} = 812 \mu\text{V}\cdot\text{ms}$ ,  $SE = 94.8 \mu\text{V}\cdot\text{ms}$ ;  $\chi^2(1) = 9.12$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .06$ ,  $R^2_{\text{conditional}} = .0002$ ). There was also a significant interaction between task, response side, and electrode cluster ( $\chi^2(6) = 35.01$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = -.0005$ ). For shape trials, there were larger slow-wave amplitudes on left-side trials than right-side trials at right frontocentral ( $M_{\text{SHAPE-LEFT}} = 865 \mu\text{V}\cdot\text{ms}$ ,  $SE = 268.5 \mu\text{V}\cdot\text{ms}$ ;  $M_{\text{SHAPE=RIGHT}} = 865 \mu\text{V}\cdot\text{ms}$ ,  $SE = 268.5 \mu\text{V}\cdot\text{ms}$ ;  $\chi^2(1) = 6.07$ ,  $p = .01$ ,  $R^2_{\text{marginal}} = .11$ ,  $R^2_{\text{conditional}} = .0006$ ) and left frontocentral electrode clusters ( $M_{\text{SHAPE-LEFT}} = 1796 \mu\text{V}\cdot\text{ms}$ ,  $SE = 327.7 \mu\text{V}\cdot\text{ms}$ ;  $M_{\text{SHAPE=RIGHT}} = 1796 \mu\text{V}\cdot\text{ms}$ ,  $SE = 327.7 \mu\text{V}\cdot\text{ms}$ ;  $\chi^2(1) = 6.08$ ,  $p = .01$ ,  $R^2_{\text{marginal}} = .12$ ,  $R^2_{\text{conditional}} = .0005$ ). There was also a significant electrode cluster by age interaction ( $\chi^2(6) = 24.26$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .0007$ ), but follow-up tests revealed no significant simple effects. There were no other significant effects.

### 2.2.3. Stimulus-evoked ERPs

If after the cue children successfully prepared for the upcoming response, they should have been oriented towards the correct response side when the stimulus appeared. Therefore, the amplitude and latency of ERPs to the stimulus are informative about children's use of proactive control strategies, and lateralized effects due to motor preparatory processes are expected. Stimulus-ERPs by age group, switch condition, and electrode cluster are depicted in Fig. 5. Stimulus-Frontocentral, central, and parietocentral ERPs featured a negativity in the time range of the N1, clear P2 and P3 peaks, followed by a negativity that did not resolve by the end of the epoch. Parietal ERPs featured an early positive peak, consistent with a reversed-polarity N1, clear P2 and P3 peaks, and the same post-P3 negativity, resolving within 1400 ms of stimulus presentation. The post-P3 negativity found in the stimulus-ERPs is consistent with response preparation processes (Eimer, 1998).

**2.2.3.1. 2.2.3.1 Stimulus-P2 amplitude.** There was a significant interaction between switch condition and age group ( $\chi^2(1) = 4.58$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .004$ ,  $R^2_{\text{conditional}} = -.0004$ ; means in Table 1). Follow-up models revealed a marginal effect of switch condition in the Middle Childhood group only: Stimulus-P2 s tended to be larger on switch trials relative to stay trials ( $M_{\text{SWITCH}} = 3.96 \mu\text{V}$ ,  $SE = 0.466 \mu\text{V}$ ;  $M_{\text{STAY}} = 3.08 \mu\text{V}$ ,  $SE = 0.325 \mu\text{V}$ ;  $\chi^2(1) = 3.25$ ,  $p = .07$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .00002$ ). There was also a significant effect of response side: Right-side trials elicited larger stimulus-P2 s than left-side trials at all electrode clusters ( $M_{\text{RIGHT}} = 4.04 \mu\text{V}$ ,  $SE = 0.426 \mu\text{V}$ ;  $M_{\text{LEFT}} = 2.92 \mu\text{V}$ ,  $SE = 0.418 \mu\text{V}$ ;  $\chi^2(1) = 4.58$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .005$ ,  $R^2_{\text{conditional}} = .001$ ). No other effects were significant.

**2.2.3.2. Stimulus-P2 latency.** There was an electrode cluster by switch condition interaction ( $\chi^2(6) = 12.61$ ,  $p = .0498$ ,  $R^2_{\text{marginal}} = .007$ ,  $R^2_{\text{conditional}} = .0004$ ). Stimulus-P2 latencies were shorter in switch trials than in stay trials at the midline central ( $M_{\text{SWITCH}} = 206 \text{ ms}$ ,  $SE = 7.0 \text{ ms}$ ;  $M_{\text{STAY}} = 222 \text{ ms}$ ,  $SE = 8.3 \text{ ms}$ ;  $\chi^2(6) = 5.09$ ,  $p = .02$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = .03$ ) and midline parietocentral electrode clusters ( $M_{\text{SWITCH}} = 227 \text{ ms}$ ,  $SE = 7.4 \text{ ms}$ ;  $M_{\text{STAY}} = 247 \text{ ms}$ ,

$SE = 7.4 \text{ ms}$ ;  $\chi^2(6) = 9.79$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .03$ ,  $R^2_{\text{conditional}} = -.01$ ). There was also an interaction between response side, age, and electrode cluster ( $\chi^2(6) = 27.43$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .0006$ ), with significant effects only at the right frontocentral electrode cluster. For the Middle Childhood age group, left-side elicited shorter stimulus-P2 latencies than right-side trials ( $M_{\text{LEFT}} = 200 \text{ ms}$ ,  $SE = 6.7 \text{ ms}$ ;  $M_{\text{RIGHT}} = 240 \text{ ms}$ ,  $SE = 10.0 \text{ ms}$ ;  $\chi^2(1) = 9.96$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .14$ ,  $R^2_{\text{conditional}} = .001$ ). The Early Childhood group had shorter stimulus-P2 latencies on right-side trials than left-side trials ( $M_{\text{RIGHT}} = 191 \text{ ms}$ ,  $SE = 6.9 \text{ ms}$ ;  $M_{\text{LEFT}} = 216 \text{ ms}$ ,  $SE = 10.8 \text{ ms}$ ;  $\chi^2(1) = 5.01$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .07$ ,  $R^2_{\text{conditional}} = -.0007$ ). A significant electrode cluster by task by response side interaction was found ( $\chi^2(6) = 18.33$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .0006$ ), but follow-up tests revealed no significant simple effects.

**2.2.3.3. Stimulus-P3 amplitude.** An effect of switch condition, where switch trials produced smaller stimulus-P3 amplitudes than stay trials, was not found in either age group. A significant response side by electrode site interaction was found, reflecting motor preparatory processes (main effect of response side:  $\chi^2(1) = 5.71$ ,  $p = .02$ ,  $R^2_{\text{marginal}} = .009$ ,  $R^2_{\text{conditional}} = -.0002$ ; response side by electrode site interaction:  $\chi^2(6) = 173.68$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .1$ ,  $R^2_{\text{conditional}} = -.02$ ). Right-side trials had larger stimulus-P3 amplitudes than left-side trials at midline central ( $M_{\text{RIGHT}} = 5.06 \mu\text{V}$ ,  $SE = 1.228 \mu\text{V}$ ;  $M_{\text{LEFT}} = 3.13 \mu\text{V}$ ,  $SE = 1.007 \mu\text{V}$ ;  $\chi^2(1) = 4.13$ ,  $p = .04$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = .00003$ ), right frontocentral ( $M_{\text{RIGHT}} = 7.97 \mu\text{V}$ ,  $SE = 1.299 \mu\text{V}$ ;  $M_{\text{LEFT}} = -4.80 \mu\text{V}$ ,  $SE = 1.648 \mu\text{V}$ ;  $\chi^2(1) = 30.99$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .3$ ,  $R^2_{\text{conditional}} = .0005$ ), and right parietocentral ( $M_{\text{RIGHT}} = 6.61 \mu\text{V}$ ,  $SE = 1.142 \mu\text{V}$ ;  $M_{\text{LEFT}} = 1.18 \mu\text{V}$ ,  $SE = 1.207 \mu\text{V}$ ;  $\chi^2(1) = 10.25$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .1$ ,  $R^2_{\text{conditional}} = .0002$ ) electrode clusters. This pattern was reversed at the left frontocentral ( $M_{\text{LEFT}} = 5.17 \mu\text{V}$ ,  $SE = 1.001 \mu\text{V}$ ;  $M_{\text{RIGHT}} = -1.93 \mu\text{V}$ ,  $SE = 1.263 \mu\text{V}$ ;  $\chi^2(1) = 17.73$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .2$ ,  $R^2_{\text{conditional}} = .0005$ ) and left parietocentral ( $M_{\text{LEFT}} = 5.85 \mu\text{V}$ ,  $SE = 0.985 \mu\text{V}$ ;  $M_{\text{RIGHT}} = 2.36 \mu\text{V}$ ,  $SE = 1.014 \mu\text{V}$ ;  $\chi^2(1) = 6.17$ ,  $p = .01$ ,  $R^2_{\text{marginal}} = .05$ ,  $R^2_{\text{conditional}} = .0002$ ) electrode clusters, where left-side trials had larger stimulus-P3 amplitudes than right-side trials. A significant interaction between task, response side, and electrode cluster was found ( $\chi^2(6) = 13.56$ ,  $p = .04$ ,  $R^2_{\text{marginal}} = .008$ ,  $R^2_{\text{conditional}} = -.0004$ ), but follow-up tests revealed no significant simple effects. No other effects were significant.

**2.2.3.4. Stimulus-P3 latency.** Switch trials were associated with stimulus-P3 peaks with shorter latencies than stay trials at all electrode clusters ( $\chi^2(1) = 6.66$ ,  $p < .01$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = -.01$ ; means in Table 1). A task by response side interaction was found ( $\chi^2(1) = 4.62$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .02$ ,  $R^2_{\text{conditional}} = -.0003$ ). For shape trials, children who had the shape buttons on the right side of the screen had longer stimulus-P3 latencies than those who had the shape buttons on the left side of the screen ( $M_{\text{RIGHT}} = 562 \text{ ms}$ ,  $SE = 17.1 \text{ ms}$ ;  $M_{\text{LEFT}} = 535 \text{ ms}$ ,  $SE = 15.8 \text{ ms}$ ;  $\chi^2(1) = 6.48$ ,  $p = .01$ ,  $R^2_{\text{marginal}} = .03$ ,  $R^2_{\text{conditional}} = .00005$ ). Electrode cluster by age ( $\chi^2(6) = 13.85$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .0007$ ) and electrode cluster by task by age ( $\chi^2(6) = 15.49$ ,  $p = .02$ ,  $R^2_{\text{marginal}} = .01$ ,  $R^2_{\text{conditional}} = .0008$ ) interactions were also found. The Early Childhood group had longer stimulus-P3 latencies on shape trials than on color trials at the left frontocentral electrode cluster ( $M_{\text{SHAPE}} = 577 \text{ ms}$ ,  $SE = 8.7 \text{ ms}$ ;  $M_{\text{COLOR}} = 531 \text{ ms}$ ,  $SE = 14.5 \text{ ms}$ ;  $\chi^2(1) = 6.66$ ,  $p = .01$ ,  $R^2_{\text{marginal}} = .09$ ,  $R^2_{\text{conditional}} = .1$ ). The Middle Childhood age group had longer stimulus-P3 latencies on shape trials than on color trials at the midline parietal electrode cluster ( $M_{\text{SHAPE}} = 549 \text{ ms}$ ,  $SE = 11.5 \text{ ms}$ ;  $M_{\text{COLOR}} = 514 \text{ ms}$ ,  $SE = 15.6 \text{ ms}$ ;  $\chi^2(1) = 4.52$ ,  $p = .03$ ,  $R^2_{\text{marginal}} = .05$ ,  $R^2_{\text{conditional}} = .0004$ ). No other effects were significant.



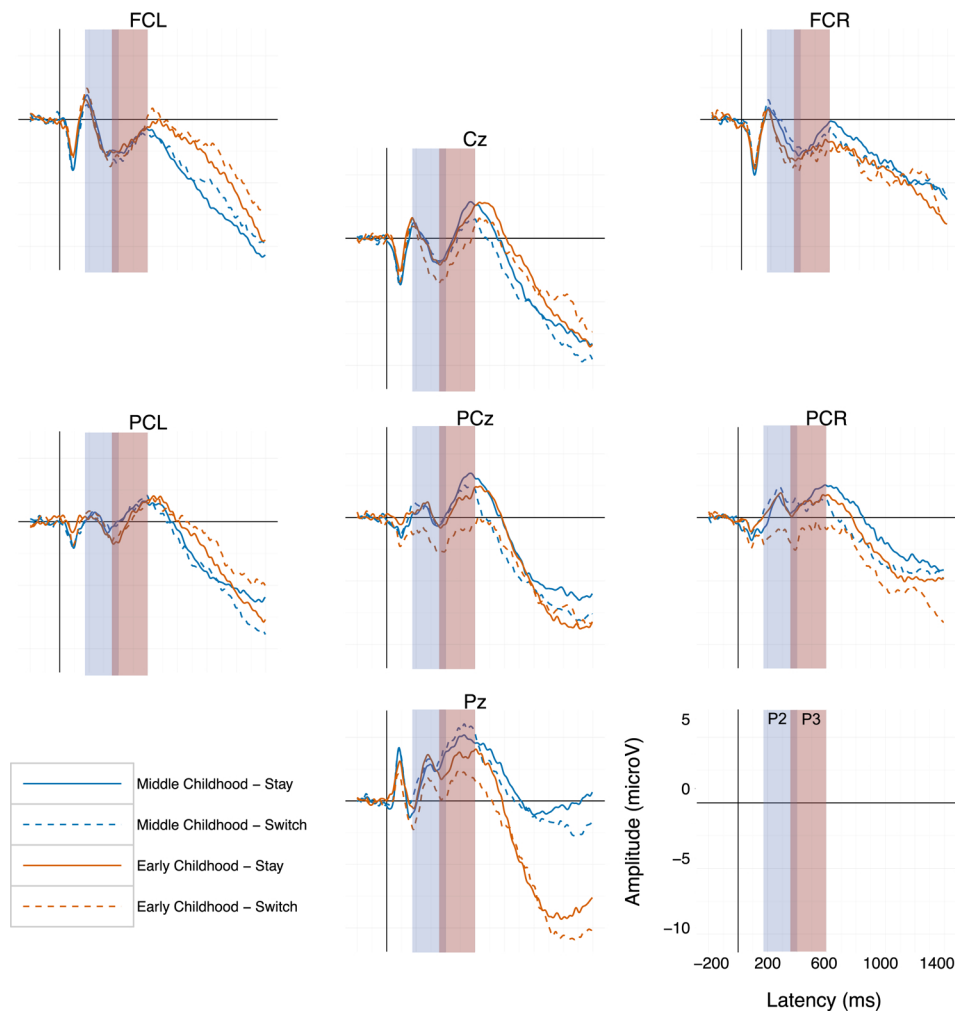


Fig. 5. Stimulus-evoked ERPs by electrode site, age group and switch condition. FCL: left frontocentral. FCR: right frontocentral. Cz: midline central. PCL: left parietocentral. PCR: right parietocentral. PCz: midline parietocentral. Pz: midline parietal.

### 3. Discussion

This study used ERPs to investigate age differences in the use of proactive strategies in the transition to school, a key period in cognitive development. Taking advantage of the high temporal resolution of ERPs, we examined the temporal dynamics of attentional resource allocation when children were required to engage with a task proactively.

The task-switching paradigm we used in this study temporally separated the cue, which indicated the task to be used on the upcoming trial, from the stimulus, thereby forcing children to engage in proactive control. Behaviorally, we expected that the Early Childhood age group would have longer response times, lower accuracy performance, and more perseverative errors than the Middle Childhood group, reflecting less honed proactive control abilities. We found that younger children had poorer accuracy than older children. They also produced longer response times than the Middle Childhood group, but only for trials completed with the right hand. Contrary to our hypotheses, we found no differences in perseverative error rates between our age groups. As expected in a set-shifting task, switch trials were associated with lower accuracy, more perseverative errors, and longer response times than stay trials, but no differences in the magnitude of these switch-stay effects between age groups were found.

In task-switching paradigms, the cue-P2 has been found to be insensitive to the differing demands of switch and stay trials (Adrover-Roig and Barceló, 2010). The findings of this study are

consistent with this interpretation of the cue-P2: We found that at right parietocentral and midline parietocentral electrode sites, cue-P2 amplitudes were larger for older children than for younger children, regardless of switch condition, consistent with our hypotheses. Contrary to our expectations, we also found cue-P2 and -P3 latencies were insensitive to switch condition, suggesting that the increased load on proactive control in switch trials does not slow cue processing.

Following previous studies (Barceló et al., 2002; Chevalier et al., 2015; Jamadar et al., 2010; Jost et al., 2008), we predicted that proactive control would result in switch-stay differences in cue-P3 amplitude, and that the magnitude of this difference would differ between the Middle and Early Childhood age groups such that older children would demonstrate larger switch-stay differences than younger children, reflecting their more effective engagement of proactive control. We did find that switch trials were associated with larger cue-P3 amplitudes than stay trials at all analyzed electrode clusters, but no age effects were found. We expected similar switch-stay differences in cue slow-wave amplitude, reflecting the working memory load of maintaining and initiating a shift of stimulus-response set. Similarly to the cue-P3 amplitude effects, we found larger cue slow-wave amplitudes in switch trials than in stay trials at several electrode clusters, but no difference between age groups in the magnitude of this. The lack of age differences in cue-P3 and positive slow-wave amplitude suggests both age groups were successful in engaging proactive control. In contrast, Chevalier et al. (2015) found switch-stay differences in cue-P3 amplitude in 10-year-old children but not in 5-year-olds. Previous

work in 5- to 10-year-old children (Chevalier et al., 2015; Manzi et al., 2011) found the slow-wave was insensitive to switch condition, unlike our findings.

At the stimulus, we expected that if older children engaged in proactive control more deeply and reliably, they would have smaller stimulus-P2s on switch trials than stay trials, as is found in adults in cued task-switching paradigms (Kieffaber and Hetrick, 2005). However, we found that for 7-8-year-olds, switch trials produced larger stimulus-P2 amplitudes than did stay trials. Not only does this contrast with the adult literature, it also differs from previous research in 9-10-year-old children that found no stimulus-P2 amplitude differences between switch and stay trials (Manzi et al., 2011). Positivity from the processes underlying the cue slow-wave have been found to continue beyond presentation of the stimulus in the kind of paradigm used in this study (Jamadar et al., 2010), a possible explanation for the unexpected direction of the difference between switch and stay stimulus-P2s. We also found that across both age groups, at midline central and parietocentral electrode clusters, switch trials had shorter stimulus-P2 latencies than did stay trials, as predicted, suggesting a facilitation of target processing in switch trials. The interpretation that processing was facilitated for switch trials was further supported by the finding that stimulus-P3 latencies for switch trials were also shorter. This facilitation could be due to the increased processing of switch trials following cue presentation, mediated by proactive control. We did not find any age differences in the magnitude of switch effects, suggesting age differences in proactive control, if any, were not sufficient to produce detectable differences in ERP measures.

The age groups in this study were chosen to bracket the transition to school. This is a period of interest because it is marked by important changes to children's cognitive control abilities and external demands of the school environment. We found that older and younger children differed in some measures, but differences were subtle and appeared quantitative rather than qualitative. Behaviorally, there were age differences in overall performance, but no age differences in the magnitude of switch costs or rate of perseveration. Electrophysiologically, most of the analyzed ERP components did not differ between age groups, with the exception of cue- and stimulus-P2s, which both suggest age-related differences in general stimulus processing rather than differences in proactive control.

In interpreting our findings, we need to acknowledge several limitations. Due to psychophysical differences between the color and shape cues in this task, we were unable to interpret differences in cue processing between tasks; this meant that we were unable to examine asymmetrical switch costs. Previous set-shifting tasks used with children have found differences in switch costs between color and shape tasks, with switch costs being larger for color than for shape tasks (Ellefsen et al., 2006). Additionally, this study did not directly manipulate proactive control and did not include conditions where children were required to use reactive control or when both proactive and reactive control were possible. With the delay between cue and stimulus and the number of trials required for the ERP analysis, including two other conditions would have made the task prohibitively long for younger children. In an ERP study using slightly different age groups, Chevalier et al. manipulated the degree to which children could engage in proactive and reactive control and found that 5-year-old children only engaged in proactive control when the conditions forced them to, favoring reactive control when they could use either mode. Including such conditions may have revealed more variability in the younger age group's performance. Finally, it is surprising that there were no significant correlations between behavioral and ERP measures of task-switching. There are several possible explanations for the absence of such relationships. For example, if children varied in the strategies used to complete the task, this heterogeneity in cognitive and neural processes could have attenuated brain-behavior correlations. If the true relationship between task performance and neural processes is nonlinear (e.g., an inverted U-shape), this would not be captured in a

correlation. However, it is important to recognize that with a sample of 39 children, this study had 80% power to detect a correlation of 0.27 in magnitude, before adjustment for multiple comparisons, and there may have been small but meaningful correlations that could not be detected due to insufficient power.

In sum, both 4-5- and 7-8-year-old children demonstrated the ability to engage proactive control, as evidenced by larger cue-P3 amplitudes in switch trials in both age groups. Furthermore, switch-stay differences in slow-wave amplitude in the cue-stimulus interval in both age groups suggest that children were able to continue task-set reconfiguration processes through the delay. However, older children appeared to engage proactive control more effectively, performing the task more accurately and, under some conditions, more quickly. Further research is needed to uncover which processes involved in task-switching are initiated proactively, whether they involve only task-set reconfiguration or novelty recognition processes, or whether processes related to response-selection are initiated proactively as well.

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#### Conflict of Interest

None.

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