Neural correlates of proactive cognitive control in preschool and middle childhood

by

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Abstract

The engagement of cognitive control has been described as occurring in two forms: reactive control, where cognitive control is engaged only as needed, and proactive control, where cognitive control is engaged in anticipation of future control demands (Braver, Gray, & Burgess, 2007; Braver, 2012). This study used event-related potentials (ERPs) to investigate the neural correlates of proactive and reactive cognitive control strategies in children. The sample included groups of younger children (*n* = 18, 4 years, 6 months to 5 years, 11 months) and older children (*n* = 21, 7 years to 8 years, 6 months). Children completed a cued task-switching paradigm while their EEG was recorded. On each trial, children were presented with a cue indicating whether to sort by colour or shape followed by an image to be sorted by the cued dimension, which children indicated on a touch-screen. Upon cue presentation, the task allowed children to prepare for the upcoming trial (i.e., a proactive strategy), activating the cued task set and selecting their response hand, or wait until stimulus presentation to do so (i.e., a reactive strategy). The paradigm was designed such that children made colour responses with one hand and shape with the other, so that lateralized ERP responses could be analyzed in the cue-stimulus interval to determine whether children were preparing their responses in anticipation of the up-coming stimulus; rule-hand assignment was counterbalanced between participants. Based on previous research, I predicted that younger children would favour a reactive control strategy, whereas older children would favour a proactive strategy. To determine which form of control children were using, I examined the P3 and lateralized readiness potential (LRP), ERP indexes of working memory load and response preparation, respectively. The P3 was analyzed after both the cue and the stimulus, and the LRP was analyzed following the cue. Older children responded more quickly and accurately than younger children and their stimulus-evoked P3s had faster latencies than those of younger children. However, ERP findings suggested that these performance differences were not due to a shift in strategy, as both age groups showed patterns consistent with a reactive strategy. It was found that children had larger cue-P3s in switch trials, when they performed different tasks on consecutive trials, than in stay trials, when they performed the same task on consecutive trials. This effect, however, was found only in younger children following the colourful colour-task cue, suggesting that children were engaging with the visual saliency of the novel cue rather than engaging their cognitive control in a proactive fashion. Children in both age groups had larger stimulus-P3 amplitudes in switch trials than in stay trials. This difference may reflect increased working memory load on switch trials that might have been avoided had children used a proactive strategy. Additionally, LRP onset was widely variable both age groups, without any systematic relation to task and trial demands or participant characteristics, but indicating that children were likely not selecting a response hand consistently following cue presentation, as would have been predicted under proactive control. Together, these results suggest that when presented with a complex task involving maintenance of multiple rule hierarchies, older children may use a reactive strategy, contrary to previous findings in a similar age group but with a more simple task (Chatham, Frank, & Munakata, 2009). Due to differing findings depending on task complexity, future research should examine the interplay between working memory demand and proactive cognitive control in a developmental context.

Preface

This thesis is an original work by Sarah Elke. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name “Brain and Cognitive Development in the Transition to School”, No. 23362, June 21, 2012.

Dedication

To all the graduate students with no programming background who find themselves doing neuroimaging

Acknowledgements

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I'm indebted to the generous families who volunteer their children for studies in the ABCD Lab. I am so impressed with their enthusiasm, curiosity about science, and their selfless sacrifice of their time with nearly no direct benefit to them. They are so patient and understanding, especially in the face of the very strange situation of a graduate student attempting to put a soaking-wet electrode cap on their precious offspring. Thank you for supporting our research.

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Introduction

The ability to anticipate future action requirements is crucial to goal-directed behaviour in daily adult life. For instance, adults frequently have to manage multiple tasks at the same time, such as preparing dinner while supervising small children. To be able to perform both tasks effectively, the timing and requirements of both must be held in mind simultaneously. Set-shifting, a component of executive control reflecting the ability to flexibly shift between two cognitive sets or tasks (Miyake et al., 2000), allows adults to juggle multiple tasks seemingly without effort. Developmentally, set-shifting becomes salient when children enter school and begin to have to apply rule-based concepts in a flexible way (e.g., “if I see ‘+’, then I add; if I see ‘-’, then I subtract). This study investigates differences in the way preschoolers and school-age children approach set-shifting, exploring hypothesized qualitative differences in the use of cue information to inform cognitive control.

Cognitive flexibility can be deployed in an anticipatory, planful way (i.e., proactive control) or “on the fly”, shifting only when needed (i.e., reactive control). The distinction between proactive and reactive control was first formally suggested in the Dual Mechanisms of Control (DMC) account of working memory (Braver et al., 2007) which has since been extended to describe cognitive control in general (Braver, 2012). Reactive responses are largely extrinsically driven, engaging more bottom-up processes, while proactive responses involve a greater intrinsic, top-down, component. The active maintenance of task requirements required for proactive control relies heavily on the lateral prefrontal cortex, whereas in reactive control, transient increases in control required to manage response uncertainty are thought to be mediated by the anterior cingulate (Braver et al., 2007) and the basal ganglia (Stuphorn & Emeric, 2012) via their connections with the prefrontal cortex.

Executive control, a group of cognitive control functions underlying goal-directed behaviour, develops rapidly between preschool and middle childhood largely due to the protracted maturation of the prefrontal cortex (Casey, Tottenham, Liston, & Durston, 2005; Welsh, Pennington, & Groisser, 1991). Because proactive control requires executive control resources, children's ability to use this planful mode of control has been argued to undergo qualitative shifts across the preschool period (Moriguchi & Hiraki, 2009), into middle childhood (Chatham et al., 2009; Chevalier, Huber, Wiebe, & Espy, 2013) and continues to develop through late adolescence (Huizinga, Dolan, & van der Molen, 2006; Killikelly & Szűcs, 2013; Waxer & Morton, 2011). Three-year-olds strongly favour a reactive strategy (Chatham et al., 2009) resulting in perseverative errors, where, when asked to switch from one task to another, they perform the first task again (Espinet, Anderson, & Zelazo, 2012; Moriguchi & Hiraki, 2009; van Bers, Visser, van Schijndel, Mandell, & Raijmakers, 2011). In contrast, five year olds seem to be able to switch task, but benefit from additional cues explicitly signalling the need to switch (Chevalier et al., 2013), suggesting that their difficulty in task switching may result from a difficulty in recognizing the need to switch rather than with switching itself. School-aged children are able to effectively use cue information to switch between tasks, reflecting proactive control. Despite not making as many perseverative errors, older children and adults nevertheless demonstrate a switch cost in reaction time and accuracy when required to switch from performing one task to the other (for a review, see Monsell, 2003). The magnitude of this switch cost decreases across the school years and into adulthood (Cragg & Nation, 2009). Differences between age groups may not be due entirely to changes in set shifting *per se*: the DMC account posits that a reactive strategy can be beneficial over a proactive strategy when working memory capacity is limited (Speer, Jacoby, & Braver, 2003), such as in early childhood when executive control is not fully developed.

To examine the shift from a reactive to a proactive response strategy, Chatham, Frank, and Munakata (2009) administered a child-adapted AX- Continuous Performance Task (AX-CPT) to 3.5- and 8-year-old children, using pupillometry to index mental effort. Children were presented with a cue (A or B) followed after a short interval by a probe (X or Y), and responded to the probe in AX and BY pairings only. The AX pairing was presented more frequently than the others; this manipulation would result in more difficulty on AY trials if a proactive strategy was used, but more difficulty on BX trials if a reactive strategy was used. Overall, they found 8 year-old children exerted greater mental effort, as indicated by increased pupil diameter, during the cue-probe interval than 3.5 year-old children, suggesting that older children were proactively maintaining the cue information over the cue-stimulus interval. On BX trials, younger children exerted greater mental effort than older children after the probe was presented, suggesting they were dealing with the conflict caused by the violation of the response contingency established by the frequent AX trials, consistent with a reactive strategy.

Cued task switching paradigms also have been used to study proactive and reactive responding and cognitive flexibility more generally. In these tasks participants sort images based on two dimensions, often color and shape (Espy, Bull, Martin, & Stroup, 2006; Zelazo, 2006). As in the AX-CPT, participants are presented with a cue indicating which task to perform and the image to sort. Stimuli are typically bivalent, containing both color and shape information, affording sorting by either rule. A key difference between cued-task switching paradigms and the AX-CPT is that task cues are presented with equal frequency, but participants are required to perform the same task on consecutive trials (stay trials) more frequently than they are required to switch tasks (switch trials).

Although behavioural indices suggest a shift from reactive to proactive responding between preschool and the elementary school years (Chevalier et al., 2013), a more direct measure of attentional dynamics would provide greater insight into the nature of this change. Pupillometry provides an indicator of mental effort, but this construct likely reflects the summation of many different concurrent mental processes (Chatham et al., 2009). Event related potentials (ERPs), voltage fluctuations measured at the scalp, can be used to observe these underlying processes more directly, with different ERP components reflecting different aspects of perceptual, cognitive, and motor functions. ERPs can be recorded non-invasively, making them ideal for measurements in children, and have good temporal resolution, allowing the detection of small shifts in neural resource allocation over the course of a trial.

Both in adults and developmentally, ERPs have been used extensively to study preparatory processes, cognitive control, and attentional load. The lateralized readiness potential (LRP), an ERP reflecting motor preparatory processes measured prior to response onset (Eimer, 1998; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Vaughan, Costa, & Ritter, 1968), has been used to examine response preparation in the cue-stimulus interval (Steinhauser, Hübner, & Druey, 2009), following the stimulus (de Jong, Gladwin, & ’t Hart, 2006; Hsieh & Yu, 2003), and before the response (de Jong et al., 2006; Hsieh & Yu, 2003; Sinai, Goffaux, & Phillips, 2007). The LRP is a difference wave computed by subtracting the activity over the motor cortex ipsilateral to the response hand from the corresponding contralateral activity while a response is being prepared (Gratton et al., 1988; Vaughan et al., 1968). Due to this subtraction, a LRP with a positive amplitude suggests the correct response hand is being prepared, and a negative amplitude suggests that response selection processes are proceeding incorrectly. In task switching paradigms, the amplitude of the LRP reflects efficiency in switch trials, where trials that are completed more quickly have larger response-locked LRPs (Gladwin, Lindsen, & de Jong, 2006); this finding is a natural extension of the LRP's sensitivity of response uncertainty, such that its amplitude is smaller when the choice of response hand is more ambiguous (Gratton et al., 1988). The latency of the stimulus-locked LRP is delayed in switch relative to stay trials, reflecting either prolonged response selection or a set-reconfiguration stage prior to response selection (Hsieh & Liu, 2005). The LRP has shorter latencies in 7 to 12 year-olds when compared to 5 and 6 year-olds (Ridderinkhof & van der Molen, 1995), suggesting more efficient response selection processes. When participants are able to use cue information to guide their future responses, if the cue is reliable (de Jong et al., 2006) and if they are given sufficient time to prepare (Steinhauser et al., 2009), the motoric processes underlying the LRP are initiated following cue presentation. Because the LRP is initiated in response to a cue, before it is even possible to make a response, it likely is elicited in the cue-stimulus interval as a product of proactive control.

The posterior-central P3 is a positive-going ERP peak comprising the summation of many cognitive processes that occur following stimulus evaluation, in the period following stimulus perception but before response selection has been completed (Kok, 2001), and has been attributed to the neural events that link perception and action (Verleger, Jaśkowski, & Wascher, 2005). The P3 is thought to be generated in temporal and parietal cortical areas and high-level limbic areas such as the anterior cingulate cortex. The amplitude of the P3 has been associated with context updating, or revision of the mental representation of the perceptual world induced by incoming stimuli (Donchin, 1981), the amount of attentional resources engaged by a task

(Isreal, Chesney, Wickens, & Donchin, 1980), or the degree of information flow mediated by attention allocation to the presented stimulus via bottom-up or top-down means (Kok, 2001). P3 amplitude has also been associated with memory processes, including habituation to repeated stimuli (Polich, 1989) or recognition of familiar stimuli (Guo, Duan, Li, & Paller, 2006; McEvoy, Pellouchoud, Smith, & Gevins, 2001). P3 latency is proportional to stimulation classification speed (Kutas, McCarthy, & Donchin, 1977) and speed of attentional resource allocation (Houlihan, Stelmack, & Campbell, 1998), and is slowed by response conflict (Duncan-Johnson & Kopell, 1981; McCarthy & Donchin, 1981). P3 latency has also been shown to decrease across childhood (Polich, Ladish, & Burns, 1990).

In cued task switching paradigms, the P3 has typically been attributed to context or task-set updating (Barceló, Escera, Corral, & Periáñez, 2006; Barceló, Periáñez, & Knight, 2002) and has been examined following both the cue and the stimulus. Following cue presentation, the P3 is consistently found to have a larger amplitude in switch trials relative to stay trials (Barceló et al., 2006; Barceló, Muñoz-Céspedes, Pozo, & Rubia, 2000; Barceló et al., 2002; Cunillera et al., 2012; Gajewski & Falkenstein, 2011; Jost, Mayr, & Rosler, 2008; Karayanidis & Coltheart, 2003; Karayanidis et al., 2010). The processes thought to underlie the cue-evoked P3 include updating stimulus and response sets and stimulus-response mappings (Karayanidis et al., 2010), and updating the task-set in working memory (Barceló et al., 2000). In contrast with the cue-evoked P3, the stimulus-evoked P3 is typically smaller in switch trials relative to stay trials (Barceló et al., 2000, 2002; Gajewski & Falkenstein, 2011; Hsieh & Liu, 2009; Ikeda & Hasegawa, 2012; Jost et al., 2008; Karayanidis & Coltheart, 2003; Karayanidis, Whitson, Heathcote, & Michie, 2011). This effect has been explained in several ways, with some drawing parallels with the finding that the P3 tends to be smaller when working memory is taxed (Kok,

2001) and others arguing that rule representation following switch trials is initially weak, and reinforced in stay trials (Barceló et al., 2000).

Although typically interpreted as an index of set-shifting, a cued task switching paradigm in combination with the LRP and the P3 can provide insight into the use of proactive and reactive control strategies across development. A cued task switching paradigm provides a situation where children can prepare proactively after the cue has been presented but, if children are able to hold the identity of the cue in mind or have the current task-set active from a previous trial, a reactive strategy can still be used. In the executive function domain, the period spanning the transition to school, from preschool to middle childhood, is of particular interest because vast gains occur rapidly as children are faced with the increased cognitive demand of a formal school setting (Hughes, Ensor, Wilson, & Graham, 2010). Similar studies examining the DMC model of cognitive control have used children as young as 3.5 years (Chatham et al., 2009) but, due to their tendency to perseverate, this age group is not ideal for an ERP study using this paradigm because a large number of accurate trials are required to generate ERPs. 4 and 5 year olds are able to perform set-shifting tasks but appear to do so in a qualitatively different way than older children or adults (Chevalier et al., 2013). Set-shifting studies have largely focused on the pre-school years due to this shift from perseverating to switching, but children continue to improve their shifting abilities through childhood and the reasons for this, though subtle, are still important to our understanding of executive control development (Best, Miller, & Jones, 2009).

To examine the LRP, some adjustments to the typical implementation of cued task switching paradigms are required (Cepeda, Kramer, & Gonzalez de Sather, 2001). In child-friendly cued task switching paradigms, response options are often bivalent and used for both tasks within the paradigm (Cepeda et al., 2001; Zelazo, 2006). This does not allow for response preparation within the cue-stimulus interval as either hand could be used for the up-coming stimulus. In the present study, to allow children to prepare in advance of the cue, each of the two tasks was consistently mapped to one hand. Upon seeing the cue, children could, in theory, anticipate which hand would be required in the upcoming trial. To maintain the complexity of the task, response options were univalent, reflecting, for example, one of two possible colour options. Another benefit of separating the response options this way is that perseverative errors, where children respond to the un-cued, incorrect stimulus attribute, can be separated from errors resulting from children responding randomly; errors are ambiguous when there are only two response options available.

The goal of the present study was to elucidate developmental differences in children's ability to plan upcoming responses using a cued task switching paradigm. Specifically, this study tested whether preschool children (4 and 5 year olds) and older children (7 and 8 year olds) prepare their responses in the cue-stimulus interval, reflecting a proactive response strategy. Using event related potentials (ERPs), I examined children's motor preparatory states and their working memory updating processes upon cue and stimulus presentation in a child-adapted cued task switching paradigm. LRP onset should occur following cue presentation if a proactive strategy is used, thus it was expected that older children, but not younger children, would have LRPs that onset in the cue-stimulus interval. With the use of a proactive strategy, the recognition of the need to switch cognitive set should result in increased P3 amplitudes following cue presentation in switch trials compared to stay trials. This was expected to be true of older children but not younger children, who were expected to have similar P3 amplitudes on switch and stay trials if they were using a reactive response strategy. Due to the high working memory demand required by proactive control, I predicted that older children would have smaller P3 amplitudes than younger children following stimulus presentation. I also expected that younger children would recognize the need to switch following the stimulus presentation rather than following the cue presentation, resulting in increased P3 amplitudes to switch trials relative to stay trials.

Variation in task switching performance and patterns of cognitive control could also be associated with sex. In the preschool years, girls have been found to have an advantage in tasks requiring inhibition of pre-potent responses (Wiebe, Sheffield, & Espy, 2012) or general executive control (Wiebe, Espy, & Charak, 2008). Children could also vary in their behavioural and neurological performance by task: in similar paradigms, the colour task has been shown to be more dominant for children, resulting in better overall performance and increased magnitude of the difference between switch and stay trials (Ellefson, Shapiro, & Chater, 2006). As the P3 was measured at two sites, centrally and parieto-centrally, ERP effects could also differ between sites, with the central electrode cluster reflecting more frontal and cingulate-mediated processes, and the parieto-central site reflecting processes associated with the temporal and parietal lobes.

Methods

Participants

The sample for this study included 18 younger children (10 girls, mean age: 5 years, 4 months; range: 4;6 – 5;11) and 21 older children (10 girls, mean age: 7 years, 7 months; range: 7;0 – 8;6). Children were recruited using the Alberta Brain and Cognitive Development Lab's participant database, comprising families who had contacted the lab after seeing posters or fliers distributed throughout the City of Edmonton or advertisements on social networking websites. Children had an average estimated IQ of 111.6, based on the Peabody Picture Vocabulary Test

(PPVT; Dunn & Dunn, 2007). IQ data from 6 participants was missing, due to child refusal (*n* = 5) or problems with the PPVT administration computer (*n* = 1). Children were from middle- to upper-middle class backgrounds: parents reported a median of 16 years of education and median family income of $90,000. The sample included 21 Caucasian, 3 Hispanic, 2 African, 2 Asian, 1 Arabic, and 8 multi-racial children. Demographic information was missing from two children because their parents failed to complete the questionnaires. Children were eligible to participate if parents reported that they were experiencing a normal course of development. Exclusionary criteria included low birth weight (< 2500 g), preterm birth (< 37 weeks gestation), and diagnosed neurological or psychiatric conditions. Children who had participated in similar studies in the past were also excluded from participation. Data from an additional 14 children were excluded following data collection due to technical difficulties (*n* = 2), refusal of the EEG net (*n* = 6), or poor performance levels that precluded ERP analysis (*n* = 6). The excluded children did not differ from the final sample in IQ ($t(9) = -0.25$, $p = 0.81$).

Procedure

All procedures were approved by the University of Alberta’s Human Research Ethics Board. Children and their parents came to the lab for a single session spanning 1.5 to 2 hours. Upon arriving at the lab, written parental consent and verbal child assent were obtained after study procedures were explained and parents’ questions were answered. During the session, children participated in four tasks: a word span task that was not included in this analysis, the Ocean Sort game, an emotion regulation task unrelated to the present research question, and the PPVT. Parents filled out a packet of questionnaires while their child completed the tasks (e.g., demographic information, parenting style). At the end of the session, child participants received a small toy or book in appreciation and their parents received a gift card.

Tasks

Ocean Sort Game. Children completed a child-friendly cued task-switching paradigm (Figure 1; adapted from Cepeda, Kramer, & Gonzalez de Sather, 2001, and Zelazo, 2006) while their electroencephalogram (EEG) was recorded. The task was presented using Eprime 2.0 (Psychological Software Tools, Pittsburgh, PA).

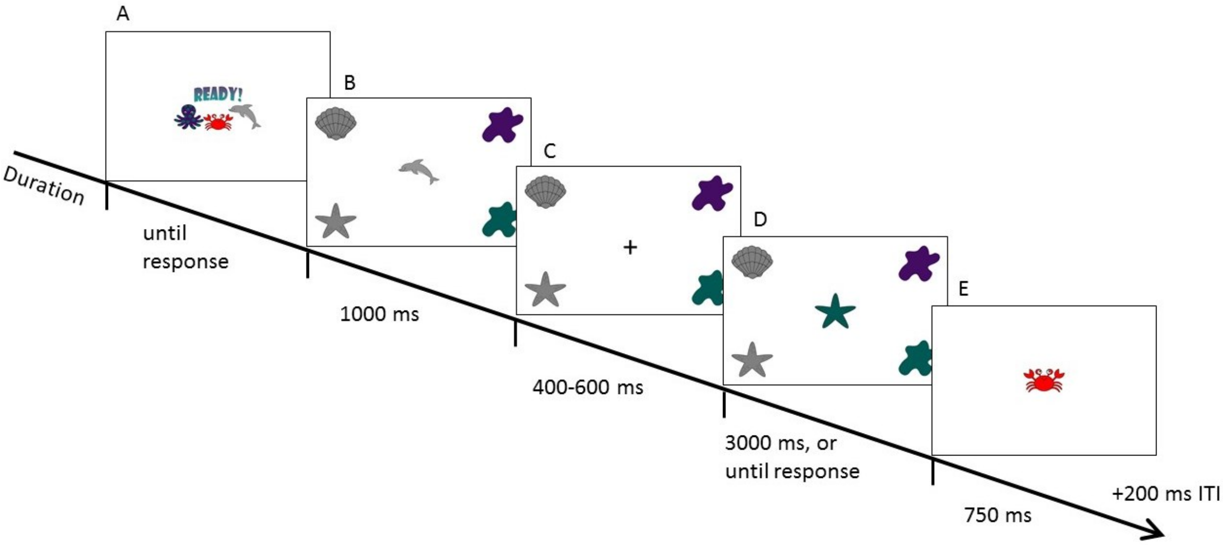

Figure 1. The events of a single trial. A) Ready screen, terminates when participants hold down the left-most and right-most buttons on a four-button response pad. B) Cue indicating the task (colour or shape), with response options. C) Cue-stimulus interval. D) Stimulus. Participants are required to respond with the cued stimulus attribute within 3000 ms. E) Feedback, with positive or error tone.

Children were told that Mrs. Crab's class was doing an art project and that they were going to help the students collect seashells and starfish for it. At the beginning of each trial, children were presented with a ready screen, indicating that they should prepare for the trial by pressing and holding the right-most and left-most buttons on a four-button response pad. Following a 250 ms delay, children were presented with a cue indicating which task they would perform on the upcoming trial and the response buttons on a touch-screen computer monitor. The cue was either a plain grey dolphin, indicating the children would sort by shape, or a colourful octopus, indicating the children would sort by colour. Response options for the colour task were paint swatches of purple or green, and for the shape task, response options were grey seashell and starfish shapes. Each task (colour or shape) was consistently mapped to one hand throughout the game, with button location counterbalanced between participants in four conditions. The cue was displayed for 1000 ms, and then a fixation cross for a random interval between 400 and 600 ms. The response options remained on the screen over this delay. Finally, the probe stimulus was presented, a green or purple seashell or starfish, and the children were required to make a response according to the cued rule within 3000 ms. Children were asked to use their left hand to perform the task associated with the buttons presented on the left side of the screen, and their right hand for the task on the right side of the screen. If the trial was completed correctly, an image of a happy crab was displayed with a pleasant bubbling sound. If the trial was completed incorrectly, a sad crab was displayed with a cartoonish “uh-oh” sound. This feedback was displayed for 750 ms followed by a 200 ms inter-trial interval with a blank screen.

Prior to the experimental blocks, children completed a training phase where they were familiarized with the cues, stimuli, and trial pacing and sequence of stimuli within each trial. Participants then completed a practice block of a maximum of 48 trials, terminating when the child had completed 6 trials in a row correctly or when they had achieved 75% accuracy after 8 trials. The experimental phase of the task included five blocks of 31 trials. Between each block, children were able to take a break and they received a sticker as a motivating reward. Two-thirds of the trials were stay trials (100 trials), where children completed the same task as the previous trial. The remaining third were switch trials (50 trials), where children completed the other task. As this context cannot be established for the first trial of each block, these trials were discarded. Trials were presented in the same pseudo-random order across participants, such that the same stimulus was not presented on two consecutive trials and two switch trials were never presented consecutively. All four possible stimuli (green starfish, green seashell, purple starfish, purple seashell) and both task cues were presented an equal number of times. Button positions were counterbalanced between participants, forming two conditions with the colour responses on the right and two with the shape responses on the left, with the buttons appearing at the top and the bottom switched within each of the two conditions.

Dependent measures included response time, accuracy, and perseverative error rate. Perseverative errors were responses that matched the incorrect stimulus attribute (e.g., pressing “starfish” instead of “purple” to the purple starfish in the colour task). Perseverative error rate was calculated as the number of perseverative errors over the total number of trials where a response was made, correct or incorrect, within 3 standard deviations of the sample’s mean response time.

Peabody Picture Vocabulary Test. (PPVT-4; Dunn & Dunn, 2008). This standardized test measures receptive vocabulary, and was used as an estimate of general intelligence. Children were presented with an array of four images and were asked to point to the image displaying a given vocabulary word. The PPVT-4 was normed with a large, representative sample of American children and adults and has high internal consistency ($\alpha = .94$).

Electroencephalography. During the Ocean Sort game only, EEG data was recorded using NetStation (EGI Software, Eugene, OR) and 128-channel Hydrocel geodesic sensor nets. Impedances were maintained below 50 kΩ. Data was sampled at 250 Hz and referenced to the vertex. EEG data was analyzed using EEGlab (Delorme & Makeig, 2004), a toolbox for MATLAB (The Mathworks Inc., Natick, MA, 2013). A 0.1 to 30 Hz bandpass filter was applied, and epochs were generated by segmenting the interval 100 ms before and 3000 ms after the cue event. Data was then baseline-corrected using the 100 ms pre-cue period, and bad channels and epochs were rejected manually by visual inspection. Independent components analysis (ICA) was applied to remove artifact attributable to stereotyped eye, muscle and line-noise artifacts (Jung et al., 2000). Data was then re-referenced to the average of all the channels and removed channels were interpolated from the remaining channels. Finally, the data was re-epoched into two windows: 100 ms before and 1000 ms after the cue (cue epoch), and 1000 ms following the stimulus (stimulus epoch).

The cue epoch was used to analyze LRP activity. To compute single-trial LRP waveforms, for right-hand responses, the activity from a left-frontal electrode cluster (the average of channels 29, 30, and 36; Figure 2A), reflecting activity over left motor cortex, was subtracted from a right-frontal electrode cluster (the average of channels 104, 105, and 111; Figure 2B), reflecting activity over right motor cortex; and the opposite subtraction was carried out for left-handed responses (Eimer, 1998). The amplitude of the LRP was determined by finding the area under the curve for each within-subject averaged LRP waveform for 200 ms bins following cue presentation.

The P3 was analyzed during both cue and stimulus epochs, at central, and parietal electrode clusters. A central electrode cluster was computed by averaging activity from channels 31, 80, and 129 (Figure 2C). Similarly, a parietal electrode cluster was computed by averaging activity from channels 62, 67, 72, and 77 (Figure 2D). Peak latency and amplitude were extracted from within-subject averaged waveforms separately for each condition (task: colour, shape, and trial type: switch, stay).

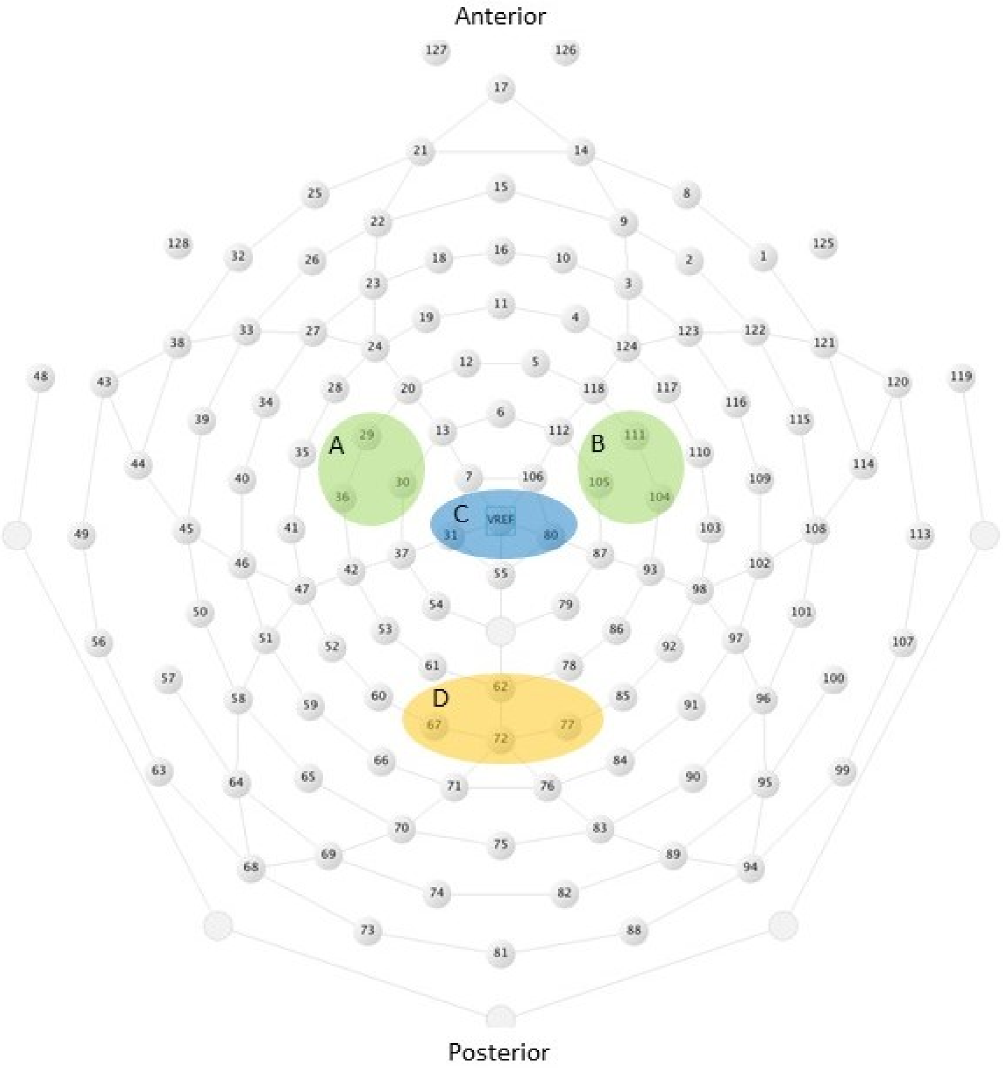

Figure 2. A representation of an EGI 128-channel Hydrocel geodesic sensor net, as seen from above. A) The electrodes over left motor cortex, used to compute the LRP. B) The electrodes over right motor cortex, used to compute the LRP. C) The electrodes used to compute the central electrode cluster. D) The electrodes used to compute the parietal electrode cluster.

Results

Behavioural data and processed EEG data were handled and relevant statistics were extracted using the pandas library (McKinney, 2011) for the IPython Notebook (Pérez & Granger, 2007). ERP and behavioural statistical analyses were conducted in R (R Core Team, Vienna, Austria, 2014) using the lme function from the nlme package. Descriptive statistics were generated using the ezStats function from the ez package. A general linear model (GLM) approach to ANOVA (Field, Miles, & Field, 2012) was conducted for reaction time, accuracy, perseverative error rate, P3 peak amplitude and peak latency, and LRP amplitude. Models contained trial type (switch, stay) and task (color, shape) as within-subject factors and age group (younger, older), sex (female, male), and button position condition (1-4) as between-subject factors. The models analyzing the LRP included an additional factor representing the latency bin (0-200 ms, 201-400 ms, 401-600 ms, 601-800 ms, 801-1000 ms following cue presentation). Interactions were assessed through simple effects using the pairwise.t.test function and p-values were corrected for multiple comparisons using the Holm method (Holm, 1979). Significance of the most theoretically interesting factor was assessed at each level of the other factor or combination of factors. Effects were deemed significant using an alpha level of .05.

For both response time and accuracy for the ocean sorting game, trials immediately following errors were omitted to eliminate effects of post-error slowing. Trials with response time greater than three standard deviations from the overall mean of all participants were replaced by this mean plus three standard deviations. For both accuracy and perseverative errors, Shapiro-Wilk normality tests were significant and visualization of quantile-quantile plots comparing the sample distributions to the normal distribution indicated a violation of normality, an assumption of GLM ANOVA tests (Field et al., 2012). Although GLM ANOVAs are more robust in the face of non-normality, the results of the ANOVAs on accuracy and perseverative error rates should be interpreted with caution. For each dependent measure, analyses were conducted using all available data (behavioural measures: n = 38; P3: n = 35; LRP: n = 31). One child contributed ERP data but not behavioural data due to computer failure. Four children's data were excluded from the P3 analyses due to artifact (n = 1) or P3 amplitudes differing by more than 3 standard deviations from the mean (*n* = 3). Data from 7 participants were excluded from the LRP analysis due to consistently outlying values for area under the curve.

For each dependent variable, several interactions involving button position condition were statistically significant, but due to the small cell size and complexity of these effects, most of these interactions were not clearly interpretable. Results of these interactions are presented separately, in the Appendix.

Table 1

Descriptive statistics for behavioural performance in the Ocean Sorting Task

Age Group	Sex	n	Task	Trial Type	Proportion Correct		Response Time (ms)		Perseverative Errors	
					M	*SE*	*M*	*SE*	*M*	*SE*
Younger	Female	10	Colour	Stay	0.91	0.024	1282	78.7	0.03	0.011
				Switch	0.92	0.026	1307	75.4	0.05	0.018
			Shape	Stay	0.91	0.027	1183	62.5	0.03	0.009
				Switch	0.82	0.064	1233	64.5	0.07	0.015
	Male	8	Colour	Stay	0.89	0.023	1166	80.4	0.05	0.014
				Switch	0.75	0.043	1216	77.5	0.20	0.036
			Shape	Stay	0.86	0.024	1163	61.6	0.06	0.018
				Switch	0.78	0.051	1234	81.6	0.14	0.037
Older	Female	10	Colour	Stay	0.81	0.048	1393	50.5	0.07	0.018
				Switch	0.73	0.058	1367	59.9	0.13	0.034
			Shape	Stay	0.80	0.039	1343	64.1	0.07	0.016
				Switch	0.73	0.051	1424	61.4	0.17	0.033
	Male	10	Colour	Stay	0.82	0.040	1362	68.6	0.05	0.012
				Switch	0.73	0.040	1451	97.5	0.16	0.032
			Shape	Stay	0.82	0.031	1339	89.3	0.07	0.014
				Switch	0.71	0.061	1385	86.5	0.12	0.024

Behavioural performance.

Descriptive statistics for behavioural performance are presented in Table 1.

Proportion correct. The accuracy analysis excluded four- and five-way interactions as models were unable to converge. Children showed switch costs for accuracy, performing stay trials (*M* = 0.85, *SE* = 0.016) more accurately than switch trials (*M* = 0.77, *SE* = 0.022; $\chi^2(1)$ = 22.43, *p* < .001). There were also age differences, such that older children (*M* = 0.85, *SE* = 0.021) performed the task more accurately than younger children (*M* = 0.77, *SE* = 0.027; $\chi^2(1)$ = 6.19, *p* = .013). Switch costs did not differ by age ($\chi^2(1)$ = 0.017, *p* = .90).

Response time. There were switch costs in RT, such that switch trials (*M* = 1322 ms, *SE* = 36.2 ms) were completed more slowly than stay trials (*M* = 1275 ms, *SE* = 34.1 ms; $\chi^2(1)$ = 9.00, *p* = .0027). There were also age differences: younger children (*M* = 1383 ms, *SE* = 44.9 ms) performed the task more slowly than older children (*M* = 1223 ms, *SE* = 45.8 ms; $\chi^2(1)$ = 6.02, *p* = .014). The predicted moderation of switch cost by age, as indicated by a trial type by age interaction, was non-significant ($\chi^2(1)$ = 0.02, *p* = .89).

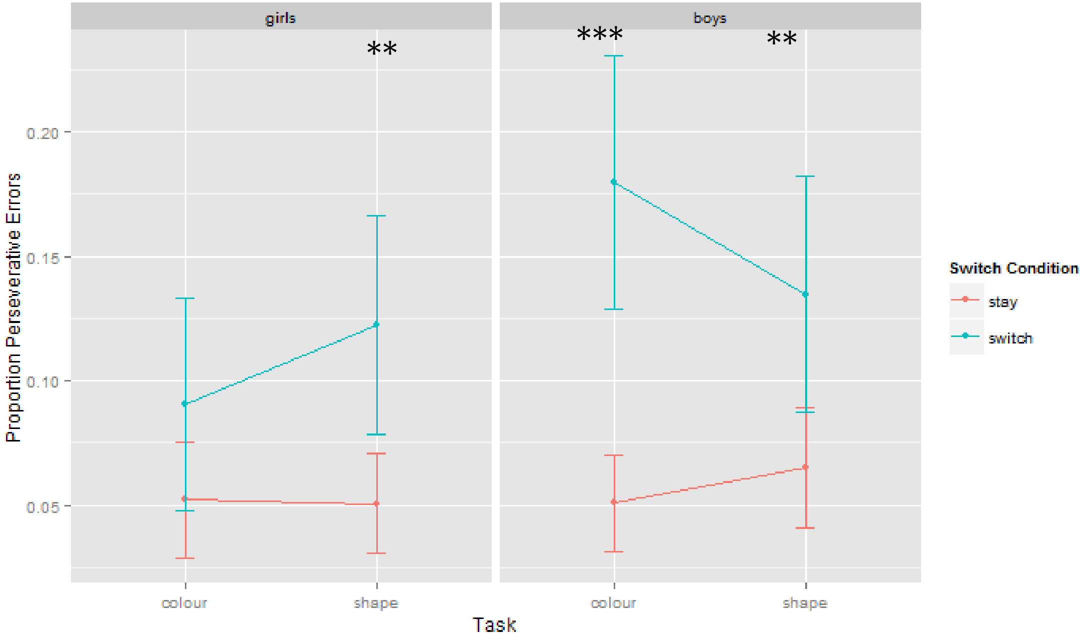

Figure 3. Proportion of trials on which a perseverative error was made, by switch condition, task, and sex. ** *p* < .01, *** *p* < .001.

Perseverative errors. Errors where children perseverate, or select the un-cued, incorrect stimulus attribute, are most indicative of conflict or interference from the other task (i.e., shape on colour trials), and as such suggest a failure of set shifting. Unsurprisingly, then, children made more perseverative errors on switch trials (*M* = 0.13, *SE* = 0.014) than on stay trials (*M* = 0.05, *SE* = 0.006; $\chi^2(1) = 27.11$, $p < .001$). This effect was qualified by an interaction between trial type, task, and sex: girls made increased perseverative errors on switch trials only when performing the shape task (stay trials: *M* = 0.05, *SE* = 0.010; switch trials: *M* = 0.12, *SE* = 0.021; $p = .0034$), not the colour task (stay trials: *M* = 0.05, *SE* = 0.011; switch trials: *M* = 0.09, *SE* = 0.020; $p = .11$), whereas boys made more perseverative errors on switch trials no matter the task (shape task: stay trials: *M* = 0.06, *SE* = 0.011; switch trials: *M* = 0.13, *SE* = 0.022; $p = .0092$; colour task: stay trials: *M* = 0.05, *SE* = 0.009; switch trials: *M* = 0.18, *SE* = 0.024; $p < .001$; $\chi^2(1) = 5.91$, $p = .0151$; Figure 3).

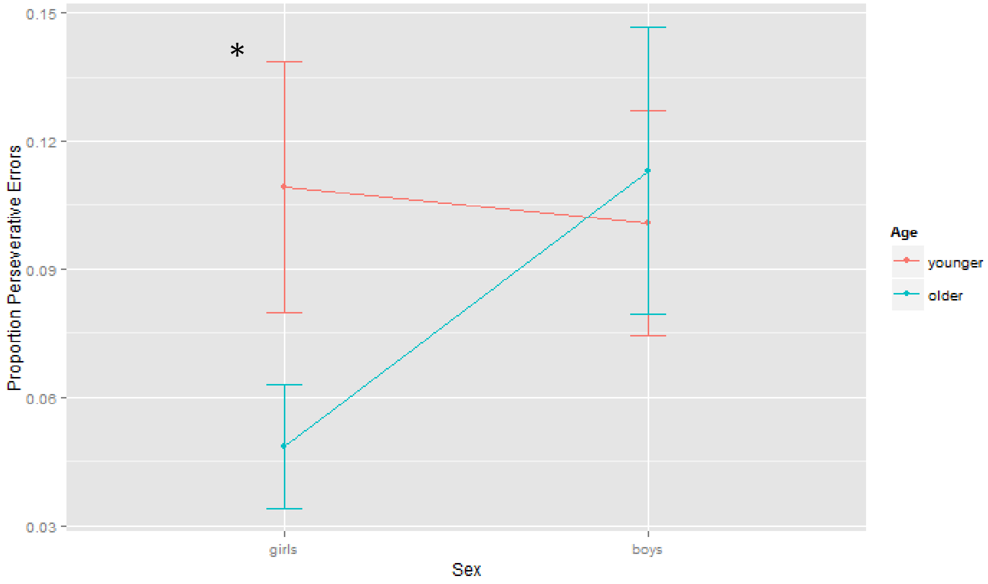

Figure 4. Perseverative errors by age and sex. * $p < .05$.

There was also an interaction between sex and age ($\chi^2(1) = 6.34$, $p = .012$). Significant age-related improvements were seen in girls, where older girls (*M* = 0.05, *SE* = 0.008) made fewer perseverative errors than younger girls (*M* = 0.11, *SE* = 0.018; $p < .001$); in contrast, boys in both age groups made equivalent numbers of perseverative errors (older boys: *M* = 0.11, *SE* = 0.018; younger boys: *M* = 0.10, *SE* = 0.011; $p = 0.58$; Figure 4), comparable to the amount of perseverative errors made by younger girls.

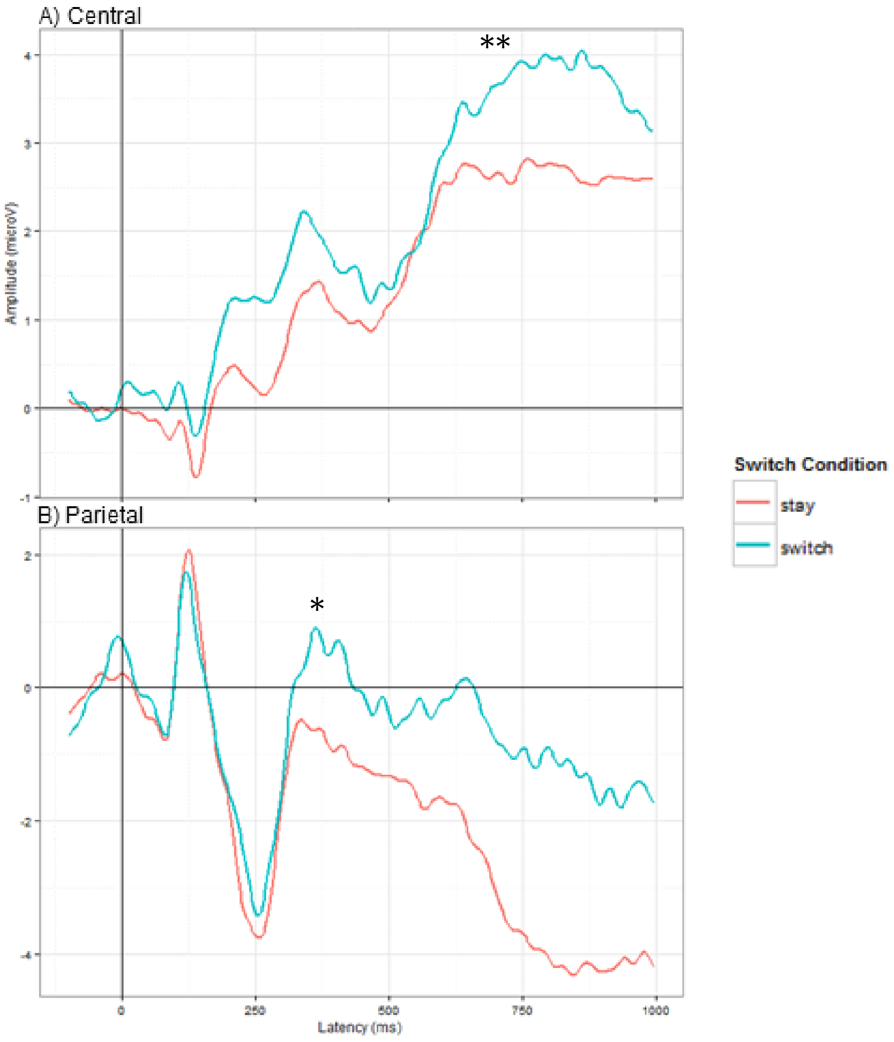

Figure 5. ERP response to cue presentation at A) the central electrode cluster, and B) the parietal electrode cluster, organized by switch condition. * $p < .05$, ** $p < .01$.

Event related potentials.

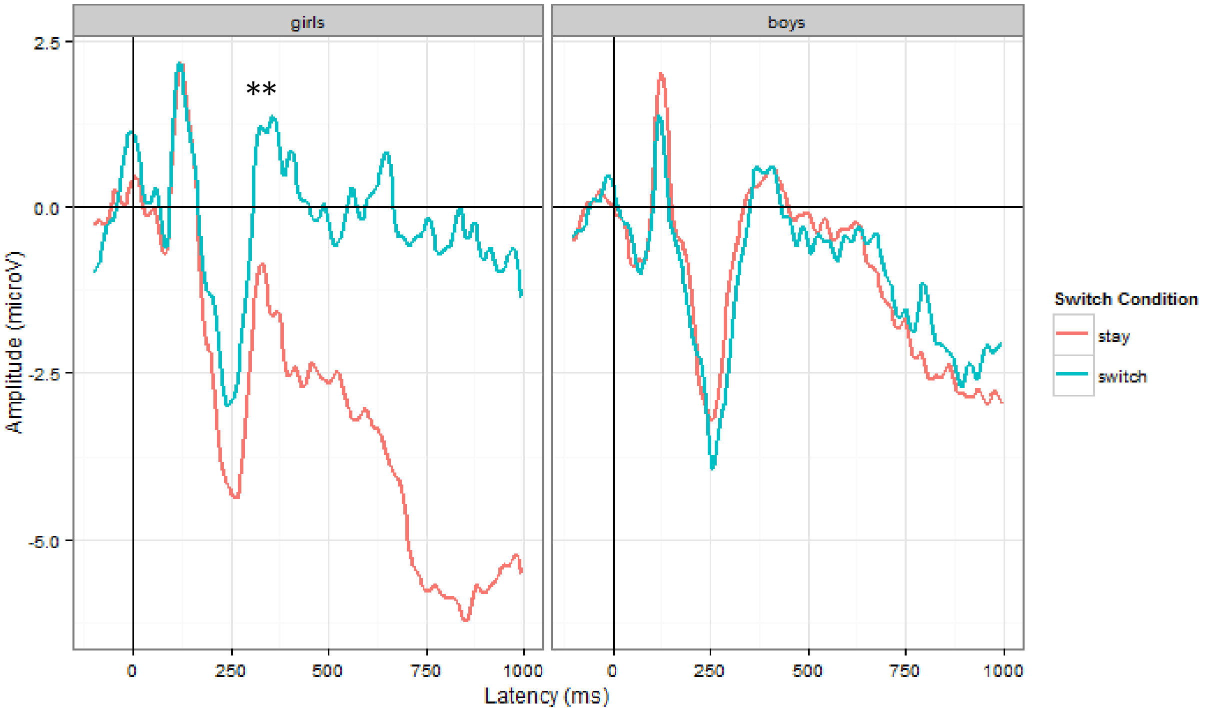

Figure 6. ERP response to cue at the parietal electrode cluster, organized by sex and switch condition. ** $p < .01$.

Cue-evoked P3. The amplitude and latency of the P3 elicited by task-cue presentation was analyzed at central and parietal electrode clusters. The P3 indexes task-set updating in task switching paradigms (Barceló et al., 2006, 2000; Karayanidis et al., 2010), resulting in larger amplitudes in switch trials than stay trials due to the required updating of task representations and response mappings (Barceló et al., 2000; Karayanidis et al., 2010). Consequently, I predicted that switch trials would result in larger P3 amplitudes than stay trials, which was confirmed at both central and parietal electrode clusters (central cluster: stay trials: $M = 4.54$ µV, $SE = 0.413$ µV; switch trials: $M = 6.18$ µV, $SE = 0.701$ µV; $\chi^2(1) = 7.09$, $p = .0078$; parietal cluster: stay trials: $M = 2.17$ µV, $SE = 0.627$ µV; switch trials: $M = 3.92$ µV, $SE = 0.519$ µV; $\chi^2(1) = 6.18$, $p = .0129$; Figure 5). At the parietal cluster, the switch effect was qualified by an interaction with sex ($\chi^2(1) = 5.13$, $p = .0235$). As shown in Figure 6, the switch effect was significant for girls (stay trials: *M* = 1.28 µV, *SE* = 0.946 µV; switch trials: *M* = 4.65 µV, *SE* = 0.671 µV; *p* = .0074) but not boys (stay trials: *M* = 3.00 µV, *SE* = 0.804 µV; switch trials: *M* = 3.24 µV, *SE* = 0.768 µV; *p* = .81).

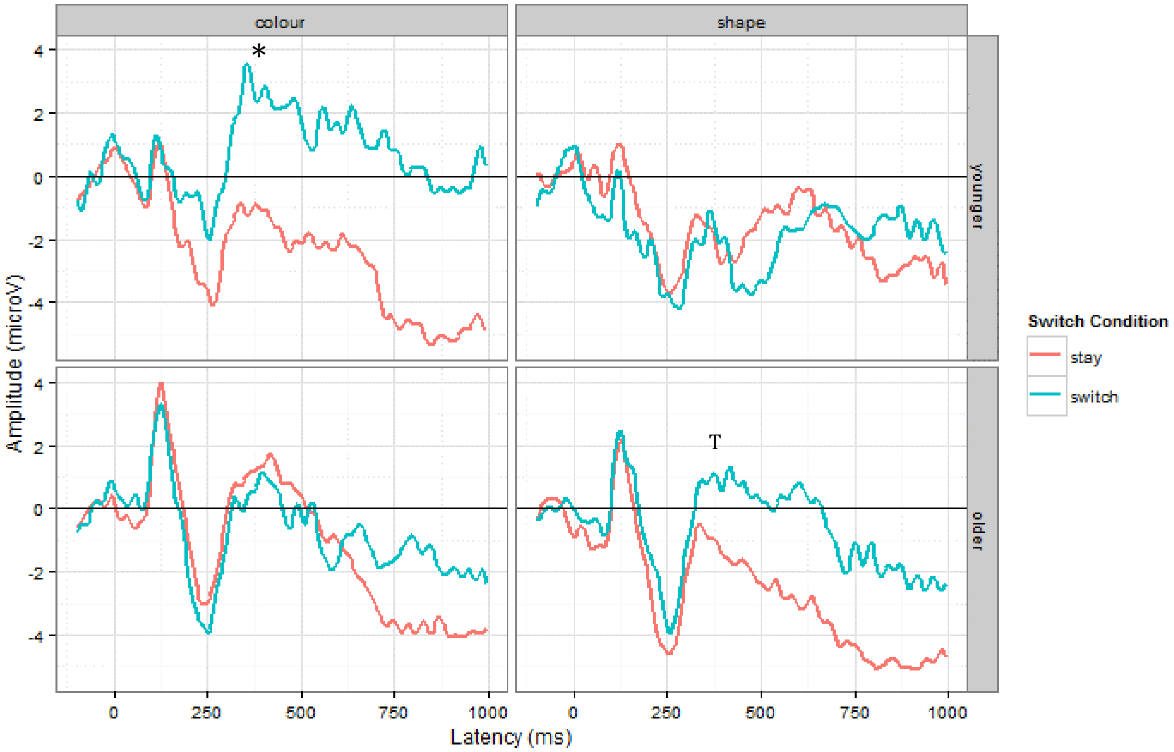

Figure 7. ERP to cue presentation at parietal electrode cluster, by age group, task, and switch condition. * $p < .05$, ${}^{T}p < .1$.

The interaction between age, task, and trial type was also significant ($\chi^2(1) = 8.27$, *p* = .004), and is depicted in Figure 7. At each age, switch effects differed by task, but the pattern of differences was moderated by age. For younger children at the parietal cluster, the P3 was larger for switch trials (*M* = 6.18 µV, *SE* = 1.307 µV) in the colour task only (stay trials: *M* = 1.72 µV, *SE* = 1.229 µV; *p* = .018; shape task: switch trials: *M* = 1.96 µV, *SE* = 0.971 µV; stay trials: *M* = 1.92 µV, *SE* = 0.987 µV; *p* = .97). For older children, the P3 was marginally larger on switch trials (*M* = 4.23 µV, *SE* = 0.914 µV) than on stay trials (*M* = 1.49 µV, *SE* = 1.102 µV; *p* = .064) in the shape task only (colour task: switch trials: *M* = 3.33 μV, *SE* = 1.118 μV; stay trials: *M* = 3.50 μV, *SE* = 1.037 μV; *p* = .91).

Because I expected age-related improvements in children's able to detect switch trial cues, resulting from greater access to proactive cognitive control strategies, I hypothesized that older children would show a greater difference in P3 amplitude in switch trials compared to stay trials than younger children would. Contrary to my prediction, the magnitude of the difference between P3 amplitude on switch and stay trials did not differ between younger and older children: there was no hint of an interaction between age and trial type at either electrode cluster (central: $\chi^2(1) = 0.02$, *p* = .90; parietal: $\chi^2(1) = 0.50$, *p* = .48).

For cue-evoked P3 latency, there were significant main effects of task ($\chi^2(1) = 6.04$, *p* = .0140) and sex ($\chi^2(1) = 4.43$, *p* = .0353) at the parietal electrode cluster. P3 peaks were earlier on shape trials (*M* = 399 ms, *SE* = 11.7 ms) than colour trials (*M* = 431 ms, *SE* = 12.6 ms), suggesting that working memory updating occurred more quickly in response to the shape cue relative to the colour cue. Girls' P3s (*M* = 395 ms, *SE* = 14.4 ms) peaked more quickly than boys' (*M* = 434 ms, *SE* =13.5 ms), suggesting increased processing efficiency in girls, consistent with other recent findings (Brumback, Arbel, Donchin, & Goldman, 2012).

At the central electrode cluster, there was a significant interaction between age and sex ($\chi^2(1) = 4.01$, *p* = .045), qualified by an interaction between age, sex, and task ($\chi^2(1) = 4.77$, *p* = .029). In the shape task only, older boys (*M* = 663 ms, *SE* = 33.1 ms) had faster latencies than younger boys (*M* = 750 ms, *SE* = 26.5 ms, *p* = .029), and younger girls (*M* = 677 ms, *SE* = 22.0 ms) had marginally faster latencies than older girls (*M* = 746 ms, *SE* = 31.9 ms, *p* = 0.056). There were no significant age differences in the colour task (boys: younger: *M* = 712 ms, *SE* = 41 ms, older: *M* = 682 ms, *SE* = 16.2 ms, *p* = .36; girls: younger: *M* = 741 ms, *SE* = 23.3 ms, older: *M* = 731 ms, *SE* = 20.6 ms, *p* = .72). Previous research has suggested that the colour task is dominant in children (Ellefson et al., 2006), so it is possible that all children reacted to colour trials similarly, leaving shape trials more sensitive to age differences in processing efficiency.

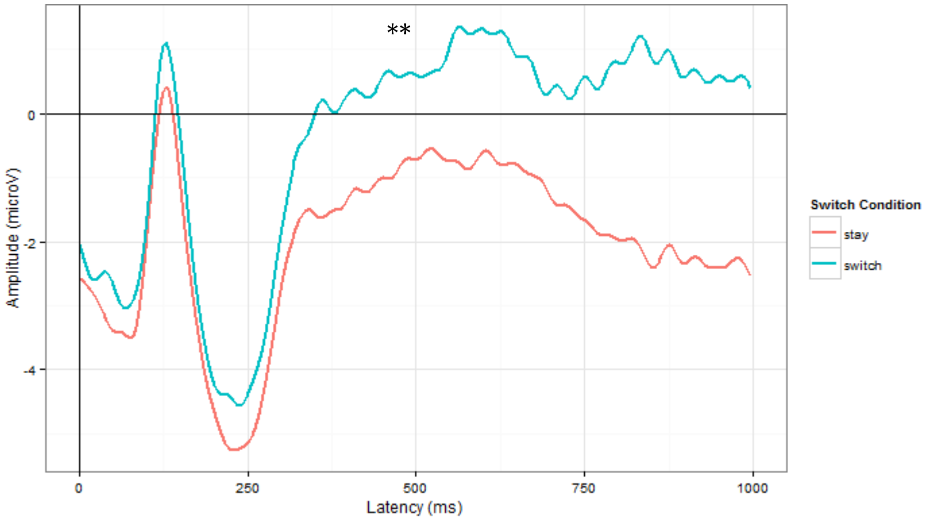

Figure 8. ERP response to stimulus presentation from parietal electrode cluster, by switch condition. ** *p* < .01.

Stimulus-evoked P3. The amplitude and latency of the P3 elicited by stimulus presentation were analyzed to determine degree that attentional resources were recruited for stimulus processing. For children who use a proactive cognitive control strategy, the current task (and thus response hand) should already be updated in working memory, so fewer attentional resources are required to process the stimulus effectively, reducing differences between switch and stay trials. Thus, I predicted that older children would have P3 amplitudes in stay trials that were comparable, or even larger than, switch trials (Barceló et al., 2000, 2002; Gajewski & Falkenstein, 2011; Hsieh & Liu, 2009; Ikeda & Hasegawa, 2012; Jost et al., 2008; Karayanidis & Coltheart, 2003; Karayanidis et al., 2011), consistent with the use of a proactive strategy. In contrast, I predicted that younger children, if they favoured a reactive control strategy, would have larger P3 amplitudes in switch trials than in stay trials at the stimulus, suggesting that all the task-switching processes were engaged at the stimulus instead of at the cue. Contrary to my prediction, there were no age differences in P3 amplitude at either cluster (central: $\chi^2(1) = 1.57$, $p = .21$; parietal: $\chi^2(1) = 2.86$, $p = .091$). Similarly, the predicted interaction between age and trial type such that younger children would have larger P3 amplitudes in response to switch trials when compared to stay trials and older children would not, or even have the reverse pattern, was also non-significant at both electrode clusters (central: $\chi^2(1) = 0.007$, $p = .94$; parietal: $\chi^2(1) = 0.03$, $p = .87$).

At the parietal electrode cluster, switch trials ($M = 5.53$ µV, $SE = 1.070$ µV) produced larger-amplitude P3s than did stay trials ($M = 2.76$ µV, $SE = 1.185$ µV; $\chi^2(1) = 7.04$, $p = .008$; Figure 8) in both age groups. This suggests that both younger and older children engaged more working memory processes in switch trials than on stay trials upon stimulus presentation, consistent with a reactive control strategy.

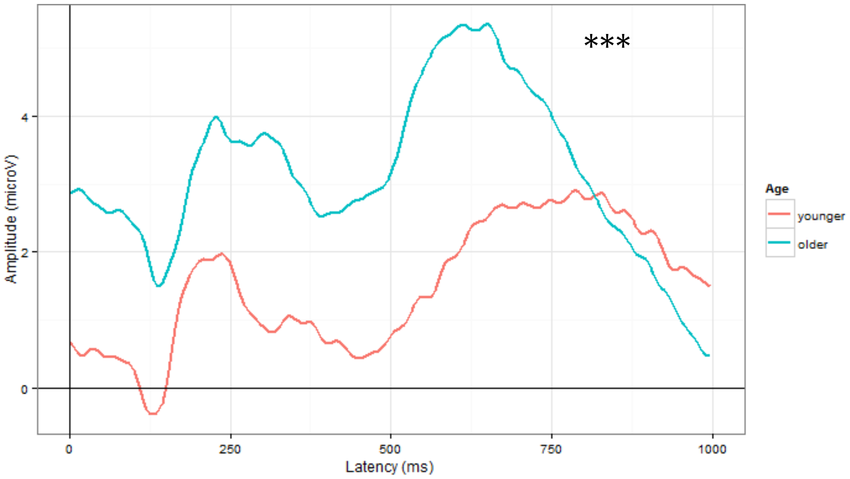

Figure 9. ERP response to stimulus presentation from central electrode cluster, by age group. *** $p < .001$.

At the central electrode cluster, older children's P3s ($M = 593$ ms, $SE = 17.2$ ms) peaked sooner than those of younger children ($M = 681$ ms, $SE = 15.4$ ms; $\chi^2(1) = 12.65$, $p < .001$;

Figure 9), consistent with increased processing speed or efficiency in older children compared to younger children.

Lateralized readiness potential. The LRP, an index of motor preparation, was analyzed following cue presentation. In similar tasks, the LRP has been found to begin at cue presentation in adults (Steinhauser et al., 2009) and is thought to reflect the proactive engagement of response selection processes. Because the LRP following cue presentation is a slow wave without a defined peak, the appropriate dependent measure was the area under the curve of the LRP waveform (in 200 ms bins) rather than the peak amplitude and latency. Models for the LRP analysis were similar to those for other behavioural and electrophysiological indices, but also included a latency factor. If children were using a proactive strategy, I predicted that LRP onset would occur following cue presentation, reflecting the selection of the appropriate response hand prior to stimulus presentation, and that this would not occur if a reactive strategy was used. The resulting age by latency bin interaction, such that older children had LRPs that began to rise before those of younger children, was not significant ($\chi^2(1) = 5.05$ $p = .28$). I also predicted that age would interact with trial type, such that older children would have larger LRPs on stay trials than on switch trials, as the LRP is sensitive to the certainty of the selection of response hand (Gratton et al., 1988); this prediction also was not supported, as the interaction was non-significant ($\chi^2(1) = 1.15$, $p = .28$).

The interaction between sex, task, and age was significant ($\chi^2(1) = 6.32$, $p = .011$; Figure 10). Younger girls had larger LRP amplitudes in the shape task ($M = 25.19$ µV, $SE = 34.200$ µV) when compared with the colour task ($M = -141.60$ µV, $SE = 64.434$ µV, $p < .001$). In contrast, older girls and, marginally, younger boys had larger LRP amplitudes in the colour task (older girls: $M = 14.38$ µV, $SE = 75.723$ µV; younger boys: $M = 32.71$ µV , $SE = 59.692$ µV) when compared with the shape task (older girls: *M* = -94.91 µV, *SE* = 76.032 µV, *p* = .012; younger boys: *M* = -21.26 µV, *SE* = 26.333 µV, *p* = .086). Older boys had equivalent amplitudes in both tasks (shape: *M* = 4.83 µV, *SE* = 32.530 µV; colour: *M* = -5.13 µV, *SE* = 29.891 µV; *p* = .63). It is important to note that these differences do not reflect the presence of the LRP: visual inspection of the waveforms in Figure 10 reveals that the LRP presence is inconsistent among subgroups of children. An LRP corresponding to the proactive selection of the correct response hand would be indicated by a positive slow-wave following cue presentation, which is visible only in young girls in the shape task and young boys in the colour task.

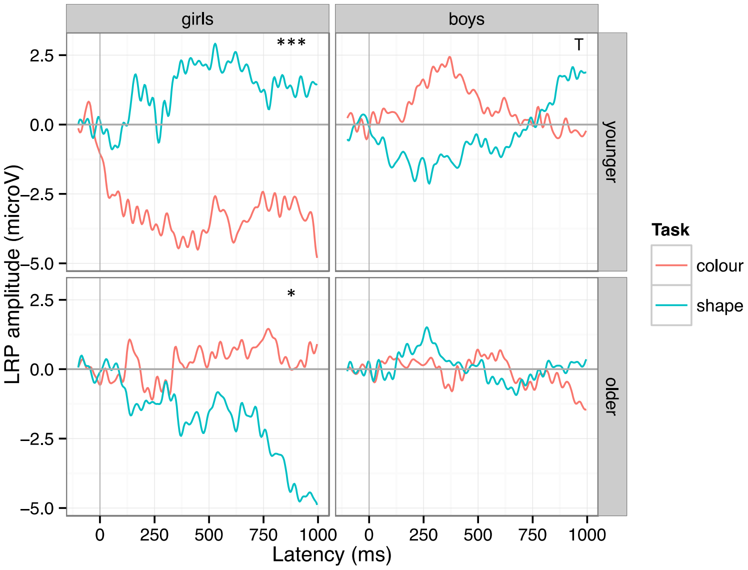

Figure 10. LRP amplitude by age, sex, and task. $^{T}p < .1$, $^{*}p < .05$, $^{***}p < .001$.

Discussion

The purpose of this study was to use ERPs to investigate age differences in the neural correlates of proactive and reactive cognitive control strategies in the period spanning the transition to school, a key period in executive control development (Best et al., 2009; Hughes et al., 2010). Specifically, 4 and 5 year olds and 7 and 8 year olds performed a cued task-switching paradigm, where performance benefitted from a proactive strategy, while their EEG was recorded. Taking advantage of the high temporal resolution of ERPs, this study described the temporal dynamics of resource allocation in attentional and motor systems when children were given the option to engage with the task reactively or proactively. To determine which form of control children were using, the P3 and LRP, ERP indexes of working memory load and response preparation, respectively, were computed.

I predicted that older children, due to their improved cognitive control and working memory capacity, would preferentially engage in a proactive control strategy, and that younger children would favor a reactive control strategy. Upon cue presentation, both age groups appeared to allocate more working memory or attentional resources towards switch trials than towards stay trials, based on the cue-evoked P3 amplitude. One could argue that children at both ages engaged with the cue proactively (Barceló et al., 2006; Barceló, Muñoz-Céspedes, Pozo, & Rubia, 2000; Barceló et al., 2002; Cunillera et al., 2012; Gajewski & Falkenstein, 2011; Jost, Mayr, & Rosler, 2008; Karayanidis & Coltheart, 2003; Karayanidis et al., 2010), recognizing the need to switch and performing the required shift of task set. However, when this effect was broken down by task, another explanation emerges. Younger children only showed this switch effect when presented with the colour cue, which was likely more visually salient than the shape cue. It is possible that younger children had larger P3s, suggesting greater attentional resource allocation, to switch trials in the colour task due to the novelty of this visually salient cue and the dominance of sorting by colour rather than shape (Ellefson et al., 2006). Older children showed the switch effect only marginally and only in the shape task, suggesting that they at most were engaging with the cue proactively to a small degree in the less-dominant shape task (Ellefson et al., 2006). Neither age group consistently demonstrated proactive engagement of response selection processes, as indicated by a consistent post-cue LRP, which has been found in similar tasks in adults (Steinhauser et al., 2009). Further evidence for a reactive strategy in both age groups was found at the stimulus-evoked P3: children allocated more attentional resources towards switch trials than stay trials upon stimulus presentation, suggesting that processes involved in the task-switch were not occurring in advance of the stimulus. Adults typically show the inverse effect, namely greater attentional resources towards stay trials than switch trials at stimulus presentation (Barceló et al., 2000, 2002; Gajewski & Falkenstein, 2011; Hsieh & Liu, 2009; Ikeda & Hasegawa, 2012; Jost et al., 2008; Karayanidis & Coltheart, 2003; Karayanidis et al., 2011). This suggests that the older children in this study were not yet demonstrating adult-like patterns of control.

Together, the results of the ERP analysis suggest that neither age group engaged with the cue in a planful, proactive manner, contrary to what was found previously using pupillometry (Chatham et al., 2009). One reason for this discrepancy may be differences in task organization. Although both tasks utilize cue-task pairings to allow for proactive control, the cued task-switching paradigm used in this study is more complex than the AX-CPT task used by Chatham et al.. The AX-CPT used by Chatham et al. requires children to only sort by one arbitrary dimension, whether or not the cued character “likes” the stimulus, requiring only two response options, “like” or “dislike”. The task used in the current study involves sorting by two separate dimensions, colour or shape, requiring four response options. Additionally, the unequal presentation distribution of cue-probe pairings in the AX-CPT, such that AX trials occur most frequently, might cause there to be a greater benefit of proactive control and makes proactive preparation easier: children know that if the A cue is presented, they are likely to need to make an X response. Although performance in the task used in the current study benefitted from proactive control, maintaining both response options for the cued attribute was complicated and likely more difficult than proactive maintenance in the AX-CPT (Chatham et al., 2009).

Although both younger and children appear to have performed the task similarly, using a reactive control strategy, older children performed much better, a difference that could be attributed to improved efficiency of the prefrontal cortex in this age range (Welsh et al., 1991). Older children performed the task more quickly and more accurately than younger children. Furthermore, following stimulus presentation, older children had faster P3 peak latencies, suggesting that, although both age groups performed the task in similar ways, older children were more efficient (Polich, 2010). It is possible that increased maturity in the connectivity between the brain regions required for reactive control, namely the prefrontal cortex, anterior cingulate, and basal ganglia allows older children to recruit reactive control more efficiently and reliably, resulting in better performance. To track, this development, it would be necessary to understand the specific ERP signatures of reactive and proactive control in the adult brain. Without a solid understanding of the endpoint of child development, it is difficult to know what more mature patterns of control look like in the present task. For the purpose of forming hypotheses, I assumed that adults favoured proactive modes in cued task switching paradigms, but it is possible that when performing a complex paradigm with the additional load of hand-dominance and colour-dominance, adults may favour a reactive strategy as well. It may be beneficial to conduct a similar analysis in adults using a complicated paradigm like that used here.

There were sex differences in performance on this task: girls performed the task more efficiently and more accurately than did boys. Older girls made fewer perseverative errors, reflecting difficulty switching task-set, than younger girls or boys in either age group. At the cue, girls showed greater attentional resource allocation towards switch trials compared to stay trials, where boys did not, suggesting that girls may have had a greater tendency to engage with the cue proactively. Girls also demonstrated greater efficiency in cue processing, consistent with previous findings (Polich, 2010), producing P3s that peaked more quickly than those of boys. Shorter P3 latencies in girls compared to boys has been found previously in pre-adolescents (Brumback et al., 2012), and, developmentally, girls have been shown to reach peak gray-matter volumes in frontal and parietal cortex earlier than boys (Giedd et al., 1999), suggesting differential developmental time courses between the sexes. Studies of preschool cognitive control have also demonstrated advantages for girls in inhibitory control (Wiebe et al., 2012) and executive function more generally (Wiebe et al., 2008). It is important to note, however, that sex differences in executive control are not consistently found (Carlson & Wang, 2007; Wiebe et al., 2011). The results of this study further demonstrate the importance of examining sex differences in studies of childhood cognitive control.

The LRP analyses failed to show evidence of proactive control. In part, this may be because the methods available proved unable to capture some of the complexity of this response, a limitation of the chosen methodology. The high level of variability in children’s LRP waveforms made it impossible to determine LRP onset latency. One previous study examining the LRP in children defined the onset latency as the point when the LRP amplitude exceeded the mean plus 1.5 standard deviations of the baseline amplitude (Ridderinkhof & van der Molen, 1995), but this definition was not appropriate in the current study because some children had absent or even negative-going LRP waveforms which never exceeded this value. Negative-going LRP waveforms could indicate that children were activating the incorrect response hand, an important result that would not be properly captured. Peak amplitude was also not an appropriate measure of the LRP in this case due to the slow-wave form of the LRP following cue presentation (Steinhauser et al., 2009). Using area under the curve in latency segments following cue presentation captured both the magnitude and direction of the LRP, but suffered from other limitations, such as a failure to capture the unfolding of the LRP over time. A further limitation of this study is the sample size, which was sufficient for the primary age comparisons but yielded small cell sizes when considering complex interactions.

Although childhood set-shifting tasks typically require children to sort by shape and colour (e.g., the Dimensional Change Card Sort (Zelazo, 2006), or the Shape School (Espy et al., 2006)), the present study's findings suggest that the two tasks are not equivalent. Although both concepts are familiar to young children, previous work has found asymmetrical switch costs (Ellefson et al., 2006): the performance difference between switch and stay trials is larger for the colour task than for the shape task. This finding has been attributed to the dominance of the colour task: in the shape task, children must allocate more attention resources towards stay trials than they do in the easier colour task, resulting in smaller switch costs in the shape task. The paradigm used in the current study was further complicated because the colour and shape tasks were lateralized to a single hand. Although this task feature was intended to reveal motor preparatory processes, interpretation was complicated by many complex, significant interactions between task and button position. In adults, one way to circumvent this complexity would be to use stimuli affording a greater degree of control, such as single digits, and have participants identify attributes of these, such as whether the presented number is greater than or less than a particular value or if it is odd or even. Unfortunately, mathematical concepts such as these are beyond the capability of young children, and the simple stimuli might also reduce children's engagement.

In conclusion, when presented with a complex, cognitively demanding task switching paradigm, both 4 and 5 year olds and 7 and 8 year olds appear to favour reactive cognitive control strategies, contrary to my expectations and similar studies with simpler tasks (Chatham et al., 2009). This study represents a novel extension of methodology that has been used to study task switching in adults to provide information about childhood cognition. The findings also suggest that proactive control may not always be optimal given high cognitive load: When children are presented with a cognitively demanding task, it might not pay to plan ahead.

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Appendix: Interactions involving button position

Behavioural performance.

Proportion correct. In addition to the main effect of age on accuracy, there was also an interaction between age group, sex, and button position that did not follow any systematic pattern ($\chi^2(1) = 8.34$, $p = .039$). Age differences were found in two of the four button conditions in girls (condition 1: $p = .0055$; condition 2: $p = .00029$), and two in boys (condition 1: $p = .0023$; condition 4: $p = .039$). Full descriptive statistics for this interaction are presented in Table A1.

Table A1

Descriptive statistics for the interaction between age, button condition and sex on proportion correct

Button Condition	Sex	Age Group	*N*	Proportion correct		*p* < .05
				M	*SE*	
1	female	older	3	0.93	0.008	*
		younger	3	0.83	0.057	
	male	older	2	0.96	0.015	*
		younger	2	0.74	0.036	
2	female	older	3	0.83	0.085	
		older	2	0.81	0.130	
	male	younger	3	0.77	0.029	
		older	2	0.83	0.081	
3	female	younger	2	0.95	0.010	*
		older	3	0.68	0.110	
	male	older	2	0.79	0.031	
		younger	2	0.82	0.067	
4	female	older	2	0.84	0.025	
		younger	2	0.76	0.051	
	male	older	3	0.80	0.053	*
		younger	2	0.69	0.003	

Response time. An age by task by button condition interaction was found in response time ($\chi^2(1) = 8.78$, $p = .03$): younger children responded more slowly than older children in the colour task when the colour buttons were presented on the left (condition 3: $p = .028$; condition 4: $p = .064$). Younger children responded more slowly than older children in the shape task when the shape task was presented on the left in one button condition (condition 1: $p = .049$) and when the shape task was presented on the right in another (condition 3: $p = .0068$). Older and younger children did not differ in any of the other button condition and task combinations. Full descriptive statistics for this interaction are presented in Table A2. Interactions between trial type, age, sex and button condition ($\chi^2(1) = 17.03$, $p < .0001$) as well as task, age, sex, and button condition were found, but neither produced significant pairwise comparisons ($\chi^2(1) = 12.59$, $p = .0056$).

Table A2

Descriptive statistics for the interaction between age, button condition and task on response time

Button Condition	Task	Age Group	*N*	Response Time (ms)		$p < .05$
				M	*SE*	
1	colour	older	5	1359	82.0	
		younger	5	1427	71.7	
	shape	older	5	1211	100.8	*
		younger	5	1371	25.8	
2	colour	older	6	1247	132.8	
		younger	4	1314	95.0	
	shape	older	6	1155	108.5	
		younger	4	1336	124.4	
3	colour	older	4	1221	112.3	*
		younger	5	1462	77.8	
	shape	older	4	1219	65.4	*
		younger	5	1484	93.7	
4	colour	older	5	1137	69.7	T
		younger	4	1337	132.4	
	shape	older	5	1241	84.9	
		younger	4	1279	141.0	

Perseverative errors. A main effect of button condition on the proportion of trials where children made perseverative errors was found, but followed no systematic pattern ($\chi^2(1) = 3.90$, $p = .048$). Children in button condition 1 made fewer perseverative errors than children in conditions 2 ($p = .028$) or 4 ($p = .037$). Full descriptive statistics describing this effect can be found in Table A3.

Table A3

Descriptive statistics for the interaction between age, button condition and task on response time

Button Condition	*N*	Perseverative Errors	
		M	*SE*
1	10	0.06	0.012
2	10	0.11	0.020
3	9	0.10	0.017
4	9	0.11	0.012

Event related potentials.

Cue-evoked P3. An interaction between task, age, sex, and button condition was found on P3 amplitude at the parietal electrode cluster ($\chi^2(1) = 15.31$, $p = .0016$). Older girls in the button condition where the colour buttons were presented on the right and the shell and purple buttons were presented on top (condition 1) had smaller P3 amplitudes than younger girls in the shape task only ($p = .0067$). This age difference was not found in any other combination of age, sex, button condition, and task. Descriptive statistics for this effect are depicted in Table A4.

Also at the parietal electrode cluster, interactions between task and button condition ($\chi^2(1) = 11.96$, $p = .0075$) and between task, sex, and button condition were found ($\chi^2(1) = 8.27$, $p = .041$). For boys, P3s in response to the colour task had shorter latencies than those elicited by the shape task, but only in the button condition where colour was presented on the right and the star and green buttons were presented on top (condition 2: $p = 0.0013$;). No other combinations of sex and button condition produced significant differences in P3 latency between the tasks. Descriptive statistics for this interaction are presented in Table A5.

Table A4

Descriptive statistics for the interaction between age, sex, button condition and task on P3 amplitude at the parietal electrode cluster

Button Condition	Task	Sex	Age Group	N	P3 amplitude		$p < 0.05$
					M	*SE*	
1	colour	female	older	3	1.94	1.241	
			younger	2	0.45	1.411	
		male	older	3	3.12	2.444	
			younger	2	5.01	3.388	
	shape	female	older	3	-1.73	0.125	*
			younger	2	5.10	1.816	
		male	older	3	2.96	1.118	
			younger	2	2.22	0.039	
2	colour	female	older	3	5.07	2.784	
			younger	2	10.18	3.123	
		male	older	2	1.75	1.383	T
			younger	2	5.08	1.505	
	shape	female	older	3	3.53	2.728	
			younger	2	-0.10	0.537	
		male	older	2	1.51	0.299	T
			younger	2	6.87	3.085	
3	colour	female	older	1	4.99	N/A	
			younger	3	2.11	0.973	
		male	older	2	3.48	0.986	
			younger	2	2.42	1.717	
	shape	female	older	1	6.13	N/A	T
			younger	3	-0.76	2.130	
		male	older	2	4.10	0.751	
			younger	2	1.23	2.854	
4	colour	female	older	1	8.68	N/A	T
			younger	2	3.76	0.501	
		male	older	3	2.31	3.976	
			younger	2	3.53	4.164	
	shape	female	older	1	6.88	N/A	T
			younger	2	2.48	1.576	
		male	older	3	4.34	3.016	
			younger	2	-0.16	3.791	

At the central electrode cluster, an interaction between task and button condition on P3 amplitude ($\chi^2(1) = 8.29$, $p = .040$) and a main effect of button condition on P3 latency ($\chi^2(1) = 8.30$, $p = .040$) both resulted in no significant pairwise comparisons.

Table A5

Descriptive statistics for the interaction between sex, button condition and task on P3 latency at the parietal electrode cluster

Button Condition	Sex	Task	N	P3 Latency (ms)		$p <$ .05
				M	*SE*	
1	female	colour	5	396	21.8	
		shape	5	385	27.5	
	male	colour	5	410	37.4	
		shape	5	429	45.1	
2	female	colour	5	378	36.7	T
		shape	5	447	30.0	
	male	colour	4	383	15.2	*
		shape	4	514	21.8	
3	female	colour	4	382	52.7	
		shape	4	396	33.6	
	male	colour	4	406	34.7	
		shape	4	479	27.9	
4	female	colour	3	365	27.4	
		shape	3	394	37.8	
	male	colour	5	449	32.5	
		shape	5	413	31.0	

Stimulus-evoked P3. A significant main effect of button position was found on P3 latency at the central electrode cluster was found, but this effect followed no systematic pattern. Button condition 1 significantly differed from condition 4, but no other differences were found $\chi^2(1) = 8.89$, $p = .031$). Descriptive statistics for this effect are presented in Table A6.

An interaction between age and button position was found on P3 latency at the central electrode cluster. Younger children had longer P3 latencies than older children in all but one button position condition (condition 2; $\chi^2(1) = 8.36$, $p = .039$). Descriptive statistics depicting this effect are presented in Table A7.

Table A6

Descriptive statistics for the main effect of button condition on P3 latency at the central electrode cluster

Button Condition	N	P3 Latency (ms)	
		M	*SE*
1	10	618	28.0
2	9	679	21.6
3	8	651	30.2
4	8	594	23.7

Table A7

Descriptive statistics for the interaction between age and button condition on P3 latency at the central electrode cluster

Button Condition	Age Group	N	P3 Latency (ms)		$p < .05$
			M	*SE*	
1	older	6	564	16.2	*
	younger	4	698	40.4	
2	older	5	677	35.3	
	younger	4	682	27.0	
3	older	3	565	31.7	*
	younger	5	703	22.0	
4	older	4	553	16.4	*
	younger	4	636	34.8	

At the central electrode cluster, an interaction between task and button condition was found ($\chi^2(1) = 14.07$, $p = .0028$): P3 amplitude was larger for shape trials than for colour trials, but only in one button position group (condition 1; $p = .016$). This difference was not significant for any of the other button position groups. This effect was further qualified by an interaction between task, button position condition, sex, and age ($\chi^2(1) = 10.93$, $p = .0121$), but due to the small cell size after breaking down by all three between-subject factors, it was not possible to compute pairwise comparisons for this effect. Descriptive statistics showing this effect are depicted in Table A8.

At the central electrode cluster, significant interactions between button condition and sex ($\chi^2(1) = 8.95, p = .030$) and between switch condition, age, sex ($\chi^2(1) = 4.54, p = .033$), and button condition ($\chi^2(1) = 11.27, p = .01$) on P3 amplitude produced no significant pairwise comparisons. Similarly, at the parietal electrode cluster, interactions between task, sex, button condition ($\chi^2(1) = 14.65, p = .0021$), and age ($\chi^2(1) = 11.73, p = .0084$) and between trial type, task, and age ($\chi^2(1) = 4.03, p = .045$) on P3 amplitude, as well as between trial type, task, sex, and button condition ($\chi^2(1) = 10.06, p = .018$) on P3 latency produced no significant pairwise comparisons.

Table A8

Descriptive statistics for the interaction between task and button condition on P3 amplitude at the central electrode cluster

Button Condition	Task	N	P3 Amplitude		$p < 0.05$
			M	*SE*	
1	colour	10	4.60	1.171	*
	shape	10	9.16	1.813	
2	colour	9	6.26	1.952	
	shape	9	8.04	1.858	
3	colour	8	6.10	2.407	
	shape	8	3.97	2.022	
4	colour	8	5.60	1.478	
	shape	8	3.83	1.090	

Lateralized readiness potential. A significant interaction between age and task according to latency bin and button condition was found in the LRP ($\chi^2(1) = 32.90, p = .001$).

Figure A1 shows mean area under the LRP curve for each combination of age, task, button condition, and latency bin.

Table A9

Descriptive statistics for the interaction between task, sex, and button condition on LRP area under the curve

Button Condition	Sex	Task	N	LRP area under curve		$p < .05$
				M	*SE*	
1	female	colour	3	35.23	40.929	
		shape	3	-34.33	80.817	
	male	colour	5	32.62	50.975	
		shape	5	32.10	47.085	
2	female	colour	3	157.61	98.519	*
		shape	3	-110.95	109.574	
	male	colour	4	43.06	86.363	
		shape	4	17.65	39.301	
3	female	colour	3	-167.53	108.594	
		shape	3	-64.45	144.601	
	male	colour	4	16.99	18.489	*
		shape	4	-44.15	37.239	
4	female	colour	4	-206.21	35.993	*
		shape	4	28.98	65.690	
	male	colour	5	-38.59	78.057	
		shape	5	-35.26	43.583	

A button condition by sex by task interaction was found in LRP amplitude ($\chi^2(1) = 8.96$, $p = .03$): girls in one of the colour-right button conditions (condition 2) had significantly larger LRP amplitudes in the colour task than in the shape task ($p < .001$), while girls in one of the shape-right button conditions (condition 4) had significantly larger LRP amplitudes in the shape task than in the colour task ($p < .001$). Boys had significantly larger LRP amplitudes in the colour task in one of the shape-right conditions (condition 3; $p = .045$). Descriptive statistics for this effect are depicted in Table A9. This effect was qualified by an interaction between task, age, sex, and button condition ($\chi^2(1) = 55.06$, $p < 0.001$), but due to having one child in some cells when broken down this way, pairwise comparisons were not computed.

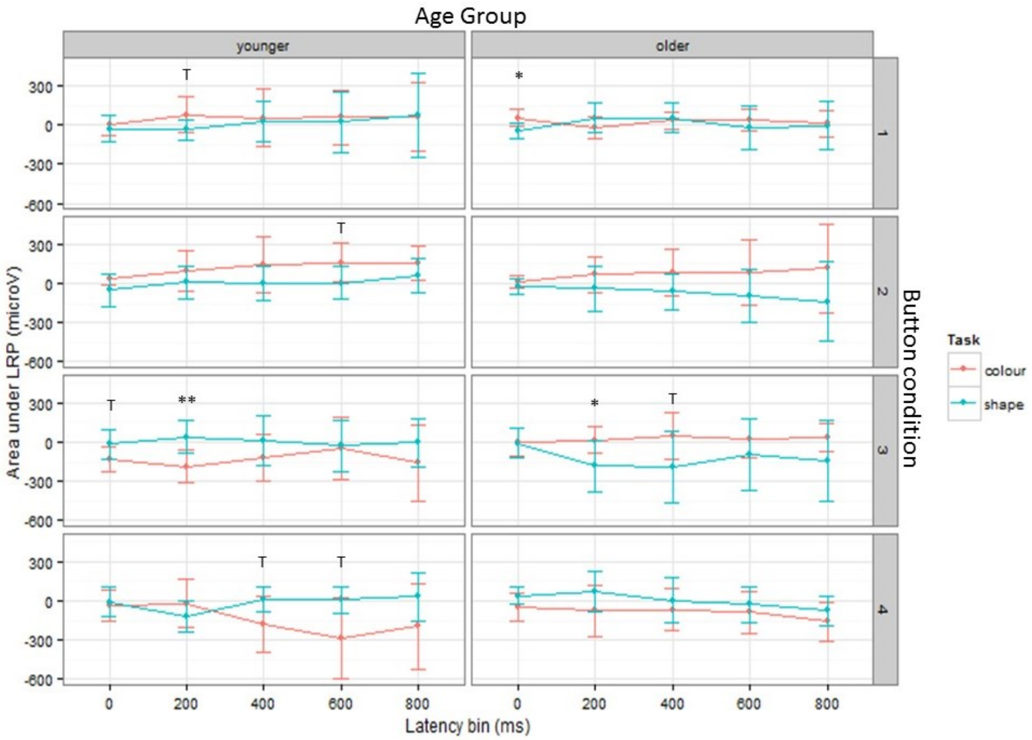

Figure A1. Mean area under the curve values for the LRP, by age group, button condition, latency bin, and task. $^{T}p < .1$, $^{*}p < .05$, $^{**}p < .01$.

There was a significant interaction between button position, latency bin, and task ($\chi^2(1) = 21.37$, $p = .045$). This interaction was followed up by examining the effects of task and latency bin separately for children in button conditions where the colour was on the right versus the left. Effects were limited to the colour task. As illustrated in Figure A2, between 400 and 600 milliseconds, one of the colour-right button conditions (condition 2: $M = 109.21$ µV, $SE = 73.198$ µV) differed from one colour-left condition (condition 4: $M = -119.61$ µV, $SE = 75.488$ µV, $p = .013$), but the other two did not differ significantly (condition 1: $M = 41.33$ µV, $SE = 45.661$ µV; condition 3: $M = -47.67$, $SE = 59.481$). Between 600 and 800 milliseconds, children had significantly larger LRP amplitudes in button conditions where colour was presented on the right (condition 1: *M* = 48.40 µV, *SE* = 49.604 µV, *p* = .04; condition 2: *M* = 118.96 µV, *SE* = 88.313, *p* = .006) than in one of the button conditions where colour was presented on the left (condition 4: *M* = -177.24 µV, *SE* = 77.112 µV), but not the other (condition 3: *M* = -14.39 µV, *SE* = 70.82 µV).

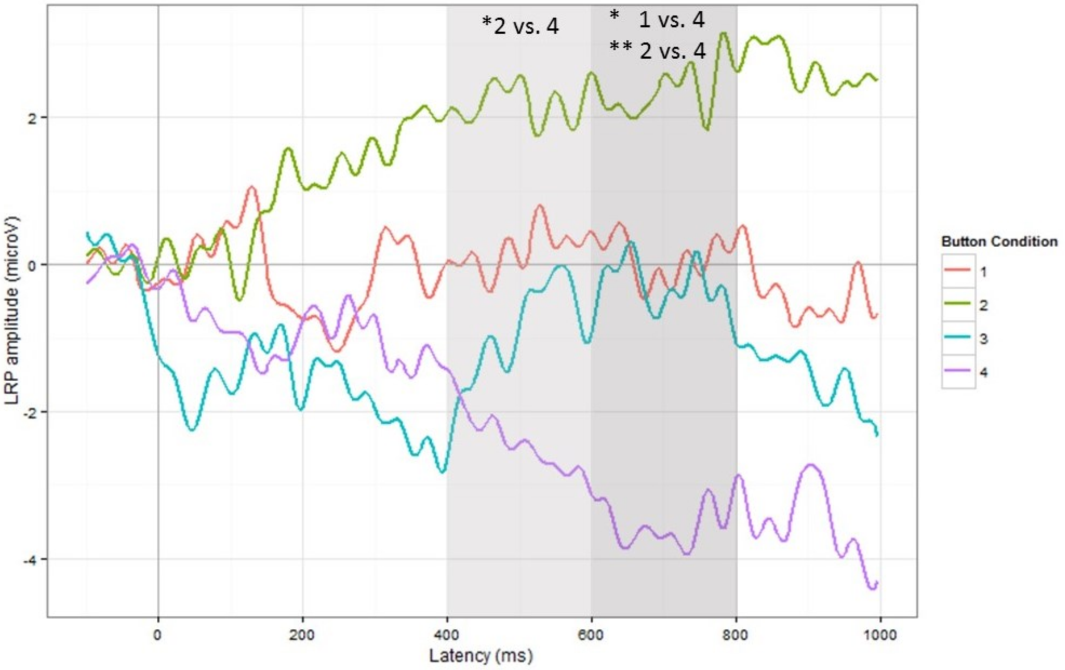

Figure A2. The lateralized readiness potential response to cue presentation on colour trials, by button position condition. Conditions 1 and 2 have the colour buttons presented on the right, and conditions 3 and 4 have colour presented on the left. * $p < .05$, ** $p < .01$.

A task by latency bin by sex interaction resulted in no significant pairwise comparisons ($\chi^2(1) = 22.79$, $p = .001$). Interactions between trial type, age, sex, and button condition ($\chi^2(1) = 8.16$, $p = .043$), between latency bin, age, sex, and button condition ($\chi^2(1) = 27.11$, $p < .001$), between task, latency bin, age, sex, and button condition ($\chi^2(1) = 85.52$, $p < .001$), and between trial type, task, latency bin, age, sex, and button condition ($\chi^2(1) = 28.40$, $p = .005$) were significant but were not investigated using pairwise comparisons as the cell-size was too small when the sample was separated by all between-subject factors.