

# The development of anticipatory cognitive control processes in task-switching: An ERP study in children, adolescents, and young adults

ALBERTO MANZI,<sup>a,b</sup> DOREEN NESSLER,<sup>b</sup> DANIELA CZERNOCHOWSKI,<sup>c</sup>  
AND DAVID FRIEDMAN<sup>b</sup>

<sup>a</sup>School of Social and Behavioral Sciences, Mercy College, Dobbs Ferry, New York, USA

<sup>b</sup>Cognitive Electrophysiology Laboratory, Division of Cognitive Neuroscience, New York State Psychiatric Institute, New York, New York, USA

<sup>c</sup>Department of Experimental Psychology, Heinrich-Heine University, Düsseldorf, Germany

## Abstract

To investigate the development of advance task-set updating and reconfiguration, behavioral and event-related potential (ERP) data were recorded in children (9–10 years), adolescents (13–14 years), and young adults (20–27 years) in a cued task-switching paradigm. In pure blocks, the same task was repeated. In mixed blocks, comprised of stay and switch trials, two tasks were intermixed. Age differences were found for stay-pure performance (mixing costs) in the 600-ms but not in the 1200-ms cue-target interval (CTI). Children showed larger reaction time mixing costs than adults. The ERPs suggested that the larger costs were due to delayed anticipatory task-set updating in children. Switch-stay performance decrements (switch costs) were age-invariant in both CTIs. However, ERP data suggested that children reconfigured the task-set on some stay trials, rather than only on switch trials, suggesting the continued maturation of task-set reconfiguration processes.

**Descriptors:** Task-switching, Mixing costs, Switching costs, ERP

Executive control refers to a set of processes involved in the conscious sequencing, organization, and monitoring of thought and action (Norman & Shallice, 1986). It consists of separable functions that have been variably described in the literature as planning, decision-making, impulse inhibition, and self-regulation (Zelazo & Muller, 2002). All are thought to depend on the integrity of the pre-frontal cortex (PFC; Alvarez & Emory, 2006; Salmon & Collette, 2005). In fact, executive functions are impacted by brain insult to the PFC (Stuss & Alexander, 2007) and their epigenetic development parallels the protracted maturation of the PFC, as myelination increases and synaptic density is selectively reduced by pruning (Bunge & Wright, 2007; Diamond, 2002). The current research was aimed at examining systematically the neurocognitive development of executive functions from childhood to young adulthood.

The emergence and optimization of executive control across development allows increasingly deliberate, goal-directed behav-

ior and cognition. In classic developmental studies (Inhelder & Piaget, 1964), young children have been described as concrete and stimulus-bound, while older children and adolescents have been shown to be capable of flexibly adapting to task demands. However, a more systematic investigation of the development of the different facets of executive control is still necessary to specify how these functions reach the sophisticated form found in adulthood. Moreover, such understanding might support sound, neuroscientifically informed applications in education (Diamond, Barnett, Thomas, & Munro, 2007; Goswami, 2006; Meltzer, 2007) and rehabilitation (Reynolds & Horton, 2008).

In past decades, most evidence on the development of executive control has accrued within a neuropsychological perspective by using instruments putatively sensitive to PFC damage. These, however, are hardly process pure (Levin et al., 1991; Welsh, Pennington, & Groisser, 1991; Zelazo & Muller, 2002). For example, in the Wisconsin Card Sorting Test (WCST; Heaton, 1981), subjects have to infer the criterion by which the experimenter is sorting stimulus cards that differ in three dimensions (color, shape, number). After a certain number of consecutive correct responses, the target dimension is changed without notice, and the subject must discover the new sorting principle. Performance is evaluated in terms of perseverative errors, number of categories achieved, and failures to maintain set. In research on school-aged children, Chelune and Baer (1986) found linear improvement on all three performance indices between the ages of 6 and 10 years, with 10-year-olds performing

The authors thank Mr. Charles L. Brown III for computer programming and technical assistance. We thank Ms. Brenda Malcom for her aid in recruitment of participants and data collection, and Ms. Rebecca Edelblum for subject recruitment. We thank Dr. Y. M. Cycowicz for her contributions to the early phases of this work. This project was supported in part by grants HD14959 (NICHD) and AG005213 (NIA), and the New York State Department of Mental Hygiene.

Please address correspondence to: Alberto Manzi, School of Social and Behavioral Sciences, Mercy College, 555 Broadway, Dobbs Ferry, NY 10522. E-mail: amanzi@mercy.edu

like healthy young adults. Although this test is useful in providing global measures of cognitive control, it does not allow teasing apart the multiple control functions that are brought on-line during test execution (see, for example, the components of updating, shifting, and inhibition proposed by Miyake et al., 2000).

Hence, to overcome the limitations of neuropsychological tests, and systematically describe executive functions and their maturation, more process-pure experimental methods have been devised (Zelazo & Muller, 2002, for a review). Among these, task-switching paradigms have been increasingly used in recent years (Kiesel et al., 2010; Monsell, 2003, for reviews). These paradigms typically require performance on two relatively simple tasks. For example, in the current paradigm (adapted from Cepeda, Kramer, & Gonzalez de Sather, 2001), subjects were shown strings of numbers (1, 3, 111, 333) and were asked to respond to digit identity (“What number?”) in one task, and to the size of the string (“How many?”) in the other task. In pure blocks, the same task is performed repeatedly. In mixed blocks, the two tasks are randomly presented and, on each trial, participants might either perform the same task as on the previous trial (stay trials) or switch to the other task (switch trials).

Variations in performance between pure, stay, and switch trials provide indices of the engagement of different executive-control processes. Mixing costs are computed as the difference between reaction times (RTs) (or errors) on stay trials in mixed blocks and pure trials in single-task blocks.<sup>1</sup> Mixing costs have been associated with different processes summarized under the term task-set updating. These processes are thought to reflect such components as the encoding of the cue, the selection and updating of the currently relevant task-set (Mayr, 2001), and the active maintenance of multiple task-sets in memory (Fagot, 1994; Los, 1996; Meiran, 2000). Switch costs (also labeled specific switch costs in Kray & Lindenberger, 2000) are measured as the difference in performance between switch and stay trials in mixed blocks. These costs are believed to capture task-set reconfiguration, including operations such as retrieval from memory of the appropriate task rules (Mayr & Kliegl, 2000), implementation of new stimulus-response mappings (Rogers & Monsell, 1995), and counteracting interference from previously active task sets (task-set inertia, Allport, Styles, & Hsieh, 1994).

To selectively investigate anticipatory cognitive control, a variant of the task-switching paradigm has been devised in which participants are cued as to which task is going to be presented on the upcoming trial (Meiran, 1996). By varying the interval between presentation of cue and target, it is possible to evaluate how performance is affected when the opportunity for advance preparation is reduced or increased (Meiran, 1996; Monsell & Mizon, 2006). In one of the first studies using this paradigm, Meiran (1996) administered a simple reaction time (RT) task using two-dimensional stimuli; on each trial a circle was presented in one of the four quadrants of a  $2 \times 2$  grid and, therefore, could be defined in terms of left-right or up-down position. At the beginning of each trial, a cue indicated which positional dimension of the target subjects had to respond to, with cues presented either  $\sim 200$  ms or  $\sim 1700$  ms before target onset. It was

found that longer cue-target intervals (CTIs) were associated with smaller accuracy and RT switch costs (Meiran, 1996). Similarly, several other studies using the explicit-cue paradigm have replicated the finding that mixing and switch costs decrease when participants are allowed time to prepare prior to the target (Gopher, Armony, & Greenspan, 2000; Rogers & Monsell, 1995; Rubin & Meiran, 2005). In the case of switch costs, results from studies varying the CTI indicate that the preparation advantage in young adults (i.e., the decrease in switch costs) plateaus at about 600 ms (e.g., Monsell & Mizon, 2006, Exp. 2; Rogers & Monsell, 1995, Exp. 2). To the best of our knowledge, whether mixing costs are reduced at longer CTIs has not been investigated. A CTI longer than 600 ms does not usually show any additional performance benefits, although a *residual switch cost* is still observed.

At present, the exact processes that are responsible for the beneficial effect of preparation are still to be determined. The advantage is thought to index endogenous, top-down, anticipatory control that can be effectively brought on-line before presentation of an imperative stimulus (Monsell & Mizon, 2006; Rubin & Meiran, 2005). Specifically, the preparation interval could be used to orient attention towards task-relevant attributes of the upcoming target stimulus, to retrieve task rules and stimulus-response mappings, and to adjust decision and response criteria (Monsell, 2003). In turn, residual switch costs have been attributed to the need for bottom-up, stimulus-driven control processes that cannot be prepared in advance, but might be initiated only after target presentation (Monsell, 2003).

Task-switching paradigms are a valuable tool for investigating selective aspects of cognitive control across the lifespan, because their simplicity makes them suitable for administration to a wide range of age groups, from preschoolers to older adults (Cepeda et al., 2001). However, there is, to date, a paucity of developmental behavioral data. Consequently, prior research has not yet provided unambiguous evidence on the differential developmental progression of mixing and switch costs. Furthermore, of the extant investigations, only a small set has focused on developmental differences in mixing costs, which was one of the factors motivating this investigation (Crone, Bunge, van der Molen, & Ridderinkhof, 2006; Crone, Ridderinkhof, Worm, Somsen, & van der Molen, 2004; Karbach & Kray, 2007; Kray, Eber, & Lindenberger, 2004; Kray, Eber, & Karbach, 2008; Reimers & Maylor, 2005). With one exception (Crone, Bunge, et al., 2006), all reported a decrease in mixing costs from childhood through adolescence, presumably reflecting increased efficiency in task-set coordination and updating the currently relevant task-set. By contrast, developmental studies of switch costs have produced conflicting results, with almost equal numbers reporting no differences in switching performance across development (Crone et al., 2004; Karbach & Kray, 2007; Reimers & Maylor, 2005) as those describing larger switch costs in 7–9- and 10–12-year-old children compared to young adults (Cepeda et al., 2001; Davidson, Amso, Anderson, & Diamond, 2006). In the latter case, increased slowing on switch trials in children might indicate immaturity in implementing task-set reconfiguration processes.

In the current study, we were interested in investigating further the development of anticipatory control processes elicited in cued task-switching paradigms. However, the RT response reflects the “final common pathway” or end point of decision processes. Therefore, it cannot provide insight into the temporal course of advance preparatory processes set in train by the explicit cue and terminated with the decision. Accordingly, we

<sup>1</sup>Some authors compute mixing costs as the performance difference between all trial types in mixed blocks (averaging across stay and switch trials) and pure trials in single-task blocks (Los, 1999; see also the definition of *general switch cost* in Kray & Lindenberger, 2000). However, we believe that this definition might lead to an inflated estimate of mixing costs, in that it also includes switch costs, which we computed separately.

employed the event-related potential (ERP) technique because its high temporal resolution enables the tracking, in real time, of presumed control processes reflected in the neuroelectric activity occurring after presentation of a task cue and before a response is produced. To date, a few explicit-cue, ERP task-switching studies have investigated post-cue differences between stay and pure trials, but only in young adults (Jost, Mayr, & Rösler, 2008; Kray, Eppinger, & Mecklinger, 2005; West, 2004; Wylie, Murray, Javitt, & Foxe, 2008). All found that cues signaling stay trials evoked larger positive amplitudes than cues signaling pure trials (~500 ms) at central and parietal scalp locations. The greater positivity on stay trials has been interpreted as indexing the implementation of endogenous, anticipatory task-set updating.

More abundant data are available on ERP activity occurring in advance of switch compared to stay trials in mixed blocks. Several studies have reported that a sustained posterior positivity emerging around 400 ms post cue was greater when participants prepared to switch than stay (Asthle, Jackson, & Swainson, 2006, 2008; Hsieh & Cheng, 2006; Karayanidis et al., 2009; Kieffaber & Hetrick, 2005; Miniussi, Marzi, & Nobre, 2005; Moulden et al., 1998; Nicholson, Karayanidis, Davies, & Michie, 2006; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005; Rushworth, Passingham, & Nobre, 2002, 2005; Swainson et al., 2003; Tiegges, Snel, Kok, Plat, & Ridderinkhof, 2007). Further evidence indicated that the differential switch positivity predicted successful switching performance (Lavric, Mizon, & Monsell, 2008; Swainson, Jackson, & Jackson, 2006). This positivity has also been reported in alternating-run paradigms. In these, no cue is given, but task switches can be predicted because the two tasks alternate in a fixed sequence, thus enabling advance preparation (Karayanidis, Coltheart, Michie, & Murphy, 2003; Wylie, Javitt, & Foxe, 2003). On these bases, this sustained posterior positivity could index the endogenous task-set reconfiguration processes that can be initiated in anticipation of the imperative stimulus, as hypothesized in the behavioral literature (Monsell, 2003).

As noted, executive functions follow a long developmental trajectory from childhood through adolescence into adulthood (Davidson et al., 2006). To the very best of our knowledge, prior developmental ERP studies of task-switching performance do not exist. Consequently, in an attempt to gain additional evidence on the development of anticipatory control processes involved in task switching, we recorded ERPs during the cue-response interval, as well as performance data, in 9–10-year-old children, 13–14-year-old adolescents, and young adults engaged in a task-switching paradigm, with informative task cues presented 600 ms and 1200 ms before target onset. These intervals were chosen on the basis of previous research showing, as noted earlier, that young-adult switch costs plateau at approximately 600 ms (Cepeda et al., 2001). Although the data of Cepeda and colleagues suggested that children can benefit as much from a long CTI as young adults (e.g., 1200 ms in Cepeda et al., 2001), these authors recorded only performance indices. Critically, we recorded neural activity during the entire cue-target interval. This afforded us the additional capability of determining whether developmental improvements in mixing and/or switch costs were accompanied by concomitant latency changes in onset and/or offset of ERP indicators of advance preparatory control that differed for the short compared to the long CTI. Single- and mixed-task blocks were administered so that stay and pure trials (*mixing costs*) and switch and stay trials (*switch costs*) could be compared in order to examine the arguably unique control processes that the two types of costs are believed to capture.

Following the developmental task-switching behavioral literature, we expected more marked age differences in mixing than switch costs (Crone et al., 2004; Karbach & Kray, 2007; Reimers & Maylor, 2005). Based on the results showing that the reduction of switch costs plateaus at a CTI of 600 ms, we expected young adults to show an anticipatory-control positivity onsetting early after the cue and offsetting at or around target onset, reflecting, respectively, engagement in and completion of anticipatory control processes. In the case of children and adolescents, less definite predictions could be made due to the lack of developmental ERP data. However, it is reasonable to predict that larger mixing and/or switch costs in children and adolescents compared to young adults might be associated with reduction or delayed onset and offset of the cue-related positivity. This would tend to indicate an inefficient or delayed engagement in anticipatory control, which would overlap with and slow the processing of the target and the production of the response, thus resulting in larger costs to performance.

## Method

### Participants

Twenty-three children, 16 adolescents, and 20 young adults were recruited. Eleven participants were eliminated for failure to perform or complete the task (5 children, 2 adolescents) and because of excessive EEG artifacts (4 children). Fourteen children (9 females, mean age: 10.1, range: 9–11 years), 14 adolescents (6 females, mean age: 14.0, range: 13–15 years), and 20 young adults<sup>2</sup> (16 females, mean age: 23.3, range: 20–27 years) were retained for the study. All were native English speakers, with normal or corrected-to-normal vision, no history of neurological or psychiatric disorders, and free from medications known to affect the central nervous system. All young adults and one parent of every child and adolescent signed consent forms according to criteria of the New York State Psychiatric Institute's Institutional Review Board. Children and adolescents signed assent forms. All participants received monetary compensation.

The demographic and neuropsychological data for the three groups are listed in Table 1. Young adults were administered the Modified Mini-Mental Status examination (mMMS; Mayeux, Stern, Rosen, & Leventhal, 1981). IQ scores were estimated from the Vocabulary and Block design subtests of the Wechsler Intelligence Scale for Children and Adolescents (WISC-III; Wechsler, 1991) and the Wechsler Adult Intelligence Scale-III for young adults (WAIS-III; Wechsler, 1997). In addition, participants were administered the story, design, and picture memory subtests of the Wide Range Assessment of Learning and Memory battery (WRAML; Sheslow & Adams, 1990). All participants had scores within or above the average range on all of these instruments.

### Stimuli and Experimental Procedure

Participants were seated comfortably in a sound-damped and electrically shielded room. They sat facing a 17" computer monitor about 100 cm from the screen and held a small response box on their laps. Stimuli were presented centrally on the computer

<sup>2</sup>The behavioral and response-locked ERP data from the same sample of young adults have been presented in an earlier study on the effects of aging on cognitive control (Czernochowski, Nessler, & Friedman, 2010).

**Table 1.** Demographic Characteristics and Neuropsychological Measures for Children, Adolescents, and Young Adults

	Children Mean (SD)	Adolescents Mean (SD)	Young adults Mean (SD)
Age	10.1 (.7)	14.0 (.5)	23.3 (2.0)
SES	40.8* (21.3)	52.5* (29.9)	55.5 (13.2)
Years of education	3.4 (.7)	7.4 (.7)	16.1 (1.5)
mMMS	NA	NA	54.8 (2.6)
Digits forward <sup>1</sup>	6.6 (.8)	7.2 (.9)	7.5 (1.4)
Digits backward <sup>1</sup>	4.5 (1.1)	5.7 (.9)	5.7 (1.3)
LQ	66.8 (34.0)	63.4 (40.3)	88.1 (15.6)
Verbal IQ <sup>2</sup>	132.5 (7.8)	116.1 (14.3)	130.8 (14.5)
Performance IQ <sup>2</sup>	114.3 (20.2)	107.9 (17.9)	115.3 (14.4)

Notes: NA: not applicable, mMMS: Modified Mini-Mental Status Exam (Mayeux, Stern, Rosen, & Leventhal, 1981, maximum score = 57), SES: socioeconomic status (Watt, 1976, higher score = lower SES), LQ: laterality quotient (Oldfield, 1971).

<sup>1</sup>Digit-span (uncorrected scores).

<sup>2</sup>WAIS-III (Wechsler, 1997) for young adults; WISC-III (Wechsler, 1991) for children and adolescents.

\*Based on a score averaged across the SES values for both parents.

monitor, within a gray box (visual angles:  $7.4^\circ \times 7.4^\circ$ ) on a black background. Participants made choice button-press responses in an explicit-cue, task-switching paradigm based on the design introduced by Cepeda and colleagues (2001). They viewed one of four possible stimuli (1, 3, 111, 333) and were asked to respond to digit identity (“What number?”) in one task, and to the size of the string (“How many?”) in the other task. For both tasks, the response options (“1” and “3”) were mapped to opposite hands.

The experiment included pure and mixed blocks. During pure blocks, one task was performed throughout. During mixed blocks, participants switched between the two tasks. Switch trials (i.e., when a change of task was required) occurred after 0, 1, or 2 stay trials (i.e., when the task set remained the same on consecutive trials), with switch and stay trials occurring equally often. Figure 1 illustrates a schematic of the task sequence for pure and mixed blocks. In each trial, a cue signaling the task to be performed appeared for 300 ms and consisted of the words “How many?” or “What number?” enclosed in an oval shape (visual angles:  $5.4^\circ$  horizontally  $\times$   $2.3^\circ$  vertically). Cues for the two tasks were presented in oval shapes of different colors (yellow and blue, rendered in light and dark gray in Figure 1), in order to facilitate cue discrimination (see Crone, Bunge, et al., 2006 for a similar argument on cue design). For each subject, the color assigned to a task cue remained the same throughout the experiment. Color-to-task pairing was counterbalanced across participants. In the short CTI condition (depicted in Figure 1), the cue was followed by a fixation cross displayed for 300 ms, thus resulting in a cue-target interval of 600 ms. In the long CTI condition, the fixation cross was displayed for 900 ms, thus resulting in a cue-target interval of 1200 ms. The target stimulus was displayed until a response was made by pressing one of two buttons with the left or right index fingers. Equal emphasis was placed on speed and accuracy. The next trial started after a fixed 1000 ms response interval (RCI), during which the fixation cross appeared.

For each CTI condition, participants completed, in the following order, two consecutive pure blocks (one per task, each including 36 trials), followed by three mixed blocks (each including 96 trials), and concluding with two pure blocks (one per task). The order in which task (“How many?” or “What number?”) was assigned to the first pure block, the order of presen-

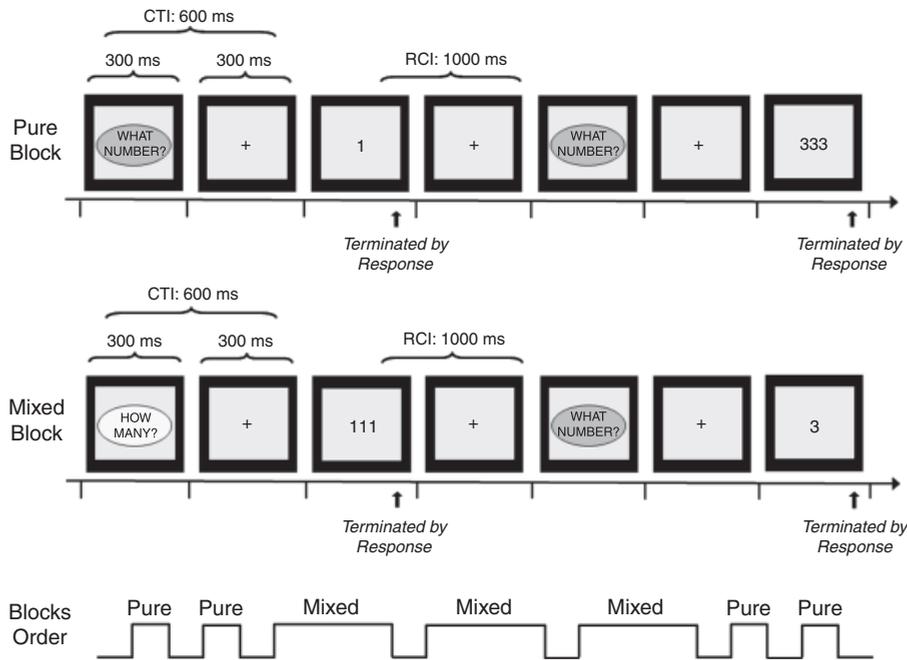
tation of short and long CTI conditions, as well as response-hand mappings were counterbalanced across participants. Moreover, left- and right-hand responses as well as switches from left- and right-hand responses to, respectively, right- and left-hand responses were randomized for pure, stay, and switch trials. Therefore, it is unlikely that differential, age-related hand-switching effects could have systematically impacted the developmental results reported below. To ensure that participants understood the instructions and could perform accurately, practice versions of two pure blocks (10 trials each) and a mixed block (20 trials) were performed prior to the experiment.

**Electroencephalographic (EEG) recording.** EEG was recorded with 62 sintered Ag/AgCl electrodes embedded in an elastic cap over scalp sites in accordance with the extended ten-twenty system (Sharbrough et al., 1990; ground: right forehead, electrode impedance  $< 5k\Omega$ ). All electrodes were initially referenced to the nose tip and rereferenced offline to averaged mastoids. Horizontal and vertical electrooculograms (EOG) were recorded bipolarly with electrodes placed, respectively, at the outer canthi of both eyes and above and below the left eye. EOG and EEG were recorded continuously with SynAmp amplifiers (Compumedics Neuroscan, Charlotte, NC; DC; 100 Hz low-pass filter; 500 Hz digitization rate).

#### Data processing and analyses.

**Behavioral data.** Because a response deadline was not imposed, the data were trimmed to reject outliers using two criteria. First, only correct trials with RTs between 200 and 4000 ms were included. Second, individual mean RTs and standard deviations (SDs) were computed for each of the three Trial Type conditions (pure, stay, switch). Trials were rejected if they were more than 2.5 standard deviations from the relevant individual mean RT. Mean percentages of total trials excluded by these two rejection criteria were, respectively, 0.08% and 3.2% for children, 0.02% and 3.2% for adolescents, 0.03% and 2.9% for young adults.

The trimmed dataset was used to create mean RTs and mean error rates separately for pure, stay, and switch trials. Mixing costs were computed to estimate the error increase and response slowing on stay trials in mixed blocks compared to trials in pure blocks. Error mixing costs were obtained for each participant by subtracting the error rates for pure from those for stay trials. Error switch costs were computed to estimate the impact on performance induced by switching between the two tasks in a mixed block. In this case, switch costs were obtained by subtracting the error rates for stay from those for switch trials. Raw RT mixing and switch costs were computed, respectively, by subtracting RTs on pure trials from those on stay trials, and RTs on stay trials from those on switch trials. To ensure that any group differences in these costs did not merely reflect prolonged overall RTs (i.e., baseline response speed) in the children and/or adolescents relative to young adults, we computed proportional scores for RT mixing and switch costs. Proportional RT mixing costs were computed using the formula  $(\text{Stay RT} - \text{Pure RT}) / \text{Pure RT}$ . Proportional RT switch costs were computed using the formula  $(\text{Switch RT} - \text{Stay RT}) / \text{Stay RT}$ . In order to evaluate age-related differences in task-switching effects, error and proportional RT mixing, and switch costs were submitted to between-Age Group analyses of variance (ANOVAs). For these and all of the following analyses, the Greenhouse-Geisser epsilon ( $\epsilon$ ) correction (Jennings & Wood, 1976) was used when appropriate. Uncorrected degrees of freedom are reported along with



**Figure 1.** Schematic of the experimental paradigm (adapted from Cepeda et al., 2001). A single-task block (pure trials for the “What number?” task) and a mixed block (depicting a task-switch) in the short CTI condition are shown. Block order is shown at the bottom. CTI: cue-target interval, RCI: response-cue interval.

the epsilon value; the  $P$  values reflect the epsilon correction. Partial eta squared ( $\eta^2$ ) is given as an estimate of effect size.

**ERP data.** Only trials accepted on the basis of the behavioral criteria specified above were included in the ERP analyses. Eye-movement artifacts were corrected off-line (Semlitsch, Anderer, Schuster, & Presslich, 1986), and remaining artifacts (e.g., muscle activity) were manually rejected. If single channels showed artifacts, a spherical spline algorithm was used for interpolation on a trial-by-trial basis (Perrin, Pernier, Bertrand, & Echallier, 1989), with a maximum of four channels interpolated for a given trial (Picton et al., 2000). EEG epochs had a 100-ms pre-cue baseline and included the cue-target interval and the 400 ms following target presentation. Averages were obtained for each of the three Trial Type conditions (pure, stay, switch), in short- and long-CTI conditions, separately for the three age groups.<sup>3</sup> Mixing costs were investigated by comparing pure with stay trials and switch costs by comparing stay with switch trials. A 15 Hz low-pass filter was applied to all averages before statistical analysis.

In order to capture early and sustained ERP effects presumably indexing anticipatory control processes initiated following the cue and sustained until or past target presentation, mean amplitudes were computed for consecutive 100-ms windows, starting at cue onset. Activity in the post-target interval, potentially reflecting continued preparatory processing, was analyzed only if cue-related activity extended to the end of the CTI. The analysis of the post-target interval was terminated with the first

100-ms time interval that did not return a significant stay-pure or switch-stay difference. Based on previous studies and the primarily midline topographic distribution of the effects depicted in the maps of the difference waveforms (see Results section for details), amplitudes were analyzed at five midline electrodes (Fz, Fcz, Cz, Cpz, Pz). In a first step, to test whether pure-stay and stay-switch differences were present in each age group and to determine their timing, mean amplitudes in each time window were submitted to Trial Type (pure vs. stay or stay vs. switch) by Electrode (Fz, Fcz, Cz, Cpz, Pz) repeated measures ANOVAs, separately for each age group. Because we were interested in ERP effects underlying mixing and switch costs, only effects involving the Trial Type factor are reported. Interactions involving the Electrode factor were further explored in repeated measures Trial-Type ANOVAs at each electrode site using a modified Bonferroni correction for multiple comparisons (Jaccard & Wan, 1996). In a second step, differences between age groups were examined using Age Group  $\times$  Trial Type  $\times$  Electrode ANOVAs for the 100-ms windows that had demonstrated significant stay-pure or switch-stay differences in at least two of the groups in the initial, within-group analyses. To test whether significant 3-way interactions reflected topographic differences between the groups, these interactions were followed up by Age Group  $\times$  Electrode ANOVAs on the stay-pure or switch-stay normalized amplitude differences. Normalization controls for the effect of overall amplitude differences among the three groups (vector scaling, McCarthy & Wood, 1985). Topographic maps were computed only for significant stay-pure (mixing costs) and switch-stay (switch costs) differences by calculating spherical spline contours (Perrin et al., 1989) on the data from all 62 electrodes. The maps illustrate amplitude differences for individual 100-ms intervals when differences between groups were significant. The maps are collapsed across contiguous intervals when scalp distribution differences among groups were not significant in those time periods.

<sup>3</sup>Minimum and maximum trial numbers for each group and trial type are provided below.

Short CTI: Children, pure (55–129), stay (45–115), switch (37–105). Adolescents, pure (77–126), stay (56–115), switch (63–108). Adults, pure (113–141), stay (96–122), switch (90–121).

Long CTI: Children, pure (37–128), stay (35–106), switch (32–104). Adolescents, pure (48–125), stay (31–104), switch (30–106). Adults, pure (100–138), stay (91–121), switch (89–119).

## Results

### Behavioral Data

Table 2 shows mean error rates and mean raw RTs for pure, stay, and switch trials, as well as the mean raw mixing and switch costs in short and long CTI conditions for the three age groups.

#### Mixing costs—short cue-target interval (600 ms).

**Errors.** Mixing costs were significantly different from zero (assessed via *t*-tests) in the three groups (see Table 2). A between-Age Group ANOVA performed on the mixing costs revealed a main effect of Age Group [ $F(2,45) = 5.38, p < .01, \eta^2 = .19$ ]. Tukey's HSD *post-hoc* testing indicated that executing the same task in mixed- compared to pure-blocks caused a greater increase in errors for adolescents than young adults, although these groups did not differ reliably from children.

**RT.** Raw mixing costs differed from zero in all groups (Table 2). The between-Age Group ANOVA performed on the proportional mixing costs revealed a reliable main effect of Age Group [ $F(2,45) = 3.85, p < .05, \eta^2 = .15$ ]. Tukey's HSD *post-hoc* tests confirmed larger mixing costs in children than young adults; children did not differ significantly from adolescents, nor did young adults and adolescents.

**Ancillary analyses.** To rule out the possibility that developmental differences in vigilance and/or motivation might be responsible for the age difference in mixing costs, we queried the data to determine if block position and trial position within blocks influenced age-related changes in RT mixing costs. To this end, RTs on pure and stay trials were analyzed separately in between-Age Group ANOVAs with the repeated measures factors of Block Position (4 levels for pure trials; 3 levels for stay trials) and Trial Position (first half, second half of each block). For pure trials, this analysis returned significant main effects of Age Group [ $F(2,45) = 20.6, p < .0001, \eta^2 = .48$ ] and Block Position [ $F(3,135) = 6.93, p < .0001, \eta^2 = .13$ ], and a significant

Age Group  $\times$  Block Position interaction [ $F(6,135) = 3.69, p < .01, \eta^2 = .14$ ]. Main effects of and interactions with the factor of Trial Position were not reliable [ $ps > .08$ ]. As assessed by follow-up analyses, the Age Group  $\times$  Block Position interaction reflected adults' and children's tendency to speed up in the second and fourth blocks, whereas adolescents' RTs were not significantly different across blocks. The ANOVA performed on stay-trial RTs returned significant main effects of Age Group [ $F(2,45) = 16.2, p < .0001, \eta^2 = .42$ ] and Trial Position [ $F(1,45) = 4.64, p < .05, \eta^2 = .09$ ]. There were no significant effects of Block Position ( $F < 1$ ) and no Age group  $\times$  Trial Position or Block Position interactions ( $Fs < 1$ ). Overall, these results indicate that, although Block and Trial Position influenced RTs, these effects did not differ among the three age groups in a way that could have explained the larger RT mixing costs for children compared to young adults.

#### Switch costs—short cue-target interval (600 ms).

**Errors.** As shown in Table 2, switch costs differed from zero in all groups. The between-Age Group ANOVA did not return a significant effect ( $F < 1, p > .8$ ), indicating that error switch costs were age-invariant.

**RT.** Raw switch costs were significantly different from zero for all groups (Table 2). The between-Age Group ANOVA performed on the proportional switch costs did not return a significant effect of Age Group ( $p > .05$ ), indicating that RT switch costs did not differ among the three age groups.

#### Mixing costs—long cue-target interval (1200 ms).

**Errors.** Mixing costs were significantly different from zero in adolescents and young adults, but not children (Table 2). However, the between-Age Group ANOVA showed no significant differences in mixing costs among the three groups ( $p > .09$ ).

**RT.** Raw mixing costs differed from zero in all groups (Table 2). Group differences in proportional mixing costs were not reliable ( $p > .3$ ).

#### Switch costs—long cue-target interval (1200 ms).

**Errors.** Table 2 indicates that switch costs differed from zero in all groups. Nonetheless, the between-Age Group ANOVA did not return a significant effect ( $F < 1$ ), indicating that error switch costs were age-invariant.

**RT.** Raw switch costs were significantly different from zero for children and adolescents, but not for young adults (Table 2). However, group differences in proportional switch costs were not significant ( $p > .1$ ).

Overall, the behavioral results showed that age influenced mixing and switch costs differently in the short CTI. Repeating the same task in mixed compared to pure blocks (*mixing costs*) increased errors in adolescents, whereas it slowed RTs in children. Conversely, switching tasks within mixed blocks (*switch costs*) engendered similar performance decrements in the three age groups. By contrast, in the long CTI condition, age-related changes in RT and accuracy mixing and switch costs were not observed. Importantly, the greater RT mixing costs in children than young adults in the short CTI cannot be explained by general cognitive slowing (i.e., age-related differences in baseline response speed) or by differences in vigilance and/or motivation.

**Table 2.** Mean Error Rates (in percent  $\pm$  SE) and Mean RTs (in ms  $\pm$  SE), Mixing and Switch Costs for Children, Adolescents, and Young Adults

	Pure	Stay	Switch	Mixing cost	Switch cost
Error rates	Children $N = 14$				
Short CTI	5.6 (0.9)	7.3 (1.0)	12.2 (2.0)	1.7 (0.7)*	4.9 (1.4)**
Long CTI	5.7 (0.9)	7.9 (1.2)	10.7 (1.7)	2.2 (1.1)	2.8 (1.2)*
	Adolescents $N = 14$				
Short CTI	6.2 (1.0)	10.3 (1.5)	15.1 (1.9)	4.2 (1.0)***	4.7 (1.4)**
Long CTI	5.9 (1.0)	9.6 (1.6)	12.8 (2.0)	3.7 (1.0)**	3.2 (1.3)*
	Young adults $N = 20$				
Short CTI	2.7 (0.5)	3.8 (0.7)	6.9 (0.9)	1.1 (0.4)*	3.2 (0.7)***
Long CTI	3.2 (0.6)	4.4 (0.8)	6.8 (0.9)	1.1 (0.5)*	2.4 (0.5)***
RTs	Children $N = 14$				
Short CTI	555 (33)	711 (58)	747 (56)	156 (29)***	36 (13)*
Long CTI	559 (34)	682 (57)	736 (64)	123 (27)***	54 (21)*
	Adolescents $N = 14$				
Short CTI	438 (22)	507 (34)	549 (41)	69 (18)**	41 (10)***
Long CTI	431 (24)	505 (38)	527 (42)	74 (20)**	22 (10)*
	Young adults $N = 20$				
Short CTI	367 (8)	423 (16)	436 (15)	55 (10)***	14 (5)*
Long CTI	370 (8)	420 (17)	429 (19)	50 (12)***	8 (6)

Notes: One-sample *t*-tests difference from zero.

\* $p \leq .05$ ; \*\* $p \leq .01$ ; \*\*\* $p \leq .001$ .

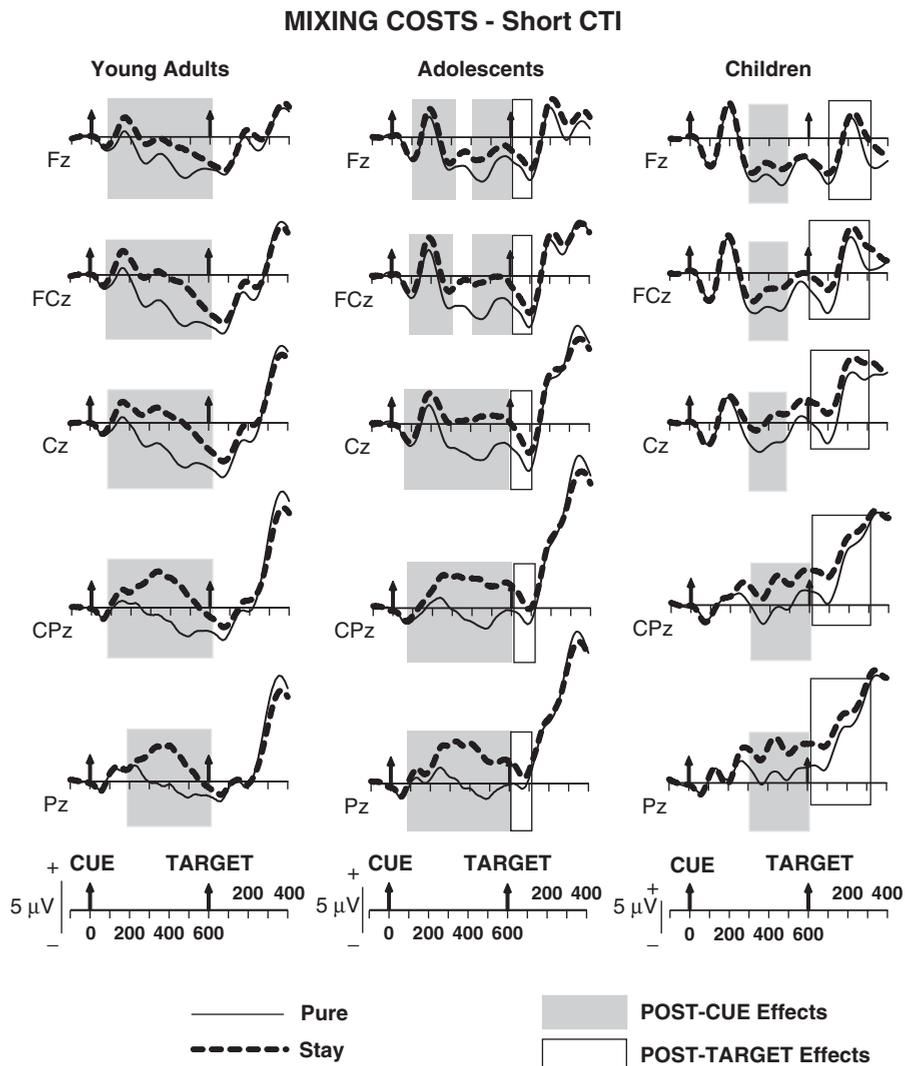
## ERP Data

**Mixing costs—short cue-target interval (600 ms).** The waveforms for pure and stay trials for each age group are displayed in Figure 2. Topographic maps of the time windows with reliable stay-pure differences are shown in Figure 3.

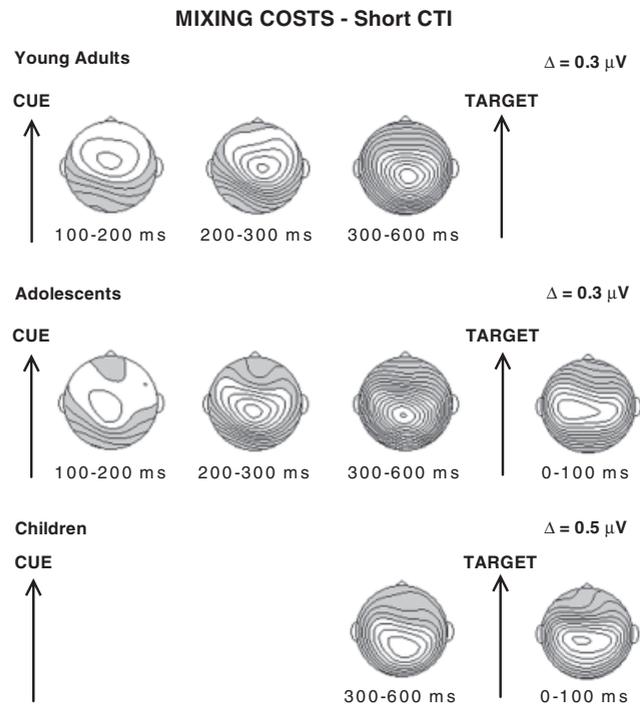
**Cue-target interval.** Following cue onset in the short CTI condition, young adults showed a positive-going difference between stay and pure trials from 100 to 600 ms (Trial Type main effects: see Table 3 for  $F$ -values). This effect was largest at fronto-central sites from 100–300 ms and at centro-parietal sites from 300–500 ms (Trial Type  $\times$  Electrode Interactions: see Table 3). Similar to young adults, in adolescents, amplitudes for stay relative to pure trials were more positive going from 100–600 ms after cue onset (Trial Type main effects: see Table 3). These effects extended across the midline from 100–300 ms and from 400–600 ms, and were largest at centro-parietal sites from 300–400 ms (Trial Type  $\times$  Electrode interactions: see Table 3). In contrast with young adults and adolescents, children did not display any difference between pure and stay trials from 100–300 ms after cue

onset (Table 3). However, a reliably increased positivity for stay compared to pure trials emerged from 300–600 ms (Trial Type main effects: see Table 3), with largest amplitudes at centro-parietal sites from 500–600 ms (Trial Type  $\times$  Electrode interactions: see Table 3).

**Age-related differences.** For the 100–200 and 200–300 ms intervals, there were only significant stay-pure differences for adolescents and young adults. Between-Age Group ANOVAs did not reveal any differences in effect magnitude (Age Group  $\times$  Trial Type interactions:  $ps > .6$ ). However, reliable Age Group  $\times$  Trial Type  $\times$  Electrode interactions in these intervals ( $F_s > 3.38$ ,  $ps < .05$ ) suggested a difference in topography between young adults and adolescents. Nonetheless, only the difference from 200–300 ms was confirmed by a reliable Age Group  $\times$  Electrode interaction computed on the normalized stay-pure differences [ $F(4,128) = 3.75$ ,  $p < .05$ ,  $\epsilon = .39$ ,  $\eta^2 = .11$ ]. This result indicated that stay-pure differences were larger for young adults than adolescents at Fz, but larger for adolescents than young adults at Pz. From 300–600 ms, all age groups showed reliable stay-pure differences. Age Group  $\times$  Trial Type  $\times$  Electrode ANOVAs



**Figure 2.** Grand mean cue-locked ERPs for pure and stay trials in the short CTI condition. A 10-Hz low-pass filter was applied. Shading indicates intervals with significant stay-pure differences. Vertical, unshaded rectangles indicate significant post-target differences, putatively reflecting continued preparatory processing.



**Figure 3.** Surface potential scalp topographies for the stay minus pure difference waveforms in the short CTI condition, depicted for the time windows in which the magnitude differences were reliable. Front of the head is at the top. Shaded areas reflect negativity; unshaded areas reflect positivity.

comparing raw amplitudes in 100-ms windows among young adults, adolescents, and children did not return either significant Trial Type  $\times$  Age Group or 3-way interactions ( $ps > .2$ ). These findings suggest the lack of magnitude and topographic differences among the three age groups, consistent with the similar centro-parietal scalp foci observed for the 300–600 ms interval in the maps depicted in Figure 3.

**Post-target interval.** Young adults did not show a continuation of the difference between pure and stay trials observed in the CTI—no significant differences were found between 0–100 ms post-target onset (Table 3). Unlike young adults, adolescents showed a stay-pure positive difference from 0–100 ms post target across all midline electrodes (Trial Type main effect: Table 3), but similar to young adults, no difference was found between 100–200 ms. In contrast with young adults and adolescents, children showed a reliable continuation of the cue-driven, stay-pure positive difference from 0–300 after target onset (Table 3). This effect was circumscribed to centro-parietal sites from 0–100 ms and extended across the midline from 100–300 ms (Trial Type main effects and interactions: see Table 3 and Figure 3). Despite the significant Trial Type  $\times$  Electrode interaction for the 300–400 ms post-target interval, *post-hoc* tests at each electrode site did not return Trial Type differences after modified Bonferroni correction.

**Age-related differences.** From 0–100 ms post target, stay-pure differences were observed for children and adolescents. The Age Group  $\times$  Trial Type  $\times$  Electrode ANOVA did not reveal significant Trial Type  $\times$  Age group or 3-way interactions

( $ps > .2$ ), indicating a lack of magnitude and topographic differences between the two age groups.

In sum, explicit-task cues triggered larger positive-going potentials on stay compared to pure trials, possibly indexing the preparatory cognitive control necessary to perform the same task in mixed compared to pure blocks. This preparatory activity started early in young adults and adolescents ( $\sim 100$  ms post cue) and, although it included frontal and parietal contributions in both groups, the frontal contribution appeared to be smaller in the adolescents compared to the young adults. In the children, preparatory activity onset later than in the other two groups (starting at  $\sim 300$  ms). Immediately after target onset, the positive difference between stay and pure trials appeared resolved in young adults, whereas it appeared to continue in adolescents (for 100 ms post target) and children (for 300 ms post target).

**Switch costs—short cue-target interval (600 ms).** Figure 4 depicts the ERP waveforms for stay and switch trials, and Figure 5 shows the topographic maps of the time windows with significant switch-stay differences.

**Cue-target interval.** In young adults, switch trials elicited more positive amplitudes than stay trials from 300–600 ms at central and parietal sites (Table 4). Adolescents showed their first significant switch-stay difference from 200–300 ms post cue in the form of a negative-going difference at frontal and fronto-central sites. This was followed by a significant positive switch-stay difference at centro-parietal sites starting at 400 ms post cue and continuing for the remainder of the cue-target interval (Table 4 and Figure 4). By contrast, children failed to show significant switch-stay differences up to 500 ms after cue onset. From 500–600 ms, a reliable positive switch-stay difference was observed at centro-parietal and parietal electrodes (Trial Type  $\times$  Electrode interactions: Table 4).

**Age-related differences.** Switch-stay differences were observed for young adults and adolescents from 400–500 ms and for all age groups from 500–600 ms. Age group  $\times$  Trial Type  $\times$  Electrode ANOVAs did not return significant Trial Type  $\times$  Age Group or 3-way interactions ( $ps > .3$ ), suggesting that there were no age-related differences in effect magnitude or scalp distribution.

**Post-target interval.** In young adults, switch trials elicited more positive-going activity than stay trials from 0–200 ms post-target onset, which was reliable at centro-parietal sites (Trial Type main effects and interactions: Table 4 and Figure 4). In contrast, adolescents showed a positive switch-stay difference from 0–300 ms, predominantly circumscribed to centro-parietal sites (Trial Type main effects and interactions: Table 4). Children showed a switch positivity across the midline that was reliable only from 0–100 ms post target (Table 4).

**Age-related differences.** There were no significant differences in effect magnitude or topographic distribution among the three age groups from 0–100 ms or between young adults and adolescents from 100–200 ms (Trial Type  $\times$  Age Group interactions:  $ps > .06$ ; Trial Type  $\times$  Electrode  $\times$  Age Group interactions:  $ps > .2$ ).

In sum, in all age groups, cues signaling a task switch elicited a posterior positivity. This effect had an earlier onset in young adults and adolescents, and appeared to be delayed by  $\sim 200$  ms in children. The posterior positivity continued after the target for

**Table 3.** Results of the Trial Type (Pure, Stay) × Electrode (Fz, FCz, Cz, CPz, Pz) ANOVAs for the Short Cue-Target Interval Condition

Stay vs. Pure	Short CTI	Time window	Trial type		Trial type × Electrode			Follow-up <sup>†</sup>
			F	$\eta^2$	F	$\epsilon$	$\eta^2$	
Young adults		0–100	ns		4.2*	.42	.18	none
		100–200	14.1***	.43	11.5***	.41	.37	Fz <u>FCz</u> <u>Cz</u> <u>Cpz</u>
		200–300	26.3***	.58	9.1***	.43	.32	Fz <u>FCz</u> <u>Cz</u> <u>Cpz</u> <u>Pz</u>
		300–400	63.5***	.77	14.6***	.42	.44	Fz <u>FCz</u> <u>Cz</u> <u>Cpz</u> <u>Pz</u>
		400–500	105.2***	.85	6.4*	.34	.25	Fz <u>FCz</u> <u>Cz</u> <u>Cpz</u> <u>Pz</u>
		500–600	19.9***	.51	ns			
		Post-target	0–100	ns		ns		
Adolescents		0–100	ns		ns			
		100–200	4.8*	.27	ns			
		200–300	12.9**	.50	ns			
		300–400	10.6**	.45	7.7**	.37	.37	Cz <u>Cpz</u> <u>Pz</u>
		400–500	27.2***	.68	ns			
		500–600	14.4**	.52	ns			
		Post-target	0–100	7.6*	.37	ns		
Children		0–100	ns		ns			
		100–200	ns		ns			
		200–300	ns		ns			
		300–400	8.5*	.40	ns			
		400–500	12.1**	.48	ns			
		500–600	7.6*	.37	6.3*	.39	.32	<u>CPz</u> <u>Pz</u>
		Post-target	0–100	11.2**	.46	5.6*	.36	.30
Children		100–200	6.7*	.34	ns			
		200–300	5.3*	.29	ns			
		300–400	ns		4.1*	.50	.24	None
		Post-target	0–100	ns		ns		

Notes: Degrees of freedom for main effects and interactions, respectively, are (1,19) and (4,76) for young adults, and (1,13) and (4,52) for adolescents and children. ns: not significant,  $\eta^2$ : partial eta squared,  $\epsilon$ : Greenhouse-Geisser coefficient.

\* $p \leq .05$ ; \*\* $p \leq .01$ ; \*\*\* $p \leq .001$ .

<sup>†</sup>Sites showing reliable Trial Type effects in single-electrode ANOVAs with Bonferroni correction (see text); underlining indicates sites where effects are largest.

a longer duration in adolescents, but had a shorter duration in young adults and children.

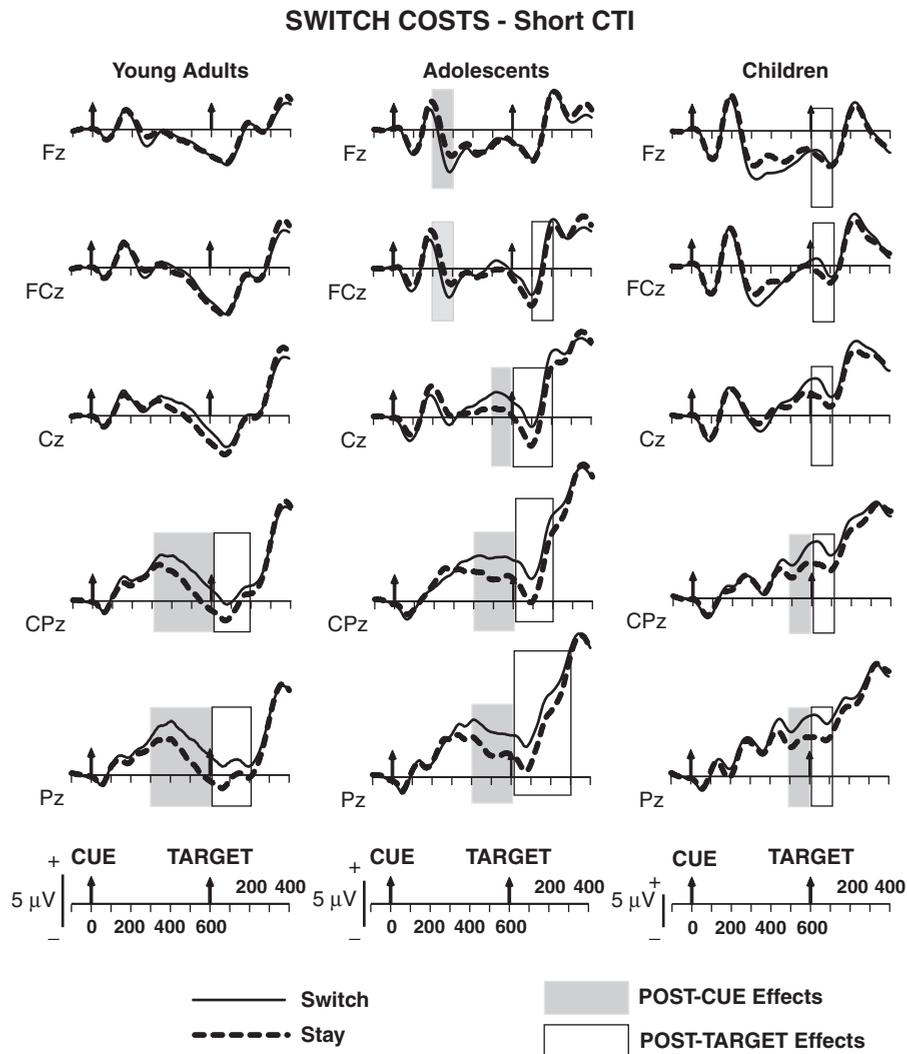
**Mixing costs—long cue-target interval (1200 ms).** The waveforms for pure and stay trials for each age group are displayed in Figure 6. Topographic maps of the time windows with reliable stay-pure differences are shown in Figure 7.

**Cue-target interval.** As found in the short CTI condition, young adults showed a positive-going difference between stay and pure trials from 100–600 ms, while stay-pure differences were not present between 600–1200 ms (Trial Type main effects, see Table 5). The stay-pure positivity was reliable at fronto-central sites from 100–200 ms, and distributed across the midline between 200–600 ms, with larger centro-parietal stay-pure differences from 300–400 ms (Table 5). For adolescents, amplitudes for stay relative to pure trials were more positive going from 100–600 ms and 700–1200 ms post-cue onset (Trial Type main effects: see Table 5). These effects were distributed across the midline throughout the long CTI with larger centro-parietal stay-pure differences from 300–400 ms and 1000–1100 ms (see Table 5). Children displayed more positive waveforms for stay than pure trials beginning 200–300 ms post-cue onset. These differences remained significant throughout the long CTI (200–1200 ms, see Table 5). Between 200–900 ms, stay-pure differences were limited to centro-parietal recording sites, but spread to fronto-central sites between 900–1200 ms (Trial Type × Electrode interactions: see Table 5).

**Age-related differences.** From 100–200 ms, stay-pure differences were only present in adolescents and young adults. The Age Group × Trial Type × Electrode ANOVA did not reveal differences in effect magnitude (Age Group × Trial Type interaction:  $p > .2$ ), but did return a significant Age group × Trial Type × Electrode interaction [ $F(4,128) = 4.17, p < .01, \epsilon = .39, \eta^2 = .12$ ]. Topographic differences, confirmed by the analysis on normalized difference scores [ $F(4,128) = 4.59, p < .05, \epsilon = .39, \eta^2 = .13$ ], reflected the absence of reliable posterior stay-pure differences in young adults compared to adolescents.

From 200–600 ms, stay-pure differences were found for all age groups. The Age Group × Trial Type × Electrode ANOVAs did not return significant Age Group × Trial Type interactions in any of the four intervals ( $ps > .1$ ). However, significant 3-way interactions in all four intervals ( $F_s > 2.7, ps < .05$ ), all of which remained significant after normalization ( $F_s > 3.3, ps < .05$ ), indicated group differences in scalp distribution. Whereas young adults and adolescents showed stay-pure differences at frontal and parietal locations, only children displayed these at parietal sites.

From 700–1200 ms, significant stay-pure differences were exhibited only by children and adolescents. Magnitude differences in these intervals were not reliable (Age Group × Trial Type interactions:  $ps > .07$ ). Between 700–800 ms, the Age Group × Trial Type × Electrode ANOVA returned a significant 3-way interaction [ $F(4,104) = 5.1, p < .05, \epsilon = .31, \eta^2 = .16$ ], which remained reliable for the normalized amplitudes [ $F(4,104) = 4.93, p < .05, \epsilon = .31, \eta^2 = .16$ ]. This interaction reflected the lack of a frontal stay-pure difference in children com-



**Figure 4.** Grand mean cue-locked ERPs for switch and stay trials in the short CTI condition. A 10-Hz low-pass filter was applied. Shading indicates intervals with significant switch-stay differences. Vertical, unshaded rectangles indicate significant post-target differences possibly reflecting continued preparatory processing.

pared to adolescents. Finally, topographic differences between children and adolescents did not emerge between 800–1200 ms ( $p > .06$ ).

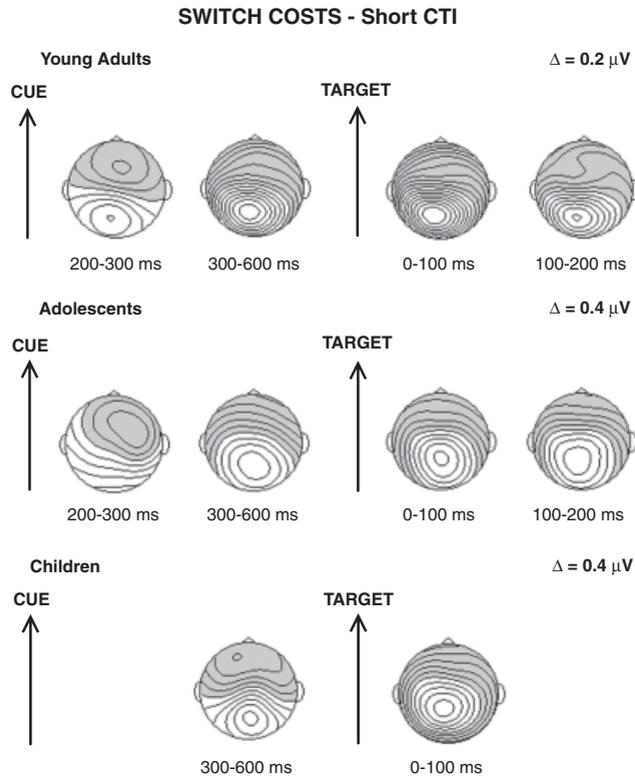
**Post-target interval.** In young adults, stay-pure differences were not significant starting at 600 ms post cue. Therefore, potential continuation effects were not investigated. In children and adolescents, although the waveforms for stay and pure trials appear to differ in the post-target interval (Figure 6), reliable stay-pure differences were not found from 0–100 ms post-target onset ( $p > .3$ ).

To summarize, in the long CTI just as in the short CTI, young adults completed preparation during stay compared to pure trials within 600 ms post-cue onset, as reflected by the termination of the centro-parietal stay-pure positivity. By contrast, children and adolescents appeared to engage in sustained preparatory-control activity that lasted until target onset. These differences were accompanied by changes in scalp distribution suggesting that, between 200–600 ms, young adults and adolescents exhibited more frontally oriented scalp distributions than children.

**Switch costs—long cue-target interval (1200 ms).** Figure 8 depicts the ERP waveforms for stay and switch trials in the long CTI condition, and Figure 9 depicts the topographic maps of the time windows with significant switch-stay differences.

**Cue-target interval.** Young adults first displayed a reliable switch-stay positive-going difference across the midline, from 100–200 ms post-cue onset. Between 300–1000 ms, switch trials elicited more positive-going activity than stay trials mainly at centro-parietal locations (see Table 6). By contrast, adolescents did not evince greater positive-going activity to switch than stay trials until later in the post-cue interval, between 600–700 ms at centro-parietal electrode locations (Table 6). Unlike young adults and adolescents, children did not show reliable differences between stay and switch trials in the long CTI condition.

**Age-related differences.** To test for age-related differences, an Age group  $\times$  Trial Type  $\times$  Electrode ANOVA was computed for the 600–700 ms time window (young adults vs. adolescents). Neither the Age Group  $\times$  Trial Type nor the Age Group  $\times$  Trial Type  $\times$  Electrode interaction was significant, suggesting that



**Figure 5.** Surface potential scalp topographies for the switch minus stay difference waveforms in the short CTI condition, depicted for the time windows in which the magnitude differences were reliable. Front of the head is at the top. Shaded areas reflect negativity; unshaded areas reflect positivity.

reliable differences in effect magnitude and scalp distribution were not present ( $ps > .2$ ).

**Post-target interval.** As observed in Figure 8 and confirmed by statistical analyses, stay-switch differences terminated prior to target presentation for all age groups. Therefore, switch-stay differences in the post-target interval were not examined.

In summary, when preparing for a switch, both young adults and, to a limited extent, adolescents produced a reliable switch-stay positivity, which onset earlier for young adults and was sustained for a longer time period relative to that elicited by stay cues. By contrast, children did not evince reliable switch-stay positive activity at any time interval during the long CTI.

**Discussion**

The aim of the current study was to investigate age-related differences in anticipatory cognitive control in a cued task-switching paradigm. Behavioral and ERP indices for mixing and switch costs, putatively reflecting different anticipatory control processes, were recorded in young adults, adolescents, and children, and will be discussed separately below.

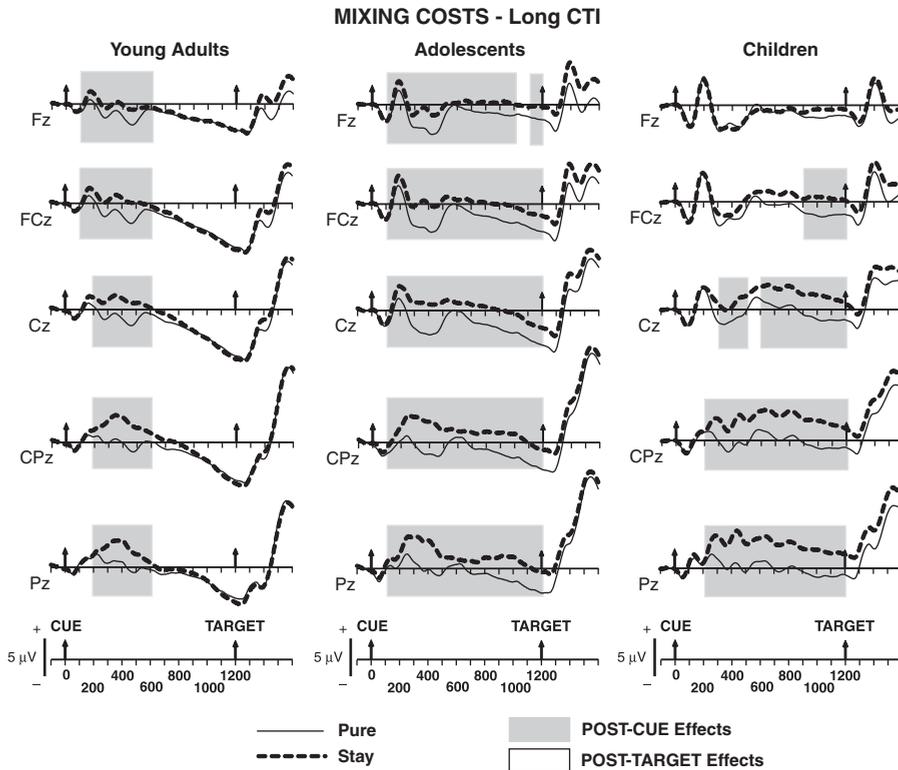
**Mixing Costs: Task-Set Updating**

All age groups showed RT and accuracy mixing costs, indicating that all participants were susceptible to the performance decrements induced by performing the same task repeatedly in mixed compared to pure blocks. Importantly, the magnitude of behavioral mixing costs for the different age groups did not differ for the long CTI of 1200 ms, while developmental differences

**Table 4.** Results of the Trial Type (Stay, Switch) × Electrode (Fz, FCz, Cz, CPz, Pz) ANOVAs for the Short Cue-Target Interval Condition

Switch vs. Stay	Time window	Trial type		Trial type × Electrode			Follow-up <sup>†</sup>	
		F	ηp <sup>2</sup>	F	ε	ηp <sup>2</sup>		
Young adults	0–200	ns		ns				
	200–300	ns		20.6***	.47	.52	None	
	300–400	ns		13.9***	.45	.42	CPz Pz	
	400–500	8.3**	.30	22.9***	.50	.54	CPz Pz	
	500–600	10.9**	.36	41.7***	.51	.69	CPz Pz	
	Post-target	0–100	6.1*	.24	28.4***	.49	.60	CPz Pz
Adolescents	100–200	ns		15.1***	.35	.44	CPz Pz	
	200–300	ns		ns				
	0–200	ns		ns				
	200–300	ns		5.5***	.37	.30	Fz (neg) FCz (neg)	
	300–400	ns		7.7**	.38	.37	None	
	400–500	7.4*	.36	8.3**	.36	.39	CPz Pz	
	500–600	11.3**	.47	8.5**	.37	.40	Cz CPz Pz	
	Post-target	0–100	15.6**	.55	7.9**	.39	.38	Cz CPz, Pz
	100–200	23.1***	.64	4.9**	.38	.27	FCz Cz CPz Pz	
	200–300	ns		5.4***	.45	.29	Pz	
Children	300–400	ns		ns				
	0–300	ns		ns				
	300–400	ns		9.6**	.38	.42	None	
	400–500	ns		9.1**	.40	.41	None	
	500–600	ns		14.4***	.40	.50	CPz Pz	
	Post-target	0–100	10.3**	.44	ns			
	100–200	ns		ns				

Notes: See Table 3. neg indicates a negative switch-stay difference.

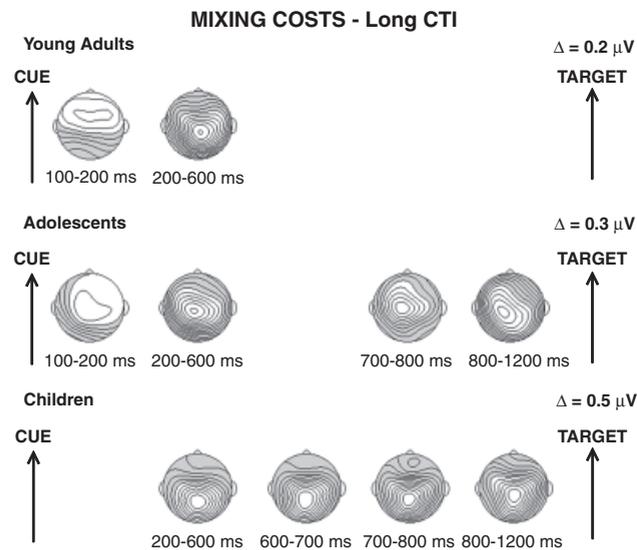


**Figure 6.** Grand mean cue-locked ERPs for pure and stay trials in the long CTI condition. A 10-Hz low-pass filter was applied. Shading indicates intervals with significant stay-pure differences.

emerged for the short CTI of 600 ms. Specifically, adolescents showed significantly larger accuracy costs than young adults, although accuracy rates were near ceiling for both groups. Hence, this finding should not be given undue weight. More important, children showed larger RT mixing costs than young adults in the short CTI. Overall, these results are compatible with

the extant literature, reporting age differences in RT mixing costs (Crone et al., 2004; Crone, Bunge, et al., 2006; Karbach & Kray, 2007; Kray et al., 2004, 2008; Reimers & Maylor, 2005; but see Crone, Bunge, et al., 2006, for an exception).

Different theoretical accounts have been provided to explain such developmental differences in mixing costs. According to the working-memory load theory (Los, 1996; Rogers & Monsell, 1995), the reduction in mixing costs throughout development has been interpreted as reflecting an increase in working memory capacity (Gathercole, 1999; Gathercole, Pickering, Ambridge, & Wearing, 2004). Alternatively, increased efficiency in task-set updating might account for the developmental trajectory of mixing costs that we and others have observed. Developmental differences in mixing costs might also be primarily related to the use of bivalent stimuli; that is, stimuli that can activate multiple task sets depending on which rule is currently active (Rubin & Meiran, 2005). For instance, in our paradigm, the digit 3 is associated with the response “3” for the task “Which digit?” (compatible response), but it is associated with the response “1” for the task “How many?” (incompatible response). The ambiguity generated by bivalent stimuli needs to be overcome by reinstating or updating the currently active task set and its associated response contingencies. Children might be especially challenged in recruiting these cognitive processes on incompatible trials leading to increased RT mixing costs compared to young adults. However, contrary to this argument, RT mixing costs on incompatible relative to compatible trials did not differ among age groups. That is, Age Group × Compatibility (compatible, incompatible) ANOVAs on proportional RT mixing costs failed to return reliable Age Group × Compatibility interactions ( $p_s > .05$ ). This result reduces the force with which the ambiguity account can be applied to explain the age differences



**Figure 7.** Surface potential scalp topographies for the stay minus pure difference waveforms in the long CTI condition, depicted for the time windows in which the magnitude differences were reliable. Front of the head is at the top. Shaded areas reflect negativity; unshaded areas reflect positivity.

**Table 5.** Results of the Trial Type (Pure, Stay) × Electrode (Fz, FCz, Cz, CPz, Pz) ANOVAs for the Long Cue-Target Interval Condition

Stay vs. Pure Long CTI	Time window	Trial type		Trial type × Electrode			Follow-up <sup>†</sup>
		F	$\eta^2$	F	$\epsilon$	$\eta^2$	
Young adults	0–100	ns		ns			
	100–200	5.32*	.22	6.1*	.36	.24	Fz, FCz
	200–300	17.04***	.47	ns			
	300–400	29.97***	.61	8.03***	.41	.30	Fz, FCz, Cz, <u>CPz</u> , <u>Pz</u>
	400–500	44.47***	.70	ns			
	500–600	8.82**	.31	ns			
Post target Adolescents	600–1200	ns		ns			
	0–100	ns		ns			
	0–100	ns		3.99*	.35	.23	none
	100–200	6.05*	.32	ns			
	200–300	13.7**	.51	ns			
	300–400	21.91***	.63	8.42***	.55	.39	Fz, FCz, Cz, <u>CPz</u> , <u>Pz</u>
	400–500	48.76***	.79	ns			
	500–600	6.55*	.33	ns			
	600–700	ns		ns			
	700–800	5.60*	.30	ns			
	800–900	8.15*	.39	ns			
	900–1000	15.85**	.55	ns			
Post target Children	1000–1100	12.24**	.48	5.26*	.46	.29	FCz, Cz, CPz, Pz
	1100–1200	9.80**	.43	ns			
	0–100	ns		ns			
	0–100	ns		4.6*	.54	.26	none
	100–200	ns		ns			
	200–300	ns		5.89*	.37	.31	CPz, Pz
	300–400	8.11*	.38	13.65***	.33	.51	Cz, CPz, Pz
	400–500	8.70*	.40	16.08***	.30	.55	Cz, CPz, Pz
	500–600	ns		10.91**	.33	.46	CPz, Pz
	600–700	9.48**	.42	5.67*	.30	.30	Cz, CPz, Pz
	700–800	11.06**	.46	8.56**	.30	.40	Cz, CPz, Pz
	800–900	11.06*	.46	8.92**	.30	.40	Cz, CPz, Pz
Post target	900–1000	26.21***	.67	7.55**	.32	.37	FCz, Cz, CPz, Pz
	1000–1100	28.18***	.68	7.44**	.33	.36	FCz, Cz, CPz, Pz
	1100–1200	29.28***	.69	5.51*	.32	.30	FCz, Cz, CPz, Pz
	0–100	ns		ns			

Notes: See Table 3.

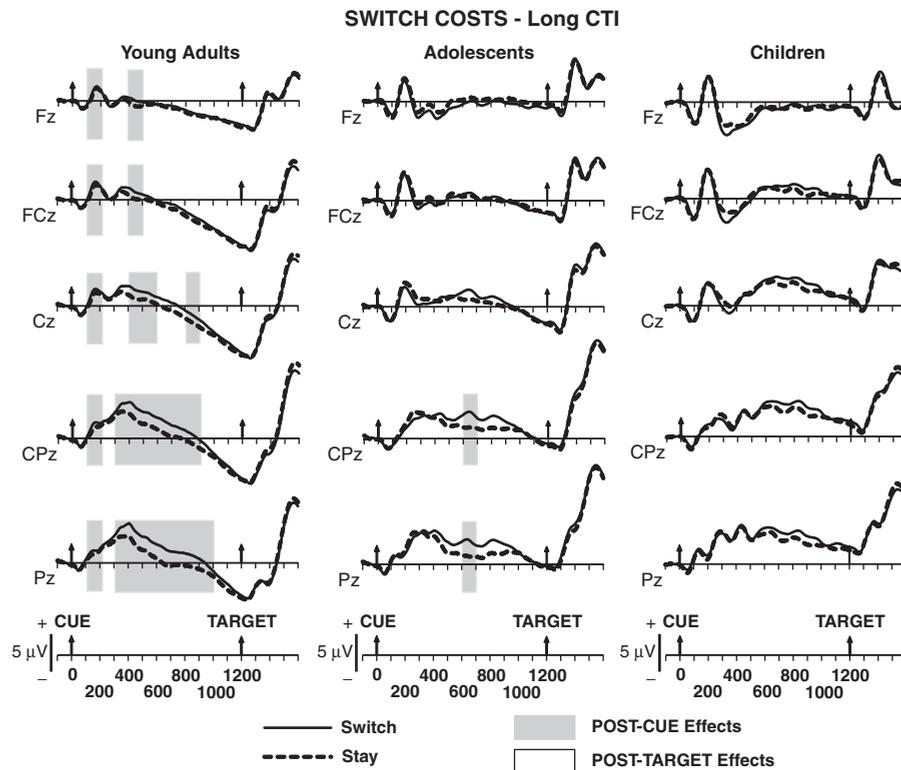
in mixing costs. On this basis, it is more likely that increased efficiency in task-set updating and/or increments in working memory capacity are key components putatively accounting for the reduction in mixing costs with increments in cognitive development.

The age-related behavioral differences in mixing costs are congruent with the age-related differences that were observed for the post-cue ERP positivity for stay compared to pure trials in the short CTI. This ERP effect has been attributed to anticipatory task-set updating (Jost et al., 2008; Kray et al., 2005; West, 2004; Wylie et al., 2008). In young adults and adolescents, cues elicited a positive stay-pure difference starting as early as ~100 ms post cue, and extending throughout the cue-target interval. Importantly, although young adults and adolescents showed frontal stay-pure differences in early time intervals (100–300 ms), these were smaller in adolescents. By contrast, children did not evince early frontal (or parietal) stay-pure differences in either of these two intervals.

Efficacious executive control of task sets is thought to require involvement of the PFC, as indicated by neuropsychological studies of patients with circumscribed lesions and hemodynamic neuroimaging studies (for a review, see Sakai, 2008). Based on these kinds of data, it could be speculated that the reduction in early frontally oriented positive activity in adolescents and its absence in children might reflect reduced involvement of prefrontal cortex in cognitive control. Admittedly, the ERP tech-

nique does not easily support neuroanatomical inferences. Nonetheless, our speculation is compatible with evidence of protracted frontal lobe maturation (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Diamond, 2002) and reduced frontal activations in fMRI studies of task switching in children and adolescents (Bunge & Zelazo, 2006; Crone, Donohue, Honnichl, Wendelken, & Bunge, 2006). In showing evidence of early-latency frontal ERP effects in young adults in association with reduced mixing costs, our findings supplement the extant task-switching literature, which has predominantly concentrated on switch costs and their associated centro-parietal, positive-magnitude effects.

The stay-pure ERP differences for children may reflect an early point in the development of the processes involved in task-set updating. First, children did not show an adult-like pattern of frontal scalp activity for the stay-pure differences during either the short or long CTI, even though, in the latter, the potential for longer-duration preparatory activity was made available. Second, in contrast to young adults and adolescents, stay-pure positive differences for children did not emerge until after 300 ms post cue in the short CTI and were also delayed by 100 ms in the long CTI compared to young adults and adolescents. Nonetheless, when sufficient preparation time was available in the long CTI, children showed prominent stay-pure differences throughout the CTI at posterior locations (Figure 6). Notably, such delayed onset of preparatory activity in children in the short CTI



**Figure 8.** Grand mean cue-locked ERPs for switch and stay trials in the long CTI condition. A 10-Hz low-pass filter was applied. Shading indicates intervals with significant switch-stay differences.

most likely reflected inefficient timing of the onset of advance task-set updating, which presumably contributed to the children's longer RT mixing costs in that condition.<sup>4</sup>

To further support the hypothesis that delays in the timing of preparatory activity were associated with increments in mixing costs, correlations between the peak latency of the stay minus pure positivity and proportional RT mixing costs were computed.<sup>5</sup> The data from the midline locations were used. Because only children and young adults differed in mixing cost magnitude in the short CTI, we computed across-subject correlations between the individual latencies of this peak and the individual mixing costs. For the young adults, we obtained the peak latencies of the stay-pure positivity using a range of 100 to 600 ms post cue (i.e., within the cue-target interval). The young adults' mean peak latency ( $\pm$  SD) at Pz was 395 ms ( $\pm$  65 ms). For the children, whose amplitudes were prolonged into the target interval, the relevant search epoch was 300 to 900 ms post cue (the latter of which corresponded to 300 ms post target). The children's mean

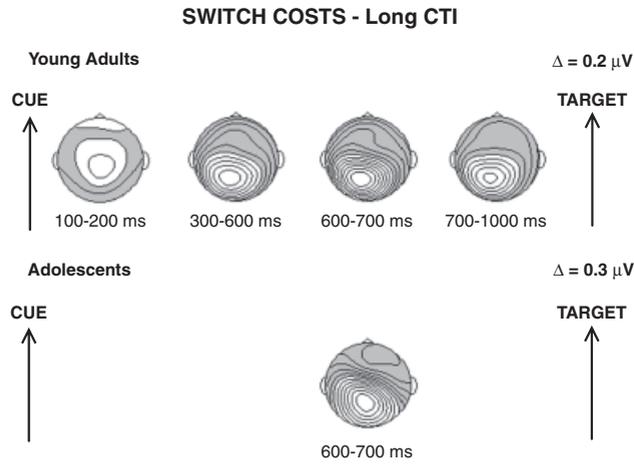
peak latency ( $\pm$  SD) at Pz was 549 ms ( $\pm$  161 ms). With the exception of Fz, the correlations at the remaining sites were positive and highly significant, 0.55 at FCz ( $p < .001$ ), 0.39 at Cz ( $p < .02$ ), 0.40 at CPz ( $p < .02$ ), and 0.46 at Pz ( $p < .007$ ). Hence, these results add strength to the argument that delayed anticipatory task-set updating may have been responsible for the larger mixing costs in the children compared to the young adults.

In addition, the three age groups differed in the offset latency of anticipatory control indexed by the stay-pure positivity. The positivity was resolved by target onset in young adults in the short CTI and, similarly, by 600 ms in the long CTI. This suggests that young adults were able to fully carry out anticipatory, endogenous control processes during the short 600-ms preparatory interval as well as the long 1200-ms CTI. This indicates that the young adults were well prepared for exogenous, stimulus-driven processing upon target presentation (see also Jost et al., 2008; Monsell & Mizon, 2006, for similar conclusions on switch costs). Although adolescents showed increased positivity for stay relative to pure trials as early as  $\sim$ 100 ms post cue, this difference was sustained for approximately 100 ms post target in the short CTI. However, as already pointed out, this short carryover effect did not translate into reliably increased RT mixing costs; rather, it was associated with decreased accuracy.

Conversely, differences in the latency of anticipatory control processes in children compared to young adults were associated with larger RT mixing costs. In the short CTI, the centro-parietal positivity onsetting at  $\sim$ 300 ms post cue was protracted for at least 300 ms following the target. Importantly, because the post-target differences were similar in scalp topography to those occurring in the CTI (i.e., centro-parietal), they most likely reflected a continuation of cue-related processing that persisted

<sup>4</sup>It should be noted, however, that caution must be exercised when interpreting the onset, offset, and duration of an ERP process. For example, the duration of an ERP amplitude difference does not necessarily reflect the duration of the underlying process (Rugg & Coles, 1995). According to Rugg and Coles (1995), the difference in onset provides an upper bound on the latency at which two processes diverge. That is, the underlying process could have onset earlier without necessarily being reflected in latency changes at the scalp. Nonetheless, as Rugg and Coles (1995) also point out, differences in timing can still be used to provide constraints on the temporal course of cognitive processing. Thus, we believe our results still proffer valuable information concerning developmental differences in the duration and timing of anticipatory processes in task switching.

<sup>5</sup>We thank an anonymous reviewer for suggesting this analysis.



**Figure 9.** Surface potential scalp topographies for the switch minus stay difference waveforms in the long CTI condition, depicted for the time windows in which the magnitude difference were reliable. Front of the head is at the top. Shaded areas reflect negativity; unshaded areas reflect positivity. Note that children did not show reliable switch minus stay differences in any of the 100-ms intervals during the CTI. Therefore, maps are not depicted for this group.

until 300 ms post target. It is plausible that this post-target activity was engendered by the delayed initiation of anticipatory task-set updating following the cue. As a result, not-yet-completed anticipatory control processes would have overlapped with and delayed the processing of the target in the short CTI, thus explaining the larger RT mixing costs in children compared

to young adults. When children were given more time for preparatory task-set updating processes in the long CTI, they, as well as adolescents, evinced similarly prolonged stay-pure preparatory neural activity. Hence, it is reasonable to assume that children and adolescents used the additional time available in the long CTI to more efficiently prepare (relative to the short CTI) for the upcoming target. This would account for the reduction in RT and accuracy mixing costs in these groups as well as the absence of age-group differences.

**Switch Costs: Task-Set Reconfiguration**

Switch costs in both short and long CTI conditions did not differ among children, adolescents, and young adults. Previous studies have shown a similar lack of developmental differences in switch costs (Crone et al., 2004; Karbach & Kray, 2007; Reimers & Maylor, 2005), possibly indicating that the cognitive control processes necessary to coordinate and reconfigure task sets are equally efficacious in the age groups examined. Perhaps, on these bases, the behavioral data from our samples could be used to support the assumption that task-set reconfiguration might be relatively mature in children aged 9–11 (but, see discussion of ERP results below).

Task-set reconfiguration processes were presumably captured by the sustained, switch-stay centro-parietal positivity observed in all age groups in the short CTI. In accord with this notion, positivities with similar latencies and topographies have been repeatedly interpreted as reflecting the processes involved in task-set reconfiguration (Astle et al., 2006, 2008; Hsieh & Cheng, 2006; Karayanidis et al., 2009; Kieffaber & Hetrick, 2005; Miniussi et al., 2005; Moulden et al., 1998; Nicholson, Karayanidis,

**Table 6.** Results of the Trial Type (Stay, Switch) × Electrode (Fz, FCz, Cz, CPz, Pz) ANOVAs for the Long Cue-Target Interval Condition

Switch vs. Stay	Time Window	Trial Type		Trial Type × Electrode			Follow-up <sup>†</sup>
		F	η <sup>2</sup>	F	ε	η <sup>2</sup>	
Long CTI	Young adults						
	0–100	ns		ns			
	100–200	5.01*	.21	ns			
	200–300	ns		5.03*	.37	.21	none
	300–400	5.13*	.21	10.86***	.40	.36	CPz, Pz
	400–500	24.80***	.57	11.38***	.38	.38	Fz, FCz, Cz, CPz, Pz
	500–600	11.61**	.38	19.97***	.39	.51	Cz, CPz, Pz
	600–700	8.42**	.30	24.19***	.38	.56	CPz, Pz
	700–800	5.45*	.22	11.57***	.36	.39	CPz, Pz
	800–900	7.50*	.28	10.82***	.37	.36	Cz, CPz, Pz
	900–1000	ns		6.14**	.47	.24	Pz
	1000–1100	ns		3.43*	.49	.15	none
	1100–1200	ns		ns			
Post target	Adolescents						
	0–100	ns		ns			
	0–400	ns		ns			
	400–500	ns		6.56**	.39	.34	none
	500–600	ns		7.27**	.36	.36	none
	600–700	5.70*	.30	10.08**	.35	.44	CPz, Pz
	700–800	ns		9.46**	.31	.42	none
	800–900	ns		5.03*	.38	.28	none
	900–1200	ns		ns			
	0–100	5.77*	.18	ns			
Children	Post target						
	0–100	ns		ns			
	100–200	ns		3.81*	.35	.12	none
	0–100	ns		ns			
	100–200	ns		ns			

Notes: See Table 3.

Davies, & Michie, 2006; Nicholson et al., 2005; Rushworth et al., 2002, 2005; Swainson et al., 2003; Tiegues et al., 2007). The centro-parietal positivity onset at approximately 400 ms post cue in children (Figure 4), whereas it was present in adolescents and young adults at an earlier point in time, approximately 300 ms post cue. Interestingly, the centro-parietal positivity remained active for 200 ms post target in young adults, suggesting that even young adults could not completely reconfigure the new task set prior to the presentation of the target. Moreover, in adolescents the positivity endured until approximately 300 ms post target, indicating a developmental delay in completely reconfiguring the new task set when the short cue-target interval presumably interrupted ongoing preparatory activity.

Surprisingly, in the short CTI, the switch-stay positive difference appeared to resolve in children at approximately 100 ms post target (Figure 4). Despite the delay in the post-cue, centro-parietal positivity, this result seems to indicate that children are able to reconfigure the new task set at an earlier time period following the target than adolescents and young adults. However, it seems more likely that the absence of switch-stay differences in most of the CTI and later in the post-target interval indicates that children, unlike young adults, performed similar operations on both stay and switch trials. That is, children might not selectively recruit task-set reconfiguration processes only on switch trials but also on some percentage of stay trials. Additional support for this argument comes from the results of the long CTI condition (Figure 8). In this condition, children did not show reliable switch-stay differences at any point in the CTI, similar to what occurred in the short CTI. By contrast, and in accord with the cascade of task-set reconfiguration processes required on switch relative to stay trials, young adults and, to some extent, adolescents exhibited long-duration, centro-parietal switch-stay positive activity that endured, at least in young adults, until ~1000 ms post-cue onset. Alternatively, because adolescents showed a reliable switch-stay difference only between 600 and 700 ms in the long CTI, it is also possible that they, like children, might have reconfigured the task set on some proportion of stay trials in the long CTI. In fact, recent data suggest that, depending upon task circumstances (for example, increased task difficulty), the preparatory processes recruited prior to switch trials might also be engaged to similar extents on stay trials, even by young adults (Kiesel et al., 2010). Hence, by contrast with the behavioral data, the ERP data suggest the continued maturation of processes associated with task-set reconfiguration in children, which may continue, perhaps to some extent, into adolescence.

The idea that task-set reconfiguration might have occurred on at least some of the stay trials in children has additional implications for the interpretation of behavioral mixing and switching costs. That is, children showed longer overall stay-trial RTs compared to adolescents and young adults (approximately 200 and 300 ms longer, respectively, than those of adolescents and young adults; Table 2), leading to increased mixing costs in the short CTI. Hence, if our interpretation for the early termination of the post-target centro-parietal positivity in the short CTI is correct, a portion of the longer stay-trial RTs in children would also reflect task-set reconfiguration processes (see also discussion above). Therefore, the delay in switch-related processing evident in the centro-parietal positivity might not have translated into increased RT switch costs for children, because the prolonged stay-trial RTs used as a baseline for the calculation of switch costs would have attenuated the overall estimate of such costs. Sim-

ilarly, this reasoning would also apply to mixing costs. That is, stay trial RTs would presumably reflect maintenance and updating of the current task set in adolescents and young adults, but task-set reconfiguration processes on some portion of these trials in children. Hence, the age-related difference in behavioral and ERP measures of mixing costs might also include contributions from these presumably unwarranted but additional task-set reconfiguration processes in children.<sup>6</sup>

Finally, the maturational changes observed here for both RT and ERP measures of temporal processing could be due to an age-related general slowing factor (Fry & Hale, 2000; Kail & Salthouse, 1994). However, this is unlikely for three reasons. First, as noted earlier, we used proportional measures of RT mixing costs, in order to eliminate the effect of baseline RT. Second, switch costs were age-invariant whereas mixing costs were not. Had general slowing accounted fully for these data, then both mixing and switch costs should have been of similar magnitudes in the three groups of participants. Third, we measured an early-onset ERP component, the P2 (see Figure 2), which is believed to reflect relatively early processing of perceptual information (Luck & Hillyard, 1994). If general slowing played a significant role in the pattern of costs we obtained, then we would have expected increased delays in this component's latency in the children (and, perhaps, adolescents). Accordingly, we compared the latency of P2 at FCz (where it was largest; peak detected between 100 and 400 ms post-cue onset) across the three age groups separately for pure, stay, and switch trials. However, significant age differences were not found ( $F_s < 1$ ; the latency averaged approximately 200 ms across trial types in each age group). Thus, in total, these analyses are consistent with the results of previous studies (Cepeda et al., 2001; Ridderinkhof & van der Molen, 1997), and add weight to the notion that general slowing cannot account, in any simple fashion, for the developmental pattern of RT costs and ERP findings reported in the current manuscript.

## Conclusions

Congruent with previous behavioral findings, mixing and switch costs seem to follow different developmental trajectories, suggesting that task-set updating and reconfiguration, respectively, are functionally separate processes with different rates of maturation. In addition, the ERP findings suggest that the delayed maturation of mixing costs could be due to delayed onset of anticipatory task-set updating in children (reflected by the centro-parietal stay-pure positivity). Moreover, further evidence for the continued development of the processes involved in anticipatory task-set updating comes from the reduction in frontal-scalp foci in children compared to young adults and adolescents. To the extent that such foci reflect contributions from frontal cortex (see, for examples, Jamadar, Hughes, Fulham, Michie, & Karayanidis, 2010), it is tempting to speculate that this finding suggests that the continued maturation of task-set updating processes could be due to the protracted development of frontal cortex. Importantly, the ERP and behavioral data further suggest that during mixed blocks children adopt a performance strategy in which they recruit task-set reconfiguration processes on at least a portion of stay trials, rather than engaging these processes solely on switch trials.

<sup>6</sup>Thanks to an anonymous reviewer who pointed this out to us.

## References

- Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and Performance (Vol. XV)*, pp. 421–452. Cambridge MA: MIT Press.
- Alvarez, J. A., & Emory, E. (2006). Executive function and the frontal lobes: A meta-analytic review. *Neuropsychology Review*, *16*, 17–42.
- Astle, D. E., Jackson, G. M., & Swainson, R. (2006). Dissociating neural indices of dynamic cognitive control in advance task-set preparation: An ERP study of task switching. *Brain Research*, *1125*, 94–103.
- Astle, D. E., Jackson, G. M., & Swainson, R. (2008). Fractionating the cognitive control required to bring about a change in task: A dense-sensor event-related potential study. *Journal of Cognitive Neuroscience*, *20*, 255–267.
- Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*, 301–311.
- Bunge, S. A., & Wright, S. B. (2007). Neurodevelopmental changes in working memory and cognitive control. *Current Opinion in Neurobiology*, *17*, 243–250.
- Bunge, S. A., & Zelazo, P. D. (2006). A brain-based account of the development of rule use in childhood. *Current Directions in Psychological Science*, *15*, 118–121.
- Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. C. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology*, *37*, 715–730.
- Chelune, G. J., & Baer, R. A. (1986). Developmental norms for the Wisconsin Card Sorting test. *Journal of Clinical Experiments in Neuropsychology*, *8*, 219–228.
- Crone, E. A., Bunge, S. A., van der Molen, M. W., & Ridderinkhof, K. R. (2006). Switching between tasks and responses: A developmental study. *Developmental Science*, *9*, 278–287.
- Crone, E. A., Donohue, S. E., Honomichl, R., Wendelken, C., & Bunge, S. A. (2006). Brain regions mediating flexible rule use during development. *Journal of Neuroscience*, *26*, 11239–11247.
- Crone, E. A., Ridderinkhof, K. R., Worm, M., Somsen, R. J., & van der Molen, M. W. (2004). Switching between spatial stimulus-response mappings: A developmental study of cognitive flexibility. *Developmental Science*, *7*, 443–455.
- Czernochowski, D., Nessler, D., & Friedman, D. (2010). On why not to rush older adults—Relying on reactive cognitive control can effectively reduce errors at the expense of slowed responses. *Psychophysiology*, *47*, 637–646.
- Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*, 2037–2078.
- Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 466–503). New York, NY: Oxford University Press.
- Diamond, A., Barnett, W. S., Thomas, J., & Munro, S. (2007). Preschool program improves cognitive control. *Science*, *318*, 1387–1388.
- Fagot, C. (1994). *Chronometric investigation of task switching*. Unpublished doctoral dissertation. University of California, San Diego.
- Fry, A. F., & Hale, S. (2000). Relationships among processing speed, working memory, and fluid intelligence in children. *Biological Psychology*, *54*, 1–34.
- Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences*, *3*, 410–419.
- Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology*, *40*, 177–190.
- Gopher, D., Armony, L., & Greenspan, Y. (2000). Switching tasks and attention policies. *Journal of Experimental Psychology: General*, *129*, 308–339.
- Goswami, U. (2006). Neuroscience and education: From research to practice? *Nature Reviews Neuroscience*, *7*, 406–411.
- Heaton, R. K. (1981). *Wisconsin Card Sorting Test Manual*. Odessa, FL: Psychological Assessment Resources, Inc.
- Hsieh, S., & Cheng, P. (2006). Task reconfiguration and carryover in task switching: An event-related potential study. *Brain Research*, *1084*, 132–145.
- Inhelder, B., & Piaget, J. (1964). *The early growth of logic in the child: Classification and seriation*. New York, NY: Harper and Row.
- Jaccard, J., & Wan, C. K. (1996). *LISREL approaches to interaction effects in multiple regression*. Thousand Oaks, CA: Sage Publications.
- Jamadar, S., Hughes, M., Fulham, W. R., Michie, P. T., & Karayanidis, F. (2010). The spatial and temporal dynamics of anticipatory preparation and response inhibition in task-switching. *NeuroImage*, *51*, 432–449.
- Jennings, J. R., & Wood, C. C. (1976). The epsilon-adjusted procedure for repeated measures analyses of variance. *Psychophysiology*, *13*, 277–278.
- Jost, K., Mayr, U., & Rösler, F. (2008). Is task switching nothing but cue priming? Evidence from ERPs. *Cognitive, Affective, & Behavioral Neuroscience*, *8*, 74–84.
- Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychologica (Amst)*, *86*, 199–225.
- Karayanidis, F., Coltheart, M., Michie, P. T., & Murphy, K. (2003). Electrophysiological correlates of anticipatory and poststimulus components of task switching. *Psychophysiology*, *40*, 329–348.
- Karayanidis, F., Mansfield, E. L., Galloway, K. L., Smith, J. L., Provost, A., & Heathcote, A. (2009). Anticipatory reconfiguration elicited by fully and partially informative cues that validly predict a switch in task. *Cognitive, Affective, & Behavioral Neuroscience*, *9*, 202–215.
- Karbach, J., & Kray, J. (2007). Developmental changes in switching between mental task sets: The influence of verbal labeling in childhood. *Journal of Cognition and Development*, *8*, 205–236.
- Kieffaber, P. D., & Hetrick, W. P. (2005). Event-related potential correlates of task switching and switch costs. *Psychophysiology*, *42*, 56–71.
- Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching—A review. *Psychological Bulletin*, *136*, 849–874.
- Kray, J., Eber, J., & Karbach, J. (2008). Verbal self-instructions in task switching: A compensatory tool for action-control deficits in childhood and old age? *Developmental Science*, *11*, 223–236.
- Kray, J., Eber, J., & Lindenberger, U. (2004). Age differences in executive functioning across the lifespan: The role of verbalization in task preparation. *Acta Psychologica*, *115*, 143–165.
- Kray, J., Eppinger, B., & Mecklinger, A. (2005). Age differences in attentional control: An event-related potential approach. *Psychophysiology*, *42*, 407–416.
- Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychological Aging*, *15*, 126–147.
- Lavric, A., Mizon, G. A., & Monsell, S. (2008). Neurophysiological signature of effective anticipatory task-set control: A task-switching investigation. *European Journal of Neuroscience*, *28*, 1016–1029.
- Levin, H. S., Culhane, K. A., Hartmann, J., Evankovich, K., Mattson, A., Harward, H., & . . . Fletcher, J. (1991). Developmental changes in performance on tests of purported frontal lobe functioning. Special Issue: Developmental consequences of early frontal lobe damage. *Developmental Neuropsychology*, *7*, 377–395.
- Los, S. A. (1996). On the origin of mixing costs: Exploring information processing in pure and mixed blocks of trials. *Acta Psychologica*, *94*, 145–188.
- Los, S. A. (1999). Identifying stimuli of different perceptual categories in pure and mixed blocks of trials: Evidence for stimulus-driven switch costs. *Acta Psychologica*, *103*, 173–205.
- Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, *31*, 291–308.
- Mayeux, R., Stern, Y., Rosen, J., & Leventhal, J. (1981). Depression, intellectual impairment, and Parkinson disease. *Neurology*, *31*, 645–650.
- Mayr, U. (2001). Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response-set overlap. *Psychological Aging*, *16*, 96–109.
- Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 1124–1140.
- McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology*, *62*, 203–208.

- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 1423–1442.
- Meiran, N. (2000). Modeling cognitive control in task-switching. *Psychological Research*, *63*, 234–249.
- Meltzer, L. (2007). *Executive function in education: From theory to practice*. New York, NY: The Guilford Press.
- Miniussi, C., Marzi, C. A., & Nobre, A. C. (2005). Modulation of brain activity by selective task sets observed using event-related potentials. *Neuropsychologia*, *43*, 1514–1528.
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49–100.
- Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*, 134–140.
- Monsell, S., & Mizon, G. A. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology, Human Perception, and Performance*, *32*, 493–516.
- Moulden, D. J. A., Picton, T. W., Meiran, N., Stuss, D. T., Riera, J. J., & Valdes-Sosa, P. (1998). Event-related potentials when switching attention between task-sets. *Brain and Cognition*, *37*, 186–190.
- Nicholson, R., Karayanidis, F., Davies, A., & Michie, P. T. (2006). Components of task-set reconfiguration: Differential effects of ‘switch-to’ and ‘switch-away’ cues. *Brain Research*, *1121*, 160–176.
- Nicholson, R., Karayanidis, F., Poboka, D., Heathcote, A., & Michie, P. T. (2005). Electrophysiological correlates of anticipatory task-switching processes. *Psychophysiology*, *42*, 540–554.
- Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation (Vol. 4, pp. 1–18)*. New York, NY: Plenum.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.
- Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, *72*, 184–187.
- Picton, T. W., van Roon, P., Armilio, M. L., Berg, P., Ille, N., & Scherg, M. (2000). The correction of ocular artifacts: A topographic perspective. *Clinical Neurophysiology*, *111*, 53–65.
- Reimers, S., & Maylor, E. A. (2005). Task switching across the life span: Effects of age on general and specific switch costs. *Developmental Psychology*, *41*, 661–671.
- Reynolds, C. R., & Horton, A. M., Jr. (2008). Assessing executive functions: A life-span perspective. *Psychology in the Schools*, *45*, 875–892.
- Ridderinkhof, K. R., & van der Molen, M. W. (1997). Mental resources, processing speed, and inhibitory control: A developmental perspective. *Biological Psychology*, *45*, 241–261.
- Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231.
- Rugg, M. D., & Coles, M. G. H. (1995). The ERP and cognitive psychology: Conceptual issues. In M. D. Rugg & M. G. H. Coles (Eds.), *Electrophysiology of mind: Event-related brain potentials and cognition (Vol. 25, pp. 27–39)*. New York, NY: Oxford Science Publications.
- Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*, 1477–1491.
- Rushworth, M. F., Passingham, R. E., & Nobre, A. C. (2002). Components of switching intentional set. *Journal of Cognitive Neuroscience*, *14*, 1139–1150.
- Rushworth, M. F., Passingham, R. E., & Nobre, A. C. (2005). Components of attentional set-switching. *Experimental Psychology*, *52*, 83–98.
- Sakai, K. (2008). Task set and prefrontal cortex. *Annual Review of Neuroscience*, *31*, 219–245.
- Salmon, E., & Collette, F. (2005). Functional imaging of executive functions. *Acta Neurologica Belgica*, *105*, 187–196.
- Semlitsch, H. V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology*, *23*, 695–703.
- Sharbrough, F., Chatrian, G. E., Lesser, R. P., Luders, H., Nuwer, M., & Picton, T. W. (1990). *Guidelines for standard electrode position nomenclature*. Bloomfield, CT: American EEG Society.
- Sheslow, D., & Adams, W. (1990). *The wide range assessment of memory and learning*. Los Angeles, CA: Western Psychological Services.
- Stuss, D. T., & Alexander, M. P. (2007). Is there a dysexecutive syndrome? *Philosophical Transactions of the Royal Society London B: Biological Sciences*, *362*, 901–915.
- Swainson, R., Cunnington, R., Jackson, G. M., Rorden, C., Peters, A. M., Morris, P. G., & Jackson, S. R. (2003). Cognitive control mechanisms revealed by ERP and fMRI: Evidence from repeated task-switching. *Journal of Cognitive Neuroscience*, *15*, 785–799.
- Swainson, R., Jackson, S. R., & Jackson, G. M. (2006). Using advance information in dynamic cognitive control: An ERP study of task-switching. *Brain Research*, *1105*, 61–72.
- Tieges, Z., Snel, J., Kok, A., Plat, N., & Ridderinkhof, R. (2007). Effects of caffeine on anticipatory control processes: Evidence from a cued task-switch paradigm. *Psychophysiology*, *44*, 561–578.
- Watt, N. F. (1976). *Two factor index of social position: Amherst modification (An adaptation of Hollingshead and Redlich, 1958)*. Unpublished manuscript.
- Wechsler, D. (1991). *Wechsler Intelligence Scale for Children—Third Edition*. San Antonio, TX: Harcourt—The Psychological Corporation.
- Wechsler, D. (1997). *Wechsler Adult Intelligence Scale—Third Edition*. New York, NY: Harcourt.
- Welsh, M. C., Pennington, B. F., & Groisser, D. B. (1991). A normative-developmental study of executive function: A window on prefrontal function in children. *Developmental-Neuropsychology*, *7*, 131–149.
- West, R. (2004). The effects of aging on controlled attention and conflict processing in the Stroop task. *Journal of Cognitive Neuroscience*, *16*, 103–113.
- Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2003). Task switching: A high-density electrical mapping study. *NeuroImage*, *20*, 2322–2342.
- Wylie, G. R., Murray, M. M., Javitt, D. C., & Foxe, J. J. (2008). Distinct neurophysiological mechanisms mediate mixing costs and switch costs. *Journal of Cognitive Neuroscience*, *21*, 105–118.
- Zelazo, P. D., & Muller, U. (2002). Executive function in typical and atypical development. In U. Goswami (Ed.), *Handbook of childhood cognitive development* (pp. 445–469). Oxford, UK: Blackwell Publishing.

(RECEIVED November 19, 2009; ACCEPTED December 22, 2010)