Multiple Processes Underlying Dimensional Change Card Sort Performance: A Developmental Electrophysiological Investigation

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Abstract

■ Cognitive flexibility follows a protracted developmental trajectory [Morton, J. B. Understanding genetic, neurophysiological, and experiential influences on the development of executive functioning: The need for developmental models. *Wiley Interdisciplinary Reviews: Cognitive Science,* 2010]. For example, performance and patterns of brain activity associated with the dimensional change card sort (DCCS) show continued age-related changes into early adolescence. According to many theoretical accounts, the DCCS places demands on a single underlying executive process. In the present study, we investigated the possibility that multiple processes unfold within the timeframe of a single DCCS trial through the use of ERPs. Children (n = 40), adolescents (n = 20), and adults (n = 20) performed a modified version of the DCCS with distinct instruction cue- and stimulus-related periods. On any particular trial, the sorting rule either changed (i.e., switch trials) or remained the same (i.e., repeat trials), and the imperative stimulus either embodied conflict (i.e., bivalent stimuli) or did not (i.e., univalent stimuli). Findings were consistent with the hypothesis that multiple distinct executive processes unfold within a single trial. First, for all age groups, rule switching and conflict processing made additive contributions to variability in RT. Second, ERPs time-locked to the instruction cue revealed a late frontal negativity whose amplitude was greater for switch trials relative to repeat trials and that was associated with the magnitude of the behavioral switch cost, whereas ERPs time-locked to the imperative stimulus revealed a fronto-central N2 whose amplitude was greater for bivalent than univalent stimuli and that was associated with the magnitude of the behavioral conflict cost. Finally, switch and conflict-related processes showed distinct developmental trajectories. Taken together, the findings suggest that multiple executive processes underlie DCCS performance and its development. Theoretical implications are discussed. ■

INTRODUCTION

The ability to flexibly attend to different dimensions of a stimulus is a core aspect of executive functioning (Miyake et al., 2000) that follows a protracted developmental trajectory (for a review, see Morton, 2010). One standard procedure for studying the development of cognitive flexibility is the dimensional change card sort (DCCS; Zelazo, 2006). In the task, children sort bivalent test cards (e.g., blue trucks and red flowers) into bins marked by bivalent target cards that each match the test cards on a single dimension (i.e., blue flowers and red trucks). On each of several preswitch trials, children are instructed to sort the cards in one way (e.g., by color). The sorting rules then change, and children are instructed on each of several post switch trials to sort the same cards in a different way (i.e., by shape). Because test cards match each of the target cards on a single dimension, the test cards embody conflict insofar as rules based on color and shape specify opposite responses to the same test stimulus. DCCS performance and associated patterns of brain activity change dramatically in the preschool years (Moriguchi & Hiraki, 2009; Zelazo, 2006). Three-year-old children, for example, typically perseverate in the DCCS by showing persistent use of the preswitch rules in the post switch phase, whereas 5-year-old children typically switch without error, and children who perseverate exhibit lower concentrations of oxygenated hemoglobin in ventrolateral pFC during preswitch and post switch trials compared with children who correctly switch. Age-related differences in patterns of brain activity associated with the DCCS, however, extend well into early adolescence with 11- to 13-year-olds showing switch-related differences in superior prefrontal and superior parietal cortex activity compared with adults (Morton, Bosma, & Ansari, 2009).

Many theoretical accounts link age-related changes in DCCS performance to changes in a single executive process or structure, such as the capacity to represent and use higher-order rules (Zelazo, Müller, Frye, & Marcovitch, 2003) or the understanding that stimuli can be described in a new way even if they have been previously described in a different way (Kloo & Perner, 2005) and base inferences about the integrity or developmental status of these processes on performance in an entire trial (or group of trials). In the standard task, for example, children are administered in six preswitch and six post switch trials and

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are classified as passing if they sort correctly on at least five post switch trials (Zelazo, 2006). Passing or failing in this way is then considered a measure of a higher-order rule use or the capacity for stimulus redescription. It is possible, however, that multiple processes unfold within the timeframe of a single DCCS trial. Trials always begin with a statement of the rule followed by the presentation of a test stimulus that embodies conflict. It is conceivable then that two processes, one related to the representation of the instruction cue and one related to processing conflict in the test stimulus, unfold within the timeframe of a single trial (for discussion, see Kirkham, Cruess, & Diamond, 2003). Disambiguating these processes, however, is difficult using standard performance measures that treat individual trials as indivisible units of analysis.

In the present study, therefore, we used ERPs to try and disambiguate distinct cue- and stimulus-related processes that we hypothesized should unfold within the timeframe of a single DCCS trial. ERPs are scalp-measured voltage fluctuations generated by the mass firing of cortical pyramidal cells. Used in the context of studies of cognition, ERPs provide a direct, inexpensive, and noninvasive measure of information processing with exquisite temporal resolution. Children, adolescents, and adults were administered a modified version of the DCCS, suitable for use with ERPs, in which rule switching was crossed with conflict processing. Trials began with an instruction cue that indicated the sorting rule on that trial, followed by the presentation of a test stimulus. On switch trials, the rule differed from the previous trial, whereas on repeat trials, the rule remained the same. On half of these trials, the test stimulus was bivalent and could be legitimately sorted in two ways. On the other half of these trials, the test stimulus was univalent and could be legitimately sorted in only one way.

To examine whether distinct cue- and stimulus-related processes underlie DCCS performance, we considered three general sources of evidence. First, we examined ERP components associated with instruction cue and test stimulus presentation. Three components were of particular interest, a cue-related late frontal negativity (LFN), a cue-related late parietal positivity (LPP), and a test-stimulus-related frontal N2, as the amplitude of these components have been shown in previous studies to be modulated by rule switching (Astle, Jackson, & Swainson, 2008; Swainson, Jackson, & Jackson, 2006; Tieges et al., 2006; Lorist et al., 2000) and conflict processing (Ladouceur, Dahl, & Carter, 2007; Nieuwenhuis, Yeung, Wildenberg, & Ridderinkhof, 2003), respectively. Evidence that the amplitude of these components is modulated in different ways by different processing demands would suggest distinct cue- and stimulus-related processes unfold within the timeframe of a single DCCS trial. Second, we examined associations between cue- and stimulus-related components and behavioral performance measures. If cue- and stimulus-related components reflect distinct underlying processes, then individual differences in these components should predict unique sources of variance in behavioral performance. Third, we examined whether rule switching and conflict processing show distinct developmental trajectories. Evidence that ERP signatures and behavioral effects are associated with these processes exhibit differential patterns of developmental change would suggest that these processes are distinct.

METHODS

Participants

Participants included 40 children (29 boys), 20 adolescents (9 boys), and 20 young adults (11 men). Children ranged in age from 9 to 11 years (M = 10.2), adolescents ranged in age from 14 to 15 years (M = 15), and adults ranged in age from 18 to 25 years (M = 19.4). Children and adolescents were recruited from a database of families who had expressed an interest in voluntary research participation; adults were students enrolled in introductory psychology courses and participated in exchange for course credit. Adults provided written consent to their participation. Parents provided written consent for their children's participation. All participants had normal or corrected-to-normal visual acuity, normal color vision, no dental braces or metal implants, and all reported being right-handed.

Task and Procedures

Participants performed a computer-administered variant of the DCCS (Morton et al., 2009; Zelazo, 2006) in which rule-switching was orthogonally crossed with conflict processing (see Figure 1). Two bivalent target stimuli (e.g., a red flower and a blue rabbit) were present at the top of the screen throughout the task. The location of the targets was counterbalanced across participants but was fixed for each individual participant. Continuously presented trials began with a 2000-msec instruction period in which a centrally presented instruction cue ("S" for shape, "C" for color) indicated the sorting rule for each trial, followed by a 1000-msec delay during which the sorting rule had to be maintained. Switch trials were trials in which the sorting rule changed from the previous trial; repeat trials were trials in which the sorting rule remained the same. Following the instruction period, either a bivalent or a univalent imperative stimulus was presented in the center of the screen. Bivalent stimuli matched each target on a single dimension (e.g., a red rabbit or a blue flower) and could, therefore, be legitimately sorted either by color or shape. Univalent stimuli matched one target on one dimension (e.g., a black rabbit, black flower, red bar, or blue bar) and could, therefore, be legitimately sorted in only one way. Participants sorted stimuli by depressing a button whose location corresponded with the location of one of the two target stimuli (e.g., pressing the right button sorted the red rabbit by color; pressing the left button sorted it by shape). Responses were registered on a PST button box (Psychological Software Tools, Pittsburgh, PA) and

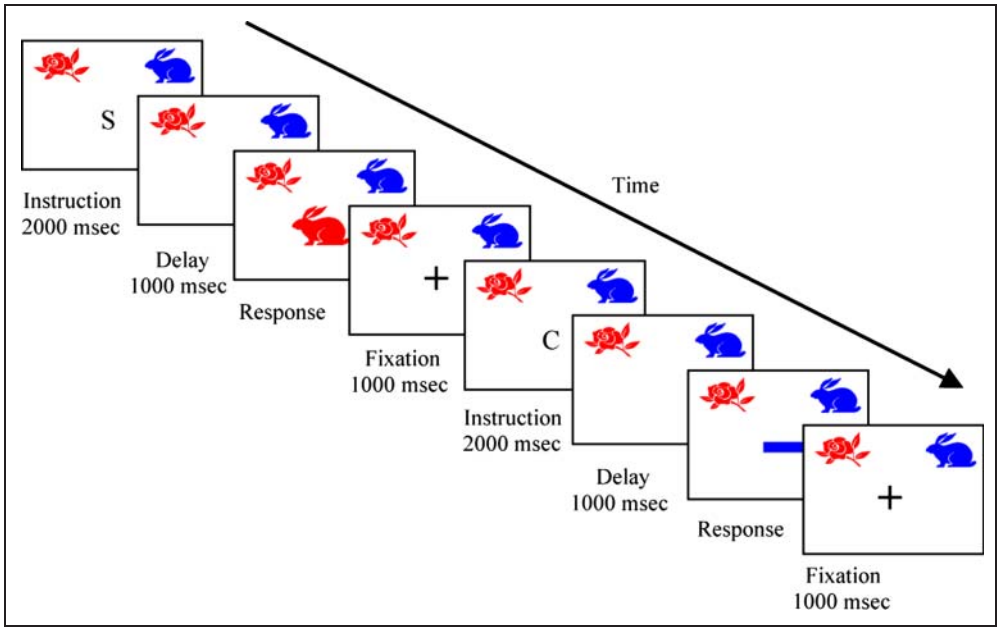

Figure 1. An illustration of two trials from the modified DCCS task used in the present study. Trials began with an instruction cue indicating the rule on that trial, followed by a delay period, followed by the presentation of a stimulus to which the participants responded, followed by a fixation point. On switch trials, the rule was different than the one on the previous trial; on repeat trials, the rule was the same as on the previous trial. Bivalent stimuli matched each target location on one dimension; univalent stimuli matched only one target location.

cancelled the response period. Individual trials were separated by a 1000-msec response–cue interval.

Trials were presented in a pseudorandom order that ensured the orthogonal crossing of rule switching and conflict processing. Thus, switch trials were followed by three repeat trials, and on 50% of these trials, the imperative stimulus was bivalent, whereas on the other 50%, it was univalent.

Participants were instructed about the basic nature of the task and the need to respond as quickly and accurately as possible. To ensure comprehension of the instructions, all participants completed 16 practice trials. Adolescent and adult participants then completed six blocks of 68 trials, and child participants completed six blocks of 36 trials. A brief rest was provided after each block.

EEG Data Collection and Processing

EEG recordings were made continuously with a 128-channel Electrical Geodesics system (EGI Inc, Eugene, OR; Tucker, Liotti, Pots, Russell, & Posner, 1993) at 200 Hz, with 0.1–80 Hz analog filtering referenced to the vertex (Channel 129). Impedance of all channels was kept below 50 kΩ. Trials with either (1) premature (faster than 200 msec) or incorrect responses, (2) responses slower than 3 *SD*s from the participant's mean RT for each trial and stimulus type combination, (3) eye movement artifacts (70 μV threshold), (4) signals exceeding 200 μV, or (5) fast transits exceeding 100 μV were rejected before averaging. Eye blinks were corrected using the algorithm developed by Gratton, Coles, and Donchin (1983). The EEG was then rereferenced to an average reference (Tucker et al., 1993; Bertrand, Perrin, & Pernier, 1985). Segmentation was carried out in two ways: (1) instruction-locked data were segmented into epochs ranging from 200 msec before to 1000 msec after instruction cue onset and (2) stimulus-locked data were segmented into epochs ranging from 200 msec before to 600 msec after imperative stimulus onset. Instruction-locked data were off-line filtered using an FIR 40 Hz lowpass filter, and stimulus-locked data were off-line filtered using an FIR 1–30 Hz bandpass filter. Both instruction-locked and stimulus-locked epochs were baseline corrected using data from the first 200 msec of the epoch.

RESULTS

Behavioral Analyses

Trials with excessively short RTs (<200 msec), error trials, and trials with RTs slower than 3 *SD*s from the participant's mean RT for each trial type and stimulus type combination were excluded from RT analysis (Ratcliff & Tuerlinckx, 2002). Additionally, the first four trials of each block were excluded from statistical analysis. RTs and error rates were submitted to separate mixed ANOVAs with age group (adults, adolescents, and children) as a between-subjects variable, and trial type (switch, Repeat 1, Repeat 2, and Repeat 3) and stimulus type (bivalent and univalent) as within-subjects variables. A Greenhouse–Geisser correction was applied when a significant violation of sphericity was indicated by Mauchly's test of sphericity.

Mean RTs for trial type, stimulus type, and age group are displayed in Figure 2. An ANOVA on RTs revealed effects of Age group, $F(2, 77) = 19.29, p < .001$, Trial type, $F(3, 231) = 26.43, p < .001$, and Stimulus type, $F(1, 77) = 92.08, p < .001$. The only higher-order interaction was a two-way interaction between Stimulus type and Age group, $F(2, 77) = 7.29, p < .001$. Post hoc contrasts, Bonferroni-corrected for multiple comparisons, indicated that conflict costs (i.e., bivalent RT − univalent RT) were larger for children than

adults, $t(58) = 3.23, p < .005$, and adolescents, $t(58) = 2.54$, $p < .05$. Conflict costs for adolescents and adults did not differ. Post hoc contrasts, Bonferroni-corrected for multiple comparisons, indicated that switch costs (i.e., switch RT − repeat RT) did not differ between any of the different age groups.

To ensure that the results of the aforementioned post hoc contrasts were not the result of age-related differences in baseline RT, a second set of post hoc contrasts, Bonferroni-corrected for multiple comparisons, were computed using scaled conflict costs (i.e., [(bivalent RT − univalent RT) / univalent RT]) and scaled switch costs (i.e., [(switch RT − repeat RT) / repeat RT]. These contrasts indicated that scaled conflict costs were larger for children than adults, $t(58) = 5.12$, $p < .001$, and adolescents, $t(58) = 4.00$, $p < .001$. Scaled conflict costs for adolescents and adults did not differ, $t(38) = .94$, *ns*. Scaled switch costs did not differ between any of the different age groups. Thus, whereas conflict costs varied as a function of age, switch costs did not differ between the three age groups.

Mean error rates as a function of trial type, stimulus type, and age group are displayed in Figure 3. An ANOVA on error rates revealed main effects of Age group, $F(2, 77) = 4.68$, $p < .01$, Trial type, $F(3, 231) = 51.53$, $p < .001$, and Stimulus type, $F(1, 77) = 126.18$, $p < .001$. There was also a three-way interaction between Trial type, Stimulus type, and Age group, $F(6, 231) = 6.07$, $p < .001$. Follow-up ANOVAs indicated that the three age groups only varied in accuracy on switch bivalent trials, $F(2, 77) = 9.32$, $p < .001$. Post hoc contrasts indicated that children were less accurate than adults, $t(58) = -4.03$, $p < .001$, and adolescents, $t(58) = -2.80$, $p < .05$, on switch bivalent trials.

ERP Analyses

Figure 4 shows the proportion of trials lost because of signal artifacts for each stimulus type and trial type combination. A three-way mixed ANOVA was used to test for effects of age group (children, adolescents, and adults), trial type (switch, Repeat 1, Repeat 2, and Repeat 3), and stimulus type (bivalent and univalent) on the proportion of trials lost because of artifacts. A Greenhouse–Geisser correction was applied when a significant violation of sphericity was indicated by Mauchly's test of sphericity. This analysis revealed main effects of Trial type, $F(3, 200) = 56.38$, $p < .001$ (more rejections on switch than on repeat trials), and Stimulus type, $F(1, 77) = 129.97$, $p < .001$ (more rejections on bivalent than univalent trials), and an interaction between Trial type and Stimulus type, $F(3, 184) = 56.14$, $p < .001$. Importantly though, there were no effects of age and no interactions with age, meaning that the artifact rejection procedure did not differentially influence the data from the different age groups.

Figure 5 shows the instruction cue-locked ERPs at electrode F3, Fz, and F4 (left, middle, and right columns, respectively) for the three age groups. As clearly shown, each age group showed a late negativity whose amplitude was greater on switch trials than repeat trials. To explore

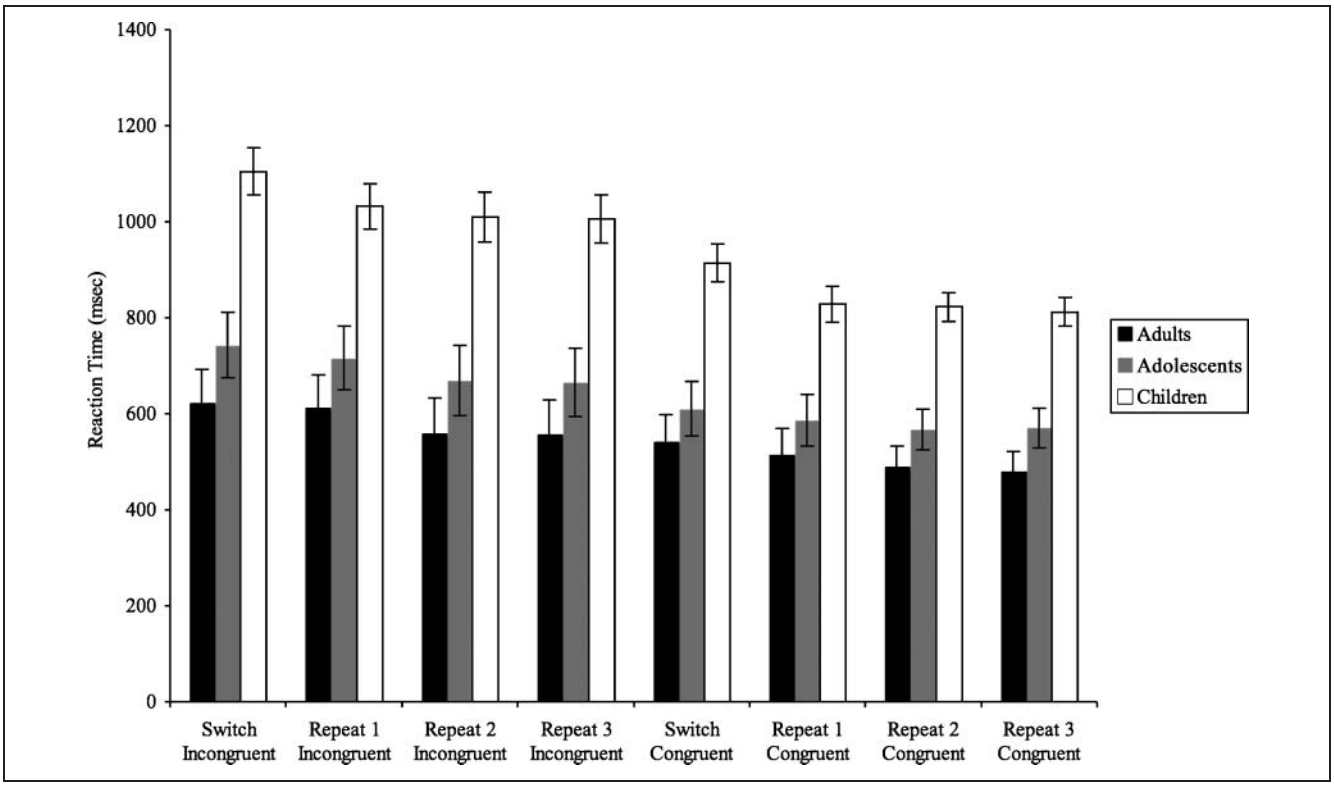

Figure 2. RTs as a function of trial type, stimulus type, and age group.

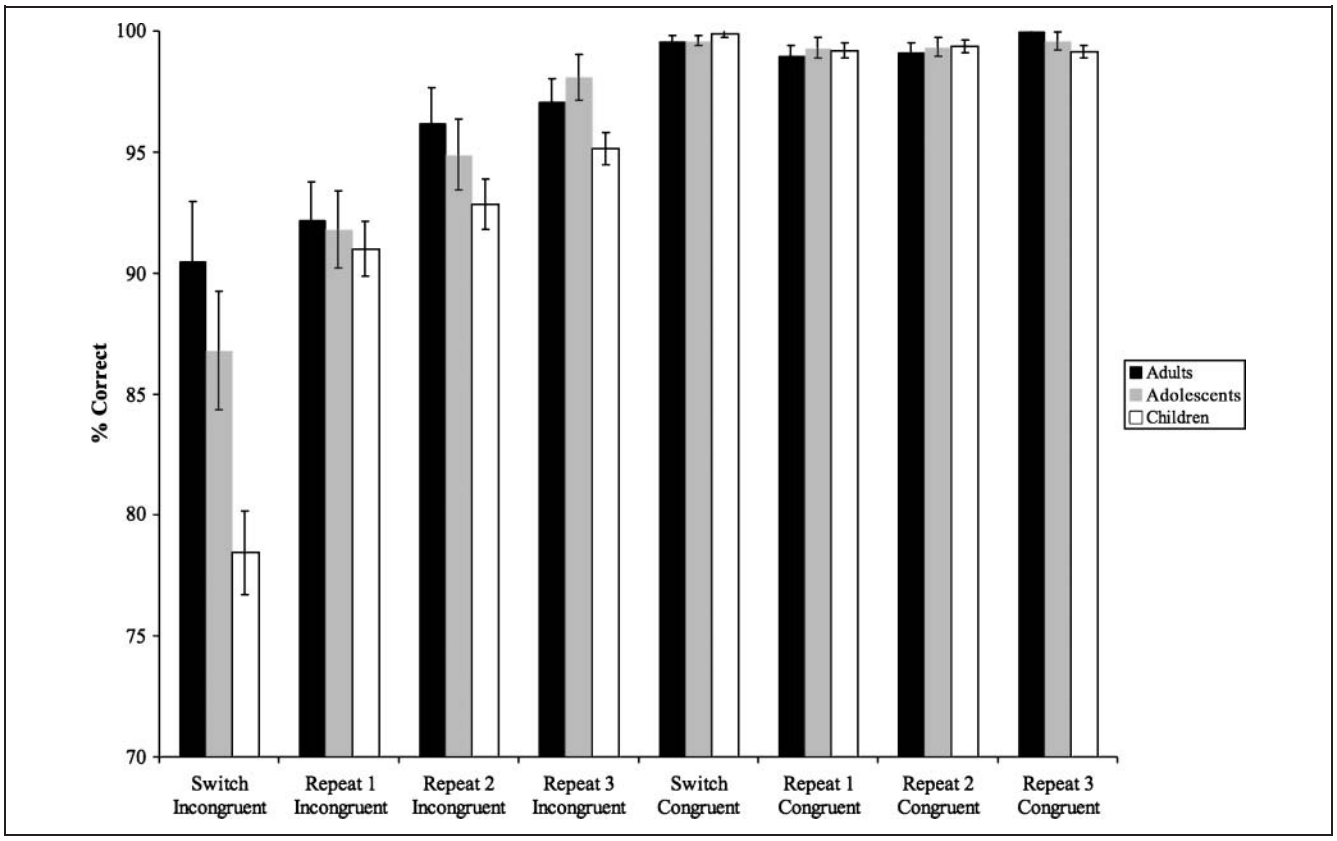

Figure 3. Error rates as a function of trial type, stimulus type, and age group.

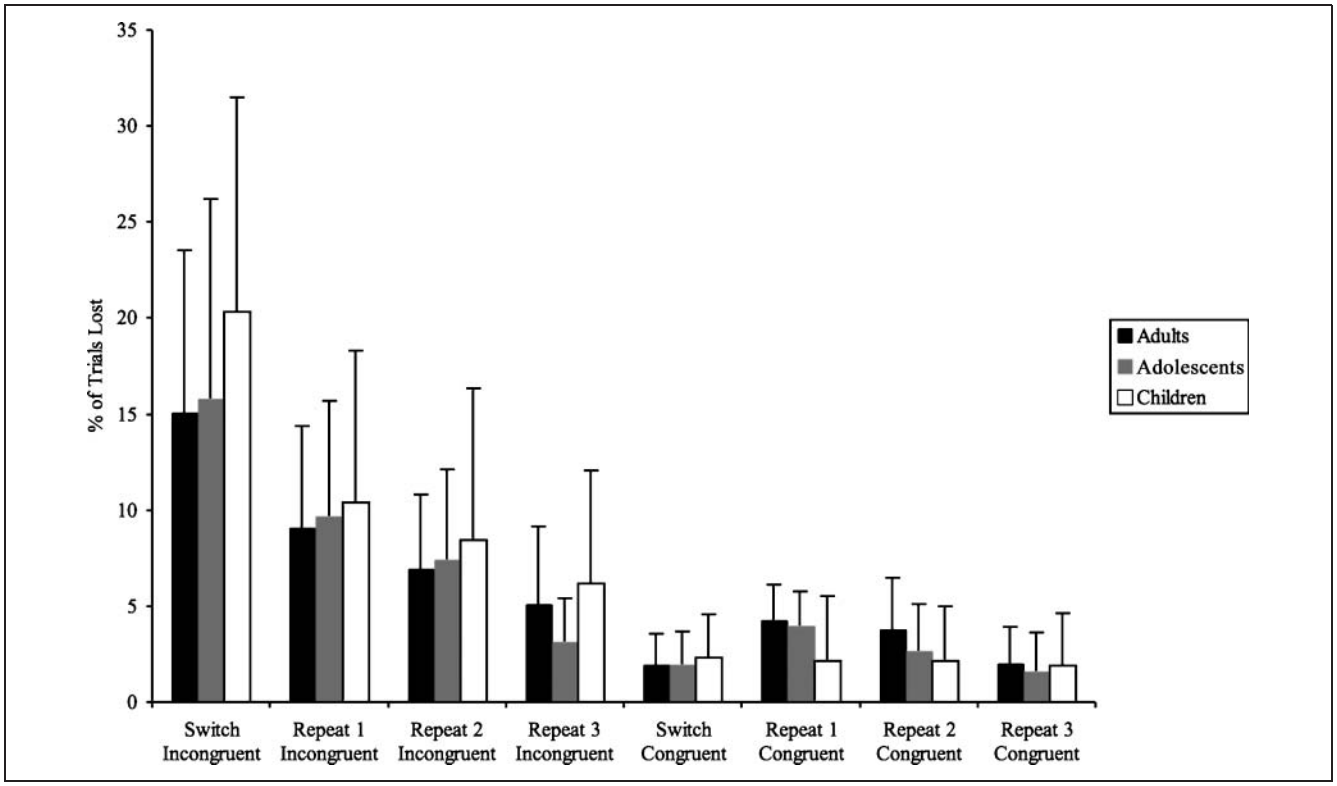

Figure 4. Proportion of trials lost because of ERP artifacts as a function of trial type, stimulus type, and age group.

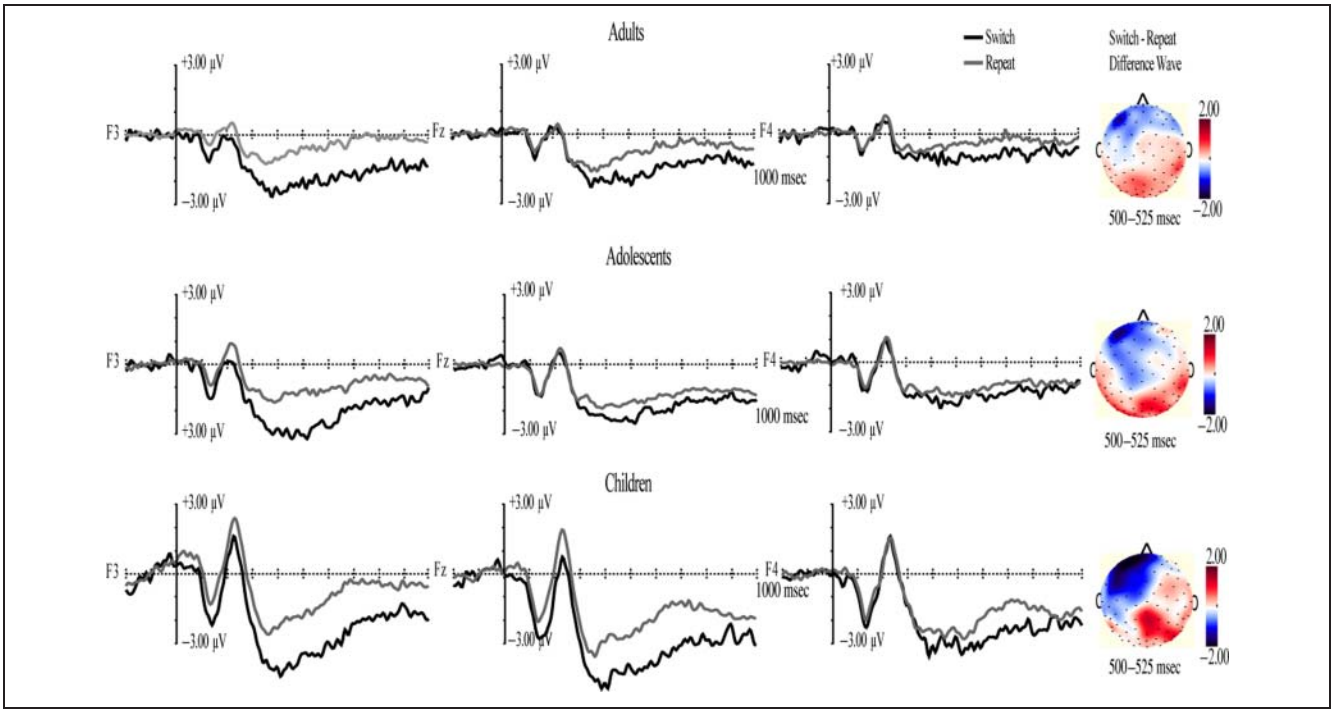

Figure 5. Grand average of instruction cue-locked waveforms and LFN difference wave topographical maps for adults, adolescents, and children. Each wave board plots a 200-msec baseline and 1000-msec post instruction cue onset. Each topographical map plots anterior electrodes on the top of the topo map.

this difference further and to distinguish whether the cue-locked component reflected an LFN or an LPP, mean instruction cue-locked LFN/LPP amplitudes were examined at three frontal sites (F3/24, Fz/11, and F4/124), three central sites (C3/36, Cz/VREF, and C4/104), and three posterior electrode sites (P3/52, Pz/62, and P4/92). Mean LFN/LPP amplitude was defined as the mean electrical activity from 300 to 1000 msec post instruction-cue onset. Mean LFN/LPP amplitudes were submitted to a four-way mixed ANOVA with Age group (children, adolescents, and adults) as a between-subjects variable, Trial type (switch, Repeat 1, Repeat 2, and Repeat 3), Electrode site (anterior, central, and posterior), and Electrode side (left, midline, and right) as within-subjects variables. A Greenhouse–Geisser correction was applied when a significant violation of sphericity was indicated by Mauchly's test of sphericity. This analysis revealed main effects of Trial type, $F(3, 211) = 5.22$, $p < .01$, and Electrode site, $F(1, 94) = 39.56$, $p < .001$. Additionally there were two-way interactions between Trial type and Electrode side, $F(5, 342) = 2.32$, $p < .05$, between Trial type and Electrode site, $F(3, 231) = 7.04$, $p < .001$, and between Electrode site and Electrode side, $F(3, 241) = 4.47$, $p < .01$. Furthermore, there was a three-way interaction between Trial type, Electrode site, and Electrode side, $F(6, 621) = 1.97$, $p < .05$.

To decompose the three-way interaction, mean LFN/LPP amplitudes were examined separately at frontal, central, and posterior electrode sites. For each electrode site mean amplitudes were submitted to a two-way repeated measures ANOVA with Trial type (switch, Repeat 1, Repeat 2, and Repeat 3) and Electrode side (left, midline, and right) as within-subjects variables. Mean amplitudes did not differ as a function of Trial type or Electrode side at either the posterior or central electrodes, suggesting that late negativity was not an LPP but an LFN (therefore, hereafter, we refer to this component as an LFN). The ANOVA for the frontal electrode sites revealed a main effect of Trial type, $F(3, 188) = 9.47$, $p < .001$. Post hoc contrasts, Bonferroni-corrected for multiple comparisons, indicated that mean LFN amplitudes were greater for switch trials than Repeat 1 trials, $t(79) = -4.35$, $p < .001$, Repeat 2 trials, $t(79) = -4.48$, $p < .001$, and Repeat 3 trials, $t(79) = -3.86$, $p < .001$. Mean LFN amplitudes did not differ between the three repeat trials. In addition to a main effect of Trial type, there was a two-way interaction between Trial type and Electrode side, $F(5, 363) = 3.39$, $p < .01$. Bonferroni-corrected post hoc contrasts indicated that the LFN difference (i.e., switch LFN − repeat LFN) was larger at electrode F3 than electrode Fz, $t(79) = -2.22$, $p < .05$, and electrode F4, $t(79) = -4.68$, $p < .001$. Additionally, the LFN difference was larger at electrode Fz than electrode F4, $t(79) = -2.75$, $p < .01$.

Figure 6 shows the stimulus-locked ERP components at Fcz for switch bivalent, switch univalent, repeat bivalent, and repeat univalent trials for the three age groups. As is clearly visible, adolescent and adult waveforms showed a pronounced negativity approximately 200 msec post stimulus (hereafter referred to as an N2) whose amplitude was more negative following bivalent than univalent stimuli and regardless of whether the trial was a switch trial or a

repeat trial. To explore these differences further, adaptive mean N2 amplitudes for each trial and stimulus type combination were examined at three frontocentral electrode sites (Cz, FCz/6, and Fz/11), where the adaptive mean measured the average voltage within a 50-msec time window surrounding the peak of the N2 (for a review, see Luck, 2005). Adaptive mean N2 amplitudes were submitted to a four-way mixed ANOVA with Age group (children, adolescents, and adults) as a between-subjects variable, Trial type (switch, Repeat 1, Repeat 2, and Repeat 3), Stimulus type (univalent and bivalent), and Electrode site (Cz, FCz, and Fz) as within-subjects variables. This analysis revealed main effects of Stimulus type, $F(1, 77) = 5.88, p < .05$, Electrode site, $F(2, 154) = 42.87, p < .001$, and Age group, $F(2, 77) = 13.23, p < .001$. There was also a two-way interaction between Stimulus type and Age group, $F(2, 77) = 3.47, p < .05$. Post hoc contrasts indicated that the amplitude of the N2 was larger on bivalent stimuli relative to univalent stimuli for the adults, $t(19) = -4.92, p < .001$, and adolescents, $t(19) = -4.47, p < .001$, but not for the children, $t(39) = .68$, *ns*. The amplitude of the N2 was not modulated by trial type, $F(3, 201) = 1.38$, *ns*, and did not interact with any other factors.

Differences in N2 latencies were examined using a four-way mixed ANOVA with Age group (children, adolescents, and adults) as a between-subjects variable, Trial type (switch, Repeat 1, Repeat 2, and Repeat 3), Stimulus type (univalent and bivalent), and Electrode site (Cz, Fcz, and Fz) as within-subjects variables. A Greenhouse–Geisser correction was applied when a significant violation of sphericity was indicated by Mauchly's test of sphericity. This analysis revealed a main effect of Age group, $F(2, 77) = 58.02, p < .001$. Post hoc contrasts, Bonferroni-corrected for multiple comparisons, indicated that the peak latency of the N2 was delayed for the children relative to the adults, $t(58) = 8.48, p < .001$, and relative to the adolescents, $t(58) = 9.09, p < .001$. Peak N2 latencies did not differ between the adults and adolescents, $t(38) = .53$, *ns*.

Although the children did not exhibit a conflict-related N2, inspection of their stimulus-locked grand average showed a greater negativity following bivalent than univalent stimuli between 400 and 450 msec post stimulus onset, which we labeled as the N4. To investigate this difference further, a Stimulus type (univalent and bivalent) by Electrode site (Cz, FCz, and Fz) repeated measures ANOVA was conducted on mean N4 amplitudes. Mean N4 amplitude was defined as the average electrical activity from 400 to 450 msec post stimulus onset. This analysis revealed a main effect of Stimulus type, $F(1, 39) = 4.53, p < .05$, that indicated that the amplitude of the N4 was greater for

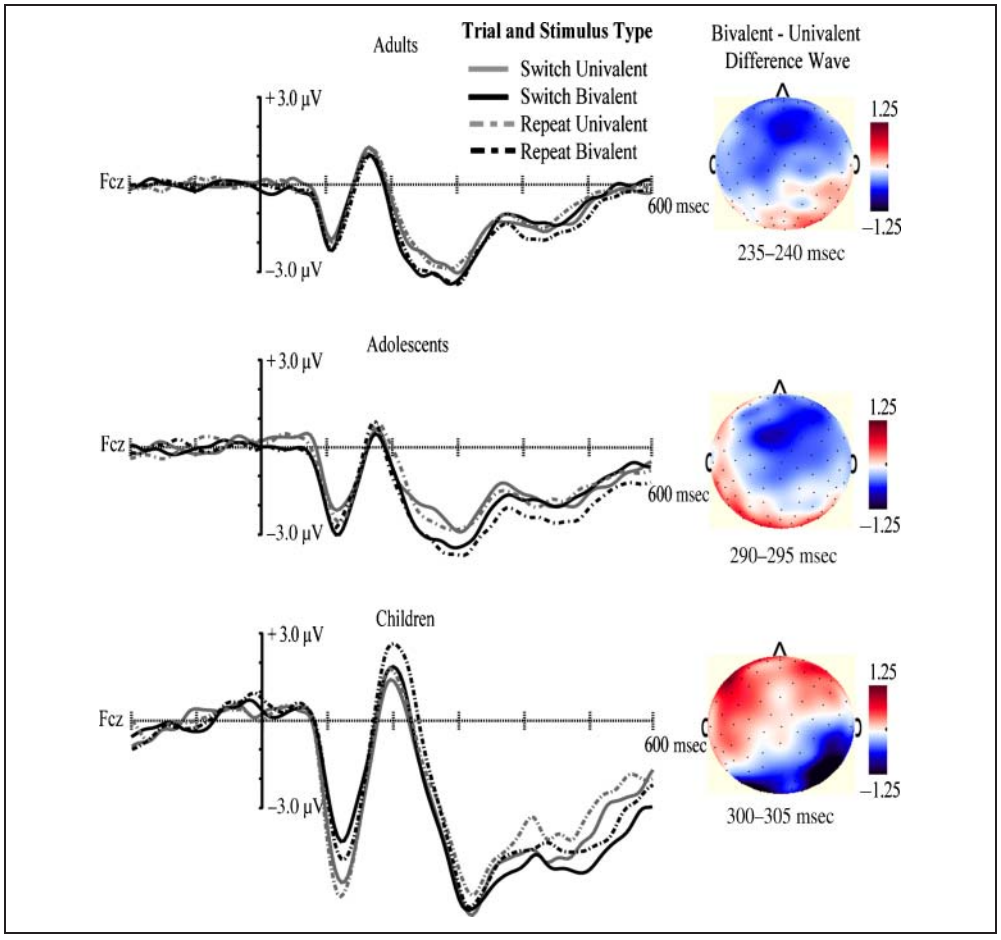

Figure 6. Grand average of stimulus-locked waveforms and N2 difference wave topographical maps for adults, adolescents, and children. Each wave board plots a 200-msec baseline and 600 msec post stimulus onset. Each topographical map plots anterior electrodes on the top of the topo map.

bivalent stimuli relative to univalent stimuli. Additionally, there was a main effect of Electrode site, $F(1, 39) = 15.42$, $p < .001$. Post hoc contrasts, Bonferroni-corrected for multiple comparisons, indicated that the mean N4 amplitude was greater at Fcz, $t(39) = -5.83$, $p < .001$, and Fz, $t(39) = -4.51$, $p < .001$, relative to Cz.

Brain Behavior Correlation Analyses

To examine possible links between instruction cue-locked ERPs and behavioral performance, two-tailed Pearson correlations were conducted between the LFN amplitude difference (i.e., switch LFN − repeat LFN), switch cost (i.e., switch RT − repeat RT), and conflict costs (i.e., bivalent RT − univalent RT) at three electrode sites (F3, Fz, and F4). These correlations were Bonferroni-corrected for multiple comparisons and were conducted separately for each age group (see Table 1). For the adults, greater switch costs were associated with a larger LFN difference at electrode site F3, $r = -.58$, $p < .05$, and at electrode site Fz, $r = -.54$, $p < .05$. For the adolescents, greater switch costs were associated with a larger LFN difference at electrode sites F3, $r = -.62$, $p < .01$, and Fz, $r = -.50$, $p < .05$. For the children, greater switch costs were associated with a larger LFN difference at electrode sites F3, $r = -.46$, $p < .001$, Fz, $r = -.33$, $p < .05$, and F4, $r = -.39$, $p < .05$. For all groups, LFN amplitude differences were unrelated to conflict costs.

To examine possible links between stimulus-locked ERPs and behavioral performance, two-tailed Pearson correlations were conducted between the N2 amplitude differences (i.e., bivalent N2 − univalent N2), conflict cost (bivalent RT − univalent RT), and switch cost (switch RT − repeat RT) at three frontocentral electrode sites (Cz, Fcz, and Fz). An additional set of correlations was conducted between the N4 amplitude difference (i.e., bivalent N4 − univalent N4), conflict cost, and switch cost for the children. These correlations were conducted separately for each age group and are displayed in Table 2. For the adults, greater conflict costs were associated with a larger N2 difference at electrode sites Fcz, $r = -.59$, $p < .01$, and Fz, $r = -.48$, $p < .05$. For the adolescents, greater conflict costs were associated with a larger N2 difference at electrode sites Fcz, $r = -.59$, $p < .01$, and Fz, $r = -.48$, $p < .05$. For both the adults and adolescents, N2 amplitude differences were unrelated to switch costs. Conflict costs and switch costs were not associated with N2 amplitude differences for the children. Additionally, switch costs were unrelated to N2 amplitudes for bivalent only and univalent only trials for all three age groups (see Table 3A and B). However, conflict costs were associated with a larger N4 difference at electrode site Fcz, $r = -.49$, $p < .05$, and electrode site Fz, $r = -.64$, $p < .01$ for the children. N4 amplitude differences were unrelated to switch costs. Additionally, switch costs were unrelated to N4 amplitudes for bivalent only and univalent only trials (see Table 3C and D).

DISCUSSION

Many theoretical accounts characterize executive demands associated with the DCCS in terms of a single process that operates over an entire trial. The present findings are consistent with the hypothesis that multiple executive processes unfold within the timeframe of a single trial. First, presentation of an instruction cue at the outset of a trial was associated with a LFN that reached maximal amplitude over electrodes F3, Fz, and F4, whereas presentation of an imperative stimulus later in the trial was associated with a frontal–central N2 that reached maximal amplitude over electrodes Cz, Fcz, and Fz. Second, LFN and N2 components were modulated by different processing demands. LFN amplitude was greater following instruction cues that denoted a rule switch compared with cues that denoted a rule repetition. By contrast, N2 amplitude was not modulated by rule switching but was modulated by conflict, with greater amplitude to bivalent stimuli than univalent stimuli. Third, LFN and N2 components were associated in unique ways with variance in RT. Larger differences between the LFN on switch versus repeat trials were associated with larger switch costs but were unrelated to

Table 1. Brain Behavior Correlations between Switch Costs, Conflict Costs, and LFN Difference Wave Amplitudes at Electrode Sites F3, Fz, and F4

Age Group		*Conflict Cost RT*	*Switch Cost RT*	*LFN Difference F3*	*LFN Difference Fz*	*LFN Difference F4*
Adults	Conflict cost RT	–	.03	−.03	.07	.25
	Switch cost RT	.03	–	−.58**	−.54*	−.39
Adolescents	Conflict cost RT	–	.03	.27	.06	−.16
	Switch cost RT	.03	–	−.62**	−.50*	−.13
Children	Conflict cost RT	–	.17	.04	−.07	.15
	Switch cost Rt	.17	–	−.46**	−.33*	−.39*

*$p < .05$, two-tailed.

**$p < .01$, two-tailed.

Table 2. Brain Behavior Correlations between Switch Costs, Conflict Costs, and Stimulus-Locked ERP Components

(A) Correlations between Switch Costs, Conflict Costs, and N2 Difference Wave Amplitudes at Electrode Sites Cz, Fcz, and Fz

Age Group		*Conflict Cost RT*	*Switch Cost RT*	*N2 Difference Cz*	*N2 Difference Fcz*	*N2 Difference Fz*
Adults	Conflict cost RT	–	−.29	−.00	−.56**	−.48*
	Switch cost RT	−.29	–	−.08	.14	−.17
Adolescents	Conflict cost RT	–	−.25	−.25	−.59**	−.48*
	Switch cost RT	−.25	–	.10	.20	−.01
Children	Conflict cost RT	–	.20	−.25	−.27	−.29
	Switch cost RT	.20	–	−.08	−.08	−.09

(B) Correlations between Switch Costs, Conflict Costs, and N4 Difference Wave Amplitudes at Electrode Sites Cz, Fcz, and Fz for the Children

Age Group		*Conflict Cost RT*	*Switch Cost RT*	*N4 Difference Cz*	*N4 Difference Fcz*	*N4 Difference Fz*
Children	Conflict cost RT	–	.20	−.19	−.49*	−.64**
	Switch cost RT	.20	–	−.13	−.23	−.20

*$p < .05$, two-tailed.

**$p < .01$, two-tailed.

differences in conflict costs. By contrast, larger differences between the N2 on bivalent versus univalent trials were associated with larger conflict costs but were unrelated to switch costs. Fourth and finally, switch and conflict-related processes showed distinct developmental trajectories. Participants of all ages took longer to respond on switch trials than on repeat trials, but the magnitude of this switch cost showed no age-related change. As well, all participants

Table 3. Brain Behavior Correlations between Switch Costs and Stimulus-Locked ERP Components

(A) Correlations between Switch Costs and N2 Amplitudes for Bivalent Stimuli Only at Electrode Sites Cz, Fcz, and Fz

Age Group		*N2 Bivalent Cz*	*N2 Bivalent Fcz*	*N2 Bivalent Fz*
Adults	Switch cost RT	−.07	−.06	.12
Adolescents	Switch cost RT	−.17	−.14	.01
Children	Switch cost RT	−.17	−.14	.01

(B) Correlations between Switch Costs and N2 Amplitudes for Univalent Stimuli Only at Electrode Sites Cz, Fcz, and Fz

Age Group		*N2 Univalent Cz*	*N2 Univalent Fcz*	*N2 Univalent Fz*
Adults	Switch cost RT	−.04	.02	.09
Adolescents	Switch cost RT	−.01	.08	.00
Children	Switch cost RT	−.01	.08	.00

(C) Correlations between Switch Costs and N4 Amplitudes for Bivalent Stimuli Only at Electrode Sites Cz, Fcz, and Fz

Age Group		*N4 Bivalent Cz*	*N4 Bivalent Fcz*	*N4 Bivalent Fz*
Children	Switch cost RT	−.04	−.11	.07

(D) Correlations between Switch Costs and N4 Amplitudes for Univalent Stimuli Only at Electrode Sites Cz, Fcz, and Fz

Age Group		*N4 Univalent Cz*	*N4 Univalent Fcz*	*N4 Univalent Fz*
Children	Switch cost RT	−.16	.03	.01

showed greater left-lateralized LFN amplitudes on switch trials compared with repeat trials, but the magnitude of this difference showed no age-related change. By contrast, participants of all ages took longer to respond to bivalent than univalent stimuli, but the magnitude of this effect was greater for children than for adolescents and adults. As well, stimulus conflict modulated an earlier component in adolescents and adults (the N2) than in children (N4), suggesting protracted changes in conflict processing. Taken together, the findings are consistent with the idea that two executive processes, one related to the representation of an instruction cue and one related to the processing of an imperative stimulus, unfold within the timeframe of a single DCCS trial. One important question concerns the nature of the processes indexed by these components.

Switch-related LFNs have been observed in a number of cued task switching paradigms (Mueller, Swainson, & Jackson, 2009; Astle et al., 2008; Tieges et al., 2006; Lorist et al., 2000), particularly paradigms in which different tasks compete for the same motor responses. When different tasks are associated with different responses, the switch-related LFN is either diminished (Astle et al., 2008) or absent (Mueller, Swainson, & Jackson, 2007). One possibility then is that the LFN reflects the inhibition of task sets that have been established by prior motor responses. Consistent with this view, asymmetrical LFN patterns have been observed in cued oculomotor switching tasks in which participants switch between prosaccade and antisaccade tasks (Mueller et al., 2009). Because prosaccadic eye movements (i.e., eye movements toward peripherally presented visual stimuli) are strongly prepotent, they need to be suppressed in order for antisaccades (i.e., eye movements away from peripherally presented visual stimuli) to be generated. To then switch from generating antisaccades to generating prosaccades, the inhibition of a prosaccadic task set must be overcome. By contrast, generating prepotent prosaccades does not require the suppression of antisaccades. Consequently, switching from a prosaccade to an antisaccade task does not require overcoming the inhibition of an antisaccade task set. Consistent with the view that the LFN indexes the overcoming of task set inhibition, larger cue-related LFNs are observed when participants switch from an antisaccade to a prosaccade task compared with when they switch from a prosaccade to an antisaccade task. It is worth noting that in the present study, the LFN was left-lateralized. The significance of this, however, is unclear. This effect could be related to participant handedness, although it seem unlikely given that participants responded to test stimuli using both hands and the LFN was observed well before participants responded (i.e., during the cue period). Regrettably, it is not possible to directly clarify these issues with the current data set, given that all participants were right-handed. These issues, therefore, await clarification in future studies.

Traditionally, the frontal N2 has been considered an index of response inhibition (Garavan, Ross, Murphy, Roche, & Stein, 2002; Falkenstein, Hoormann, & Hohnsbein, 1999; Pfefferbaum, Ford, Weller, & Koppell, 1985). However, an alternative view is that the frontal N2 indexes conflict monitoring processes subserved by the ACC (Nieuwenhuis et al., 2003; van Veen & Carter, 2002; Botvinick, Braver, Barch, Carter, & Cohen, 2001). On this view, ACC monitors and detects instances in which two or more incompatible response tendencies are simultaneously active. Having detected such instances of conflict, ACC engages brain areas (e.g., lateral pFC) capable of resolving conflict (Liston, Matalon, Hare, Davidson, & Casey, 2006; Kerns et al., 2004). Previous developmental studies have shown that, although the overall amplitude and latency of the N2 decrease with age (Lamm, Zelazo, & Lewis, 2006; Rueda et al., 2004; Davis, Bruce, Snyder, & Nelson, 2003), conflict-related modulations of the N2 follow a protracted developmental trajectory. For example, Lamm et al. (2006) found that the amplitude of the N2 decreased with increasing age and that, within age, smaller N2 amplitudes were associated with better performance on executive function tasks. With respect to conflict processing and the N2, Ladouceur et al. (2007) found that response conflict modulated N2 amplitude in older adolescents and adults but not in younger adolescents. Consistent with these prior findings, (1) within-age variability in the amplitude of the N2 in the present study was associated with within-age variability in the magnitude of the conflict-related interference effect, with larger amplitudes associated with larger conflict-related interference effects, and (2) conflict-related modulation of N2 amplitude was evident for older (adults and adolescents) but not younger participants. The present results also extend these findings by identifying a later component, the N4, in the youngest participants that was modulated by response conflict and that was associated with individual differences in the conflict-related behavioral interference effect. Whether this component reflects conflict processing that is similar to that observed in older participants but simply delayed in time is currently unclear. A more focused examination of these components and their association with age-related changes in conflict processing certainly seems warranted. For now, we can simply say that there are protracted changes conflict processing that may be related to age-related changes in the function of medial pFC.

It may be tempting to draw parallels between the cue-related effects found in the present study and processes highlighted in various accounts of DCCS performance. According to Cognitive Complexity and Control theory (CCC-r; Zelazo et al., 2003), for example, switching between pairs of lower-order rules requires the representation and use of higher-order rules, especially in instances in which lower-order rules specify opposite responses to the same stimulus. It is possible then that greater LFN amplitudes on switch relative to repeat trials reflect the representation of higher-order rules required for switching. Another alternative is that the switch-related LFN indexes working memory processes. According to the attentional inertia account (Kirkham et al., 2003), the DCCS involves working memory and the inhibitory control of attention, in so far as

participants need to keep two sets of rules in mind and inhibit attention to previously relevant stimulus features. Repeatedly sorting cards in one way is thought to establish a mind set for a particular dimension of the test cards. When instructed to switch sorting criteria, participants need to keep the new sorting rules in mind and suppress attention to the previously relevant stimulus dimension. Switch-related LFN differences may, therefore, reflect working memory processes related to keeping new sorting rules in mind. Yet another alternative is that the switch-related LFN indexes the active representation of task rules on switch trials. According to the active latent model (Morton & Munakata, 2002), repeated experience sorting cards in one way (e.g., by shape) strengthens latent representations of these features and leads to a bias to continue sorting cards in this way. When the sorting rule changes (i.e., to color), there is a need to overcome the bias to sort in the old way. This is made possible by an active representation of the new task rules. Active representations, then, need to be stronger on switch trials than repeat trials to overcome bias unique to switch trials. The accounts differ slightly in that the active latent model links age-related performance changes in the DCCS to changes in the strength with which task rules can be actively held in mind, whereas the attentional inertia account does not claim that working memory is an important locus of developmental change in the DCCS. If the LFN does index processes like working or active memory, the present findings may be more consistent with the attentional inertia than the active latent account, as these cue-related components showed little age-related variability.

Any firm parallels between processes indexed by the LFN and those described in the CCC-r, attentional inertia, and active latent accounts should, however, be drawn with caution. First, these theories are directed at characterizing changes in cognitive flexibility that occur early in development rather than the later-occurring changes that were the focus of this study. Indeed, age-related differences in switch costs were not apparent in the present data set, and thus, the possibility that between-group and/or age-related differences in switch costs are associated with differences in the LFN has yet to be explored. Even if group differences in the LFN had been observed in the present study though, it is unclear whether these differences would best be characterized as indexing differences in higher-order rule use, active memory, or working memory processes. If they did, one would presumably predict larger LFN differences to be associated with smaller switch costs. There is evidence, for example, that actively representing attention-guiding rules is associated with activity in dorsolateral pFC and that greater dorsolateral pFC activity is associated with smaller behavioral costs (MacDonald, Cohen, Stenger, & Carter, 2000). However, in the present study, larger LFN differences were associated with larger, not smaller, behavioral (i.e., switch) costs. Thus, although it remains conceivable that higher-order rule use, working, and/or active memory are important for DCCS performance, it is not clear that these processes are indexed by the LFN.

Additional parallels may be drawn between processes highlighted in several accounts of DCCS performance and the stimulus-related N2 modulation found in the present study. The CCC-r theory, for example (Zelazo et al., 2003), proposes a close association between conflict detection and higher-order rule use, such that reflection and the subsequent representation of a higher-order rule causally follows from the detection of conflict between lower-order rules. Given that N2 amplitudes were greater for bivalent than univalent stimuli and larger N2 valence effects were associated with larger conflict costs, there appears to be a close correspondence between stimulus-related N2 modulation observed in the present study and the notion of conflict detection specified in CCC-r. What is unclear from this account, however, is why the stimulus-locked N2 was not associated in any way with rule switching or the LFN, given the close association between switching and rule representation laid out in CCC-r. An alternative possibility is that stimulus-locked N2 reflects stimulus redescription (Kloo & Perner, 2005). According to the redescription account, successful DCCS performance is predicated on an understanding that bivalent test cards can be described in two different ways. Given their age, this conceptual understanding was likely not an issue for participants in this study, suggesting perhaps that the conflict-related N2 indexes the process of redescribing a stimulus. What is unclear from this account, however, is why the conflict-related modulation of N2 amplitude was not amplified on switch trials, given the close association of redescription and rule switching. Yet another possibility is that the stimulus-locked N2 reflects conflict between latent representation of color and shape that compete for representation in responses (Morton & Munakata, 2002). Although this may be true, the active latent account also predicts a close association between switching and response conflict, such that response conflict should be amplified on switch trials relative to repeat trials. However, this was not the case switch, and conflict costs did not interact. One final possibility is that the stimulus-locked N2 observed in the present study reflects the inhibition of attention. According to the attentional inertia account (Kirkham et al., 2003), attention gets "stuck" on previously relevant features and needs to be inhibited. It is possible then that greater N2 amplitudes on bivalent than on univalent trials reflect the inhibition of attention to previously relevant stimulus features, a process that presumably is more pronounced in the face of bivalent than univalent stimuli. What is not clear from this perspective, however, is why larger differences in the amplitude of the N2 across bivalent and univalent trials were associated with larger conflict costs. If differences in the amplitude of the N2 index the inhibition of attention, then larger N2 differences ought to reflect more inhibition. By extension, larger N2 differences should have been associated with smaller not larger conflict costs.

Models that are directed at fractionating executive processes involved in task switching are perhaps best positioned to accommodate the present findings. One such model (Brown, Reynolds, & Braver, 2007) proposes that switch costs and conflict costs reflect different tradeoffs between exploration (i.e., consideration of alternative means) and exploitation (i.e., focusing on relevant features of the environment). On this account, switch costs or the slowing of responses following a rule switch represent an emphasis on exploration over exploitation. Given an unstable environment with frequent rule shifts, it is difficult to predict where to allocate attention for optimal performance. One means of addressing this uncertainty is to slow the speed of response and more fully process available stimuli. By contrast, given a stable environment in which a consistent set of cues remains relevant, it makes sense to emphasize exploitation and focus attention on specific features of the environment. In this context, responses to incongruent stimuli become faster with each repeated instance, as in the Gratton effect, where responses to incongruent stimuli are faster when preceded by incongruent as compared with congruent trials (Kerns et al., 2004; Gratton, Coles, & Donchin, 1992). In this formulation then, switch costs and conflict costs are additive and reflect two distinct processes that work in tandem in the context of tasks such as the DCCS: a general slowing process, operative on switch trials, that adapts performance to unanticipated changes in task demands, but is insufficient for selecting task-relevant stimulus features; and an attentional focusing process, driven by stimulus incongruence, that attenuates interference from task irrelevant stimulus features but is insufficient for adapting to unexpected changes in task demands. This model arguably provides the most plausible and comprehensive framework for interpreting the cue-locked LFN and stimulus-locked N2, respectively. In particular, it is possible that the LFN reflects a general slowing process that occurs in response to switch cues, given that larger differences predicted greater slowing on switch trials but not conflict trials. By extension, the N2 may reflect an attentional focusing process driven by stimulus incongruence, given that larger differences predicted greater conflict costs, but not greater switch costs. Although consistent in principle, further research clearly is warranted to test the cogency of these speculations.

Whatever the underlying nature of the processes indexed by the LFN and the N2, at a minimum, the current findings suggest that distinct cue- and stimulus-related processes unfold within the timeframe of a single DCCS trial. As such, these findings help to shed light on the nature of cognitive control processes underlying successful DCCS task performance and suggest means of characterizing these processes more precisely in the future.

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REFERENCES

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.

Bertrand, O., Perrin, F., & Pernier, J. (1985). A theoretical justification of the average-reference in topographic evoked potential studies. *Electroencephalography and Clinical Neurophysiology, 62,* 462–464.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108,* 624–652.

Brown, J. W., Reynolds, J. R., & Braver, T. S. (2007). A computational model of fractionated conflict-control mechanisms in task-switching. *Cognitive Psychology, 55,* 37–85.

Davis, E. P., Bruce, J., Snyder, K., & Nelson, C. (2003). The X-trials: Neural correlates of an inhibitory control task in children and adults. *Journal of Cognitive Neuroscience, 13,* 432–443.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). EPR components in go/nogo tasks and their relation to inhibition. *Acta Psychologica, 101,* 267–291.

Garavan, H., Ross, T. J., Murphy, K., Roche, R. A., & Stein, E. A. (2002). Dissociable executive functions in the dynamic control of behavior: Inhibition, error detection and correction. *Neuroimage, 17,* 1820–1829.

Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology, 55,* 468–484.

Gratton, G., Coles, M. G. H., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121,* 480–506.

Kerns, J. G., Cohen, J. D., MacDonald, A. W., Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303,* 1023–1026.

Kirkham, N. Z., Cruess, L., & Diamond, A. (2003). Helping children apply their knowledge to their behavior on a dimension-switching task. *Developmental Science, 6,* 449–467.

Kloo, D., & Perner, J. (2005). Disentangling dimensions in the dimensional change card-sorting task. *Developmental Science, 8,* 44–56.

Ladouceur, C. D., Dahl, R. E., & Carter, C. S. (2007). Development of action monitoring through adolescence into adulthood: ERP and source localization. *Developmental Science, 10,* 874–891.

Lamm, C., Zelazo, P. D., & Lewis, M. D. (2006). Neurocorelates of cognitive control in childhood and adolescence: Disentangling the contributions of age and executive function. *Neuropsychologia, 44,* 2139–2148.

Liston, C., Matalon, S., Hare, T. A., Davidson, M. C., & Casey, B. J. (2006). Anterior cingulate and posterior parietal cortices are sensitive to dissociable forms of conflict in a task-switching paradigm. *Neuron, 50,* 643–653.

Lorist, M. M., Klein, M., Nieuwenhuis, S., De Jong, R., Mulder, G., & Meijman, T. F. (2000). Mental fatigue and task control: Planning and preparation. *Psychophysiology, 37,* 614–625.

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, MA: MIT Press.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288,* 1835–1838.

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.

Moriguchi, Y., & Hiraki, K. (2009). Neural origin of cognitive shifting in young children. *Proceedings of the National Academy of Sciences, U.S.A., 106,* 6017–6021.

Morton, J. B. (2010). Understanding genetic, neurophysiological, and experiential influences on the development of executive functioning: The need for developmental models. *Wiley Interdisciplinary Reviews: Cognitive Science, 1,* 709–723.

Morton, J. B., Bosma, R., & Ansari, D. (2009). Age-related changes in brain activation associated with dimensional shifts of attention: An fMRI study. *Neuroimage, 46,* 249–256.

Morton, J. B., & Munakata, Y. (2002). Active versus latent representations: A neural network model of perseveration, dissociation, and déclage in early childhood. *Developmental Psychobiology, 40,* 413–429.

Mueller, S. C., Swainson, R., & Jackson, G. M. (2007). Behavioural and neurophysiological correlates of bivalent and univalent responses during task switching. *Brain Research, 1157,* 56–65.

Mueller, S. C., Swainson, R., & Jackson, G. M. (2009). ERP indices of persisting and current inhibitory control: A study of saccadic task switching. *Neuroimage, 45,* 191–197.

Nieuwenhuis, S., Yeung, N., Wildenberg, W. V. D., & Ridderinkhof, K. R. (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. *Cognitive, Affective, & Behavioral Neuroscience, 3,* 17–26.

Pfefferbaum, A., Ford, J. M., Weller, B. J., & Kopell, B. S. (1985). ERPs to response production and inhibition. *Electroencephalography & Clinical Neurophysiology, 60,* 423–434.

Ratcliff, R., & Tuerlinckx, F. (2002). Estimating parameters of the diffusion model: Approaching to dealing with contaminant reaction times and parameter variability. *Psychonomic Bulletin Review, 9,* 438–481.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., et al. (2004). Development of attentional networks in childhood. *Neuropsychologia, 42,* 1029–1040.

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., Wijen, J. G., Lorist, M. M., & Ridderinkhof, K. R. (2006). Caffeine improves anticipatory processes in task switching. *Biological Psychology, 73,* 101–113.

Tucker, D. M., Liotti, M., Pots, G. F., Russell, G. S., & Posner, M. I. (1993). Spatiotemporal analysis of brain electrical fields. *Human Brain Mapping, 1,* 134–152.

van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processing in the anterior cingulate cortex. *Journal of Cognitive Neuroscience, 14,* 593–602.

Zelazo, P. D. (2006). The dimensional change card sort (DCCS): A method of assessing executive function in children. *Nature Protocols, 1,* 297–302.

Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function. *Monographs of the Society for Research in Child Development, 68,* 11–27.