Development of and change in cognitive control: A comparison of children, young adults, and older adults

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Cognitive control involves adjustments in behavior to conflicting information, develops throughout childhood, and declines in aging. Accordingly, developmental and age-related changes in cognitive control and response-conflict detection were assessed in a response-compatibility task. We recorded performance measures, pre-response time (pre-RT) activity and medial frontal negativity (MFN)—sequentially occurring, putative event-related potential (ERP) indexes, respectively, of cognitive control and response-conflict detection. When response conflict reached the highest levels by requiring incompatible responses on posterror trials, children and older adults showed the greatest performance decrements. ERPs indicated that young adults implemented control (pre-RT) and detected the increased conflict (MFN) only when that conflict was at the highest levels, whereas children and older adults did so at lower levels (e.g., posterror, compatible responses). Consequently, the developmental and age-related performance decrements observed here may be due to the undifferentiated and inefficient manner in which children and older adults recruited the processes associated with both cognitive control and response-conflict detection.

The term *executive processing* is used to describe a variety of cognitive functions that work separately and in concert to control and coordinate the selection and execution of willed actions. Such processing is a vital aspect of one's ability to adapt quickly and accurately to changing environmental circumstances. As summarized in the conflict-monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004; but see Holroyd & Coles, 2002), it is thought that these executive processes control actions by providing the means to both (1) monitor and detect response conflicts and (2) upregulate cognitive control whenever interference arises from competing information streams, such as when a prepotent response must be inhibited and overridden (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Johnson, Barnhardt, & Zhu, 2004).

A wide variety of evidence, including neuroanatomical (Huttenlocher & Dabholkar, 1997), event-related potential (ERP; Friedman, Nessler, Johnson, Ritter, & Bersick, 2008), structural magnetic resonance imaging (MRI; Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998), and functional MRI (fMRI; van Veen & Carter, 2006), indicates that such control processes depend critically on the prefrontal cortex and its interconnections. Specifically,

in the conflict-monitoring model, the anterior cingulate cortex (ACC) monitors and detects the conflict, whereas regions such as the dorsolateral prefrontal cortex (Kerns et al., 2004) are responsible for implementing top-down control (Botvinick et al., 2004). Relative to other brain regions, the prefrontal cortex appears to undergo a more protracted developmental course through adolescence and early adulthood (Sowell et al., 2003) and, as individuals age, shows greater alteration than do other brain areas (Raz, 2000). Therefore, the goal of the present study was to assess life-span changes in the monitoring and detection of response conflict and in the upregulation of cognitive control, using performance indexes and ERP components that putatively emanate from the prefrontal cortex.

In the present experiment, response conflict was manipulated via the creation of compatible- and incompatible-response conditions. In the latter, participants were required to respond in the direction opposite that indicated by a central arrow (Ridderinkhof, van der Molen, Band, & Bashore, 1997), requiring what Botvinick et al. (2004) have termed *response override*. The requirement to generate incompatible relative to compatible responses leads to slowing of response time (RT) and to increased error rates (Ridderinkhof et al., 1997; see also Nessler, Friedman, Johnson, &

Bersick, 2007). Hence, there is a necessity to upregulate control to reduce the ensuing response conflict through inhibition of the incorrect, but prepotent, response tendency. In the only extant developmental (Ridderinkhof et al., 1997) and age-related (Nessler, Friedman, et al., 2007) studies, relative to young adults, similar-magnitude RT slowing on incompatible- as opposed to compatible-response trials was found for 10- to 11-year-old children (Ridderinkhof et al., 1997) and older adults (Nessler, Friedman, et al., 2007). These data suggest that children and older adults can deal with the conflict associated with incompatible responses.

Nonetheless, the presence or absence of developmental and/or age-related changes in the processing engendered by incompatible responses may depend on whether the response on the previous trial was correct. Indeed, in addition to response override, the commission of an error heightens response conflict. For such cases, the conflict-monitoring hypothesis (Botvinick et al., 2001) posits that errors create conflict because they differ from the correct, appropriate response. Correct RTs on trials that follow the error are slower than those after a correct response (i.e., posterror slowing). Although this phenomenon could simply reflect the increased conflict on posterror trials, some authors have suggested that posterror slowing reflects the upregulation of cognitive control in order to rectify the circumstance that initially enabled the error (Gehring & Fencsik, 2001; Hajcak, McDonald, & Simons, 2003; Ladouceur, Dahl, & Carter, 2007; Rabbitt, 1966; Scheffers, Humphrey, Stanny, Kramer, & Coles, 1999; see Ullsperger, 2006, for other interpretations).

Prior investigations suggest that children and older adults are able to effectively handle posterror conflict, provided that it is not combined with incompatible-response requirements. For example, Davies, Segalowitz, and Gavin (2004) and Santesso, Segalowitz, and Schmidt (2006) reported that posterror relative to postcorrect trials led to similarly prolonged RTs in children and young adults. These limited findings imply that, to the extent that an aspect of posterror slowing reflects control processes, children can exert a measure of cognitive control in this situation. Similarly, in an age-related investigation, Nessler, Friedman, et al. (2007) found that older, relative to young, adults showed similar RT slowing and error rates on posterror compatible-response trials. Conversely, when posterror and incompatible-response conflicts were present, thereby augmenting conflict to a higher level, older adults showed increased error rates and a nonsignificant trend for greater RT slowing. These findings suggest that older adults exhibit deficiencies when posterror and incompatible-response conflicts are combined. To our knowledge, however, no comparable data have been collected from children.

Nonetheless, on the basis of the RT findings in these few investigations, it is difficult to determine unambiguously which of the processes, the upregulation of control or conflict detection, is in place, still developing, maintained, or less efficient with aging. The temporal precision of the ERP technique is advantageous here, because, as described below, two sequentially occurring ERP components have been associated putatively with cognitive-control and response-conflict detection processes.

Notably, an RT-locked positivity peaking at around 50–100 msec before RT is reduced (i.e., more negative-going) under conditions that require greater amounts of cognitive control, suggesting that an overlapping negative component underlies this phenomenon (Johnson et al., 2004; Johnson, Henkell, Simon, & Zhu, 2008; Nessler, Johnson, Bersick, & Friedman, 2007). This negative-going activity (hereafter referred to as *pre-RT activity*) onsets a few hundred milliseconds before RT and is prominent over medial frontal scalp locations. For example, Johnson et al. (2008) asked participants to make truthful and directed-lie (i.e., press in the direction opposite of the truth) responses about their attitudes. Negative-going pre-RT activity was greater in the directed-lie than in the truthful condition, supporting the idea that successful deception requires the use of control processes to ensure that the responses selected conform to the person's overall goal of lying about firmly held attitudes. Extrapolating from these results, pre-RT activity should be more negative-going on posterror than on postcorrect trials, because an error on trial n should engender the upregulation of cognitive control to reduce error propensity on trial $n + 1$. This effect might be greater when incompatible rather than compatible responses are required. To test this hypothesis directly, we compared posterror and postcorrect trials.

Closely following the pre-RT activity is a post-RT negativity (peaking within the first 100 msec after RT) that appears to reflect the amount of response conflict present when the response is generated (Botvinick et al., 2004; Hogan, Vargha-Khadem, Kirkham, & Baldeweg, 2005; Johnson et al., 2004; Nessler, Friedman, et al., 2007; West, 2004). This activity has been labeled the *medial frontal negativity* (MFN; Gehring & Willoughby, 2002) to distinguish it from the error negativity (Ne; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991) or error-related negativity (ERN; Gehring, Goss, Coles, Meyer, & Donchin, 1993) recorded on error trials.

Developmental and age-related investigations suggest that the MFN and ERN reflect at least partly distinct processes, although this interpretation is controversial (Bartholow et al., 2005; Gehring & Fencsik, 2001; Johnson et al., 2004; Masaki, Falkenstein, Stürmer, Pinkpank, & Sommer, 2007; Nessler, Friedman, et al., 2007; Taylor, Stern, & Gehring, 2007). Typically, the ERN is found to be reduced in children relative to young adults (Davies et al., 2004; Hogan et al., 2005; Segalowitz & Davies, 2004) and in older adults (Falkenstein, Hoormann, & Hohnsbein, 2001; West, 2004), suggesting alterations in the error-monitoring system. In addition, the study by Nessler, Friedman, et al. (2007) demonstrated a dissociation between error monitoring and response-conflict detection; the ERN was smaller in older than in young adults, whereas, in accord with the increased error rate, the MFN was larger in older than in young adults in the posterror incompatible-response condition. Hence, older adults appeared to detect the heightened response conflict (i.e., MFN), leading to the conclusion that the implementation of cognitive control prior to the decision may have been altered (Nessler, Friedman, et al., 2007).

To further investigate these phenomena, the present study's aims were to assess developmental and age-related change in the executive processes reflected by the ERN (error monitoring), pre-RT activity (upregulation of control), and the MFN (response conflict detection) to single and combined sources of conflict. In accord with prior studies indicating a less efficient error-monitoring system in children and older adults, we expected that ERN magnitude would be smaller in these two age groups (Falkenstein et al., 2001; Segalowitz & Davies, 2004). On the basis of ERP (e.g., Friedman et al., 2008; Nessler, Friedman, et al., 2007) and hemodynamic (Lustig, Head, Janes, & Buckner, 2006; Milham et al., 2002; Reuter-Lorenz & Mikels, 2006; Velanova, Lustig, Jacoby, & Buckner, 2007) data indicating that control processes may be recruited in an undifferentiated manner with aging, we predicted that older adults would show an increment in control processes (pre-RT activity) even on relatively low-conflict trials when only a single source of conflict was present (i.e., *post-error*, compatible-response; postcorrect, *incompatible*-response—compared with postcorrect, compatible). By contrast, young adults were expected to recruit these processes only on highest demand trials, when two sources of conflict were combined (i.e., posterror, incompatible response). We could not predict with confidence whether an undifferentiated pattern of control processing would also hold for children.

On the basis of the behavioral data indicating that children and older adults can effectively deal with a single source of conflict, it was expected that low-conflict trials would engender similar amounts of response conflict, as indicated by equivalent MFN magnitudes across the age span. However, when posterror and incompatible-response conflicts were combined, children and older adults, relative to young adults, were expected to show compromised behavioral performance. In addition, it was predicted that the performance decrement in older adults would be asso-

ciated with heightened response conflict (enhanced MFN activity; Nessler, Friedman, et al., 2007). No clear-cut prediction for the MFN could be made for children, due to the lack of prior data.

METHOD

Participants

Twenty children, 16 young adults, and 19 older adults were recruited for the study. Four children and 3 older adults were eliminated for failure to perform the task. An additional 2 older adults and 1 child were removed from the data set because they failed to provide a sufficient number of artifact-free trials ($n \geq 9$) in one or more of the critical conditions analyzed below. The demographic and neuropsychological data for the 15 children (M age = 10.2; 7 female), 16 young adults (M age = 24.7 ± 4.0 ; 12 female), and 14 older adults (M age = 72.5; 6 female) retained for study are presented in Table 1. Young and older adult volunteers were administered the Modified Mini-Mental Status examination (mMMS; Mayeux, Stern, Rosen, & Leventhal, 1981), on which they achieved a score within the normal range. IQ for the children was obtained from the Wechsler Intelligence Scale for Children (Wechsler, 1991). IQ for young adults was estimated from the vocabulary and block-design subtests of the Wechsler Adult Intelligence Scale—III (WAIS—III; Wechsler, 1997). Older adult volunteers were administered the full WAIS—III. All participants obtained IQ scores within the average to above-average range. All signed informed consent or assent forms according to the criteria of the New York State Psychiatric Institute's Institutional Review Board and were paid for their participation.

To ensure that they were free from dementia and depression and that they were not limited in the activities of daily living (see Table 1), older adult volunteers underwent a semistructured interview (SHORT-CARE; Gurland, Golden, Teresi, & Challop, 1984). A board-certified neurologist conducted a medical and neurological examination in order to assess volunteers for the presence of neurodegenerative disorders; clinically detectable neurovascular disease; disturbances in gait, visual acuity, and visual fields; and tremors or rheumatological disorders.

Stimuli and Experimental Procedures

Participants were seated comfortably in a sound-damped and electrically shielded room. They sat facing a 17-in. computer monitor

Table 1
Demographic Characteristics and Neuropsychological Measures for the Young and Older Adults and Children

Characteristics and Measures	Young Adults ($n = 16$)		Older Adults ($n = 14$)		Children ($n = 15$)	
	M	SD	M	SD	M	SD
Age	24.0	3.0	72.6	5.8	10.2	0.7
SES [‡]	54.3	13.3	40.9	15.7	40.4 [†]	19.7
Years of education	16.0	1.7	17.2	1.6	4.5	0.7
mMMS [*]	54.9	2.1	54.7	1.9	NA	
Digits forward ^a	7.7	1.0	6.5	0.8	9.8	2.0
Digits backward ^a	6.3	1.4	5.3	0.9	6.3	2.2
LQ	82.8	25.2	88.8	20.2	61.8	31.9
Verbal IQ ^a	126.2	24.7	131.7	13.4	122.1	36.1
Performance IQ ^a	111.9	24.9	118.8	11.4	113.6	35.6
Depression ^b	NA		1.30	0.9	NA	
Dementia ^b	NA		0.07	0.3	NA	

Note—NA, not applicable; mMMS, Modified Mini-Mental Status exam; SES, socioeconomic status (higher score = lower SES) (Watt, 1976); LQ, laterality quotient (Oldfield, 1971). ^aWAIS—III (Wechsler, 1997) for young and older adults; WISC—III for children. ^bFrom the SHORT-CARE (Gurland et al., 1984); cutoff is 6 for depression and 7 for dementia. ^{*}mMMS (Mayeux et al., 1981); maximum score = 57. [†]Based on a score averaged across the SES values for the child's mother and father. [‡]Higher score = lower SES.

Figure 1. Grand mean RT-locked, postcorrect ERP waveforms on correct- and erroneous-response trials averaged across the participants within each age group ($n = 16$ young adults, 14 older adults, and 15 children). The waveforms have been averaged separately for compatible- and incompatible-response conditions. The large-amplitude negative component associated with erroneous trials is the error-related negativity (ERN) or Ne. The shaded region indicates the 80-msec window for measuring ERN magnitude.

about 100 cm from the screen and held a small response box on their laps. The target stimuli were arrows pointing either to the left or to the right and presented centrally on the computer monitor for 200 msec, with a randomly jittered intertrial interval of 900–1,200 msec. Participants made buttonpress responses with their left or right index fingers, depending on the direction of a central arrow. In the incompatible condition, participants pressed the button corresponding to the direction opposite that in which the arrow pointed. In the compatible condition, participants pressed the button corresponding to the same direction in which the central arrow pointed. Participants were asked to respond as quickly as possible. Each response-compatibility condition consisted of three blocks of 120 stimuli.¹ The condition with which participants began and the order of conditions were counterbalanced across participants within each age group.

Electroencephalographic (EEG) Recording

EEG was recorded from 62 scalp sites (sintered Ag/AgCl) in accord with the extended 10–20 system (Sharbrough et al., 1990); an Electro-Cap (Neuromedical Supplies) was used. All electrodes, including the mastoids, were referred to the nose tip. Horizontal and vertical electrooculograms (EOGs) were recorded bipolarly, with electrodes placed, respectively, at the outer canthi of both eyes and above and below the left eye. EOGs and EEGs were recorded continuously with Synamp amplifiers (Neuromedical Supplies; DC, 100-Hz low-pass filter, 500-Hz digitization rate). Eye-movement artifacts were corrected offline (Semlitsch, Anderer, Schuster, & Presslich, 1986), and remaining artifacts (e.g., muscle activity) were rejected manually.

Data Analyses

For both the behavioral and ERP analyses, SPSS Version 14 for Windows (repeated measures ANOVA) was used. The Greenhouse–Geisser epsilon (ϵ) correction (Jennings & Wood, 1976) was used when appropriate. Uncorrected degrees of freedom are reported along with the ϵ value; the p values reflect the ϵ correction. Significant main effects and interaction were followed up with subsidiary ANOVAs and/or post hoc analyses using the Tukey honestly significant difference test. Because we had predicted that older adults and children might show the greatest deficiencies in upregulating control when posterior and response-incompatibility conflicts were present, planned comparisons (subsidiary ANOVAs) were performed separately for each age group when interactions in the predicted direction were marginally significant.

Behavioral Analyses

Only trials with RTs from 100 to 900 msec were analyzed. The mean percentage of trials that fell outside this criterion, and the mean percentage of timeouts, were, respectively ($\pm SE$), for young adults, 0.5 (± 0.2) and 1.5 (± 0.4); for older adults, 1.3 (± 0.4) and 2.9 (± 0.8); and for children, 3.4 (± 0.8) and 5.4 (± 1.3). The percentage of correct responses and the corresponding RTs based on these criteria are considered below.

ERP Analyses

As noted, we were interested in both ERN and response-conflict monitoring and detection (MFN). Therefore, response-locked ERP data associated with correct and incorrect responses were computed. The data were epoched into 900-msec lengths (450 msec prior to and following mean RT). Because we were also interested in control processes that might precede the RT response, a baseline immediately before the response (e.g., the 100 msec preceding RT) could not be used. A baseline placed several hundred milliseconds before the response might overcome this problem (Nessler, Friedman, et al., 2007). However, RTs could vary across age groups and conflict conditions; therefore, a baseline of this type could confound response- and stimulus-related effects. In an attempt to counteract some of these problems, each single trial was baseline corrected using the 100 msec preceding the stimulus prior to computing RT-locked averages (for a similar procedure, see Fiehler, Ullsperger, & Von Cramon, 2005; Johnson, Barnhardt, & Zhu, 2003; Johnson et al., 2004).

Determination of Latencies for the Components Under Investigation

Error-related negativity (ERN/Ne). On the basis of prior investigations (Falkenstein et al., 2001; Morris, Yee, & Nuechterlein, 2006; Nessler, Friedman, et al., 2007) and the data from this experiment (Figure 1), the ERN was measured at midline locations Fz and FCz. We first determined the peak latencies of the ERN at these sites for erroneous, incompatible-response trials (where we expected the largest amplitude) as the most negative time point between -50 msec pre- and 100 msec post-RT for each age group. This analysis indicated that older adults, young adults, and children had mean latencies of 40, 26, and 14 msec post-RT, respectively. The latencies were rounded to the nearest 10 msec, and an 80-msec window surrounding the mean value was used to capture ERN magnitude (shaded regions in Figure 1; young = -10 to $+70$, older = 0 to 80 , children = -30 to $+50$ msec).

Figure 2. Surface potential (SP) and current source density (CSD) scalp topographies for the three age groups computed on the waveforms associated with posterror trials on which an incompatible response was called for. The maps were computed at the time point for which the MFN showed maximal peak amplitude. Dots represent the 62 scalp locations. The maps were computed by calculating contours using the spherical spline method (Perrin, Pernier, Bertrand, & Echallier, 1989) and the data from all 62 electrode sites.

MFN. On the basis of previous studies (Johnson et al., 2004; Nessler, Friedman, et al., 2007) and the scalp distribution of the MFN in the present data (Figure 2), the data at electrodes AF3, AFz, AF4, F3, Fz, F4, FC3, FCz, and FC4 were chosen for statistical evaluation. These nine sites were used in determining the time interval for measuring MFN magnitude (–50 pre- to 100 msec post-RT) in the condition that showed the largest MFN (posterror, incompatible-response trials; Figure 3). The analysis revealed that older adults, young adults, and children had mean latencies of 41, 3 (both peaking post-RT), and –10 msec (pre-RT), respectively. To capture MFN magnitude, these latencies were used as the center of an averaged voltage of 80-msec length (older adults = 0–80 msec post-RT). Because young adults' and children's peaks lay close to mean RT, this point was chosen as the center of their measurement window (–40 to +40 msec).

Pre-RT activity. For older adults, the peak latency of a pre-RT positive peak on postcorrect, compatible trials (its amplitude was most positive in this condition; Figure 3) was computed at the nine sites listed above as the most positive peak between –200 msec and RT. The mean peak latency occurred 45 msec prior to RT, which was rounded to 40 msec. Hence, the averaged voltage extended from –80 msec pre-RT to 0 msec (at RT). As can be observed in Figure 3, children and young adults did not show a clear, pre-RT positivity. Therefore, averaged voltages for the 80 msec preceding the onset of the MFN measurement window (–120 to –40 msec) were used for these groups.

RESULTS

Behavioral Data: Postcorrect Versus Posterror Trials

To determine whether differential age-group changes in accuracy and RT occurred on trials for which two

sources of conflict were combined (*posterror, incompatible responses*) as opposed to trials with a single source of conflict (postcorrect, *incompatible responses*; *posterror, compatible responses*), between-age-groups ANOVAs were used to assess the within-subjects factors of correctness and response compatibility on the accuracy and RT data. These data are presented in Table 2.

Percent correct. The main effect of correctness [$F(1,42) = 16.37, p < .0001, \eta_p^2 = .28$] revealed that, relative to postcorrect trials ($M = 83$), posterror trials ($M = 77$) engendered lower accuracy. Similarly, the main effect of response compatibility [$F(1,42) = 23.17, p < .0001, \eta_p^2 = .36$] indicated that incompatible ($M = 76$) relative to compatible ($M = 84$) responses led to reduced accuracy. Importantly, correctness interacted marginally with age group [$F(2,42) = 2.50, p < .09, \eta_p^2 = .11$], as did age group, correctness, and response compatibility [$F(2,42) = 2.30, p < .10$]. Planned comparisons in the form of subsidiary ANOVAs were performed to explain the triple interaction.

Young adults were less accurate on incompatible- than on compatible-response trials [main effect of response compatibility, $F(1,15) = 9.95, p < .007, \eta_p^2 = .40$] on both postcorrect and posterror trials. The main effect of correctness was not significant ($F < 1$), but the correctness $\times$ response compatibility interaction was marginally reliable [$F(1,15) = 3.06, p < .10, \eta_p^2 = .17$]. Post hoc testing of the interaction revealed that, whereas there was no reduction in accuracy on posterror relative to postcorrect trials in the compatible-response condition, there was a reliable decrease when two sources of conflict were present in the incompatible-response condition.

For older adults, the main effects of correctness [$F(1,13) = 5.14, p < .04, \eta_p^2 = .28$] and response compatibility [$F(1,13) = 9.16, p < .01, \eta_p^2 = .41$] were significant, but were modulated by the correctness $\times$ response compatibility interaction [$F(1,13) = 8.23, p < .01, \eta_p^2 = .38$]. Post hoc testing of the interaction indicated that the accuracy reduction was greatest and larger than that found for the young (see Table 2) when two sources of conflict were combined (posterror, incompatible responses). In comparison with this highest conflict condition, the accuracy decrease was smaller when a single source of conflict was associated with incompatible responses on postcorrect trials and was absent when induced solely by posterror conflict (posterror, compatible responses).

For the children, the correctness [$F(1,14) = 18.28, p < .001, \eta_p^2 = .57$] and response compatibility [$F(1,14) = 4.78, p < .05, \eta_p^2 = .25$] main effects indicated accuracy reductions, respectively, on posterror and incompatible-response trials. The response compatibility $\times$ correctness interaction [$F(1,14) = 2.42, p > .14, \eta_p^2 = .15$] was not significant. Although the interaction was not reliable, the trend indicated the greatest accuracy decrement when both posterror and incompatible-response conflicts occurred together (Table 2).

RT. The main effect of correctness [$F(1,42) = 49.42, p < .0001, \eta_p^2 = .54$] indicated that RTs on posterror ($M = 483$ msec) relative to postcorrect ($M = 456$ msec) trials were slowed (Table 2). The main effect of response com-

Figure 3. Grand mean RT-locked ERP waveforms averaged across the 16 young adults, 14 older adults, and 15 children. The data are superimposed for postcorrect and posterror trials. The ERPs associated with compatible and incompatible responses are depicted, respectively, in the left and right columns. The waveforms are illustrated for scalp locations AFz and Fz. Dark and light shading indicate reliable differences between posterror and postcorrect waveforms for pre-RT and MFN activities, respectively.

patibility [$F(1,42) = 22.52, p < .0001, \eta_p^2 = .35$] revealed that incompatible ($M = 485$ -msec) relative to compatible ($M = 454$ -msec) responses were prolonged. However, the interactions of age group $\times$ correctness [$F(2,42) = 11.46, p < .0001, \eta_p^2 = .35$] and age group $\times$ response compatibility [$F(1,42) = 3.86, p < .03, \eta_p^2 = .16$] indicated that, as verified by post hoc testing, the slowing in each case was greatest for the older adults (i.e., posterror vs. postcorrect and incompatible vs. compatible; see Table 2). Although the three-way interaction of age group $\times$ correctness $\times$ response compatibility was only marginally significant [$F(1,42) = 2.90, p < .07, \eta_p^2 = .12$], planned comparisons (subsidiary ANOVAs) were performed to examine more closely the source of the differential slowing.

For young adults, the main effects of correctness (M difference = 21 msec) [$F(1,15) = 23.37, p < .0001, \eta_p^2 = .65$] and response compatibility (M difference = 31 msec) [$F(1,15) = 8.55, p < .01, \eta_p^2 = .36$] were significant, but the interaction was not ($F = 1.30$). Similarly, for older adults, the correctness (M difference = 53 msec) [$F(1,13) = 30.94, p < .0001, \eta_p^2 = .70$] and response compatibility (M difference = 55 msec) [$F(1,13) = 14.87, p < .002, \eta_p^2 = .53$] main effects were reliable, but the interaction was not ($F < 1$).

By contrast, for children, neither the main effect of correctness (M difference = 8 msec) [$F(1,14) = 1.67, p >$

.21, $\eta_p^2 = .11$] nor that of response compatibility (M difference = 9 msec) ($F < 1$) was reliable. Importantly, however, the response compatibility $\times$ correctness interaction [$F(1,13) = 6.56, p < .02, \eta_p^2 = .32$] was significant. As verified by post hoc tests, RT slowing was significant when only a single source of conflict was present (i.e., posterror, compatible-response trials, M difference = 23 msec; postcorrect, incompatible-response trials, M difference = 24 msec), but no further slowing was evident when the two sources of conflict were combined (i.e., posterror, incompatible-response trials; see Table 2).

In sum, the performance data indicated that children did not differ from young adults when only a single source of *incompatible-response* conflict was present, whereas older adults evinced greater RT slowing. Relative to young adults, older adults also showed greater RT slowing (associated with preserved accuracy) when only a single source of *post-error* conflict was present. By contrast, children produced a magnitude of RT slowing similar to that for young adults when only posterror conflict was present, but the amount of slowing did not prevent an accuracy decrease. Although older adults showed prolonged RTs on combined-conflict (*posterror, incompatible-response*) trials, it too did not avert an accuracy decrement. Children did not demonstrate RT slowing on these highest conflict trials, resulting in a trend for the greatest accuracy decrease in this condition.

Table 2
Mean RT and Percent Correct ($\pm SE$) on Postcorrect and Posterror Trials Under
the Compatible- and Incompatible-Response Conditions

	Percent Correct						Mean RT					
	Postcorrect		Posterror		Grand Mean		Postcorrect		Posterror		Grand Mean	
	PC	SE	PC	SE	PC	SE	RT	SE	RT	SE	RT	SE
Young adults ($n = 16$)												
Compatible	86.3	2.1	85.8	3.2	86.1	2.3	375	16	390	20	382	17
Incompatible	81.4	2.4	77.2	4.3	79.3	2.9	400	17	426	17	413	16
Grand mean	83.8	2.0	81.5	3.1			387	16	408	17		
Older adults ($n = 14$)												
Compatible	90.3	2.2	91.1	3.5	90.7	2.5	453	17	511	21	482	19
Incompatible	85.2	2.6	72.0	4.5	78.6	3.2	513	18	561	18	537	17
Grand mean	87.7	2.1	81.6	3.3			483	17	536	18		
Children ($n = 15$)												
Compatible	79.5	2.1	71.3	3.3	75.4	2.4	486	17	509	20	497	18
Incompatible	76.3	2.5	62.7	4.4	69.5	3.1	510	17	503	17	506	17
Grand mean	77.9	2.0	67.0	3.2			498	16	506	17		

ERP Data

Because, by themselves, main effects and interactions with electrode location were not of interest with respect to the hypotheses under investigation, we do not report them in the between-groups and subsidiary ANOVAs detailed below unless electrode location interacted with age group (children, young adults, older adults) and one or both of the following two factors: response compatibility (compatible, incompatible) or correctness on the previous trial (postcorrect, posterror).

Error trials: ERN magnitude.² For these analyses, the postcorrect data were averaged separately for correct- and incorrect-response trials. Because some previous studies have reported larger ERN amplitudes under conditions of greater response conflict (Bartholow et al., 2005; Nessler, Friedman, et al., 2007), averages were created for compatible- and incompatible-response trials (Figure 1 depicts the four resulting averages for the three age groups). The averaged voltages based on the data in Figure 1 were subjected to an age group $\times$ correct/incorrect $\times$ response compatibility $\times$ electrode location (Fz, FCz) ANOVA. This analysis revealed a main effect only of correct/incorrect [$F(1,42) = 54.07, p < .0001, \eta_p^2 = .56$], indicating that error trials elicited greater negative-going activity than did correct trials—that is, robust ERNs in all three age groups. Despite the impression obtained from Figure 1 of larger differences between incorrect and correct trials in young relative to older adults and children, the interaction of age group and correctness was not reliable [$F(2,42) = 1.66, p > .20, \eta_p^2 = .07$]. However, the age group $\times$ response compatibility interaction was marginally significant [$F(2,42) = 2.95, p < .06, \eta_p^2 = .12$].

To determine the source of the interaction, subsidiary ANOVAs were performed. As expected from the overall analysis, all three age groups showed significant main effects of correct/incorrect ($F_s > 8.51, p_s < .01, \eta_p^2_s > .39$). However, only older adults also exhibited a main effect of response compatibility [$F(1,13) = 12.08, p < .004, \eta_p^2 = .48$], indicating that, on both correct and erroneous trials, incompatible relative to compatible responses elic-

ited greater negative-going activity (correct/incorrect $\times$ response compatibility interaction $F < 1$). The correct/incorrect $\times$ response compatibility interaction was also not reliable for children or young adults ($F_s < 2.28, p_s > .15$).

Postcorrect versus posterror trials.³ Figure 3 depicts the grand-averaged, response-locked data for children, young adults, and older adults. The ERPs comprise two prominent components. The first, a pre-RT positivity, is reduced as a result of increased conflict (as described below), suggesting, as noted in the introduction, that an overlapping negative component produced this effect (Johnson et al., 2008). The second component, a post-RT negativity, is the MFN, which increases with increments in response conflict. To determine developmental and/or age-related differences in the upregulation of cognitive control and/or response conflict monitoring and detection, which were expected to be greatest when two sources of conflict were combined (posterror, incompatible responses), the pre-RT activity and MFN data depicted in Figure 3 were subjected to between-age-groups ANOVAs with the within-subjects factors of response compatibility, correctness, and electrode location (nine scalp sites).

Pre-RT activity. The main effect of correctness [$F(1,42) = 31.26, p < .0001, \eta_p^2 = .43$] indicated that, as predicted, trials following an error ($M = 1.61 \mu V$) produced more negative-going activity than did those following a correct response ($M = 3.88 \mu V$). The main effect of response compatibility [$F(1,42) = 7.84, p < .008, \eta_p^2 = .16$] revealed that, relative to compatible responses ($M = 3.88 \mu V$), incompatible responses ($M = 1.61 \mu V$) were more negative-going. However, age group interacted with correctness [$F(2,42) = 3.95, p < .03, \eta_p^2 = .16$], as did age group and response compatibility [$F(2,42) = 5.32, p < .009, \eta_p^2 = .20$]; see Table 3. To parse these interactions, subsidiary ANOVAs were performed.

For the young adults, the ANOVA revealed only a significant response compatibility $\times$ correctness interaction [$F(2,42) = 6.28, p < .02, \eta_p^2 = .29$]. As indicated by post hoc tests, reliable pre-RT negativity was not ob-

Table 3
Mean ($\pm SE$) Pre-RT Amplitudes Collapsed Across the Nine Sites From the ANOVA for Postcorrect and Posterror Trials Under Compatible- and Incompatible-Response Conditions

	Compatible		Incompatible		Grand Mean	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Young adults (<i>n</i> = 16)						
Postcorrect	2.2	0.8	2.6	0.7	2.4	0.8
Posterror	2.0	0.9	1.0	0.9	1.5	0.8
Grand mean	2.1	0.7	1.8	0.7		
Older adults (<i>n</i> = 14)						
Postcorrect	6.4	0.9	4.9	0.8	5.7	0.8
Posterror	3.3	0.9	0.7	0.9	1.9	0.8
Grand mean	4.9	0.8	2.8	0.8		
Children (<i>n</i> = 15)						
Postcorrect	3.6	0.8	3.5	0.8	3.5	0.8
Posterror	1.2	0.9	1.5	0.9	1.4	0.8
Grand mean	2.4	0.7	2.5	0.7		

served when only a single source of either posterror or incompatible-response conflict was present. However, when the two sources of conflict were combined on posterror incompatible-response trials, more negative-going pre-RT activity was observed (Figure 3, top two rows; Table 3).

For older adults, the main effect of correctness showed that, relative to postcorrect trials, posterror trials engendered greater negative-going activity [$F(1,13) = 34.84$, $p < .0001$, $\eta_p^2 = .73$]. The main effect of response compatibility [$F(1,13) = 20.70$, $p < .001$, $\eta_p^2 = .61$] indicated that incompatible relative to compatible responses produced greater negative-going activity. However, the response compatibility $\times$ correctness interaction was marginally significant [$F(1,13) = 3.17$, $p < .10$]. Post hoc testing indicated that, in contrast with that for the young, the pre-RT activity in older adults was present on trials with only one source of conflict; whereas, as with the young, it was largest when two sources of conflict were combined (Figure 3, middle two rows; Table 3).

For children, the main effect of correctness [$F(1,14) = 5.79$, $p < .03$, $\eta_p^2 = .29$] revealed that, relative to postcorrect trials, posterror trials produced greater pre-RT negative-going activity. For children, in contrast with older adults, incompatible as compared with compatible responses did not elicit increased pre-RT negativity (response compatibility main effect $F < 1$). The interaction of response compatibility $\times$ correctness was also not significant ($F < 1$), suggesting, by contrast with young adults, that pre-RT activity did not differ when two sources relative to a single source of conflict were present.

MFN. The main effect of correctness was reliable [$F(1,42) = 45.03$, $p < .0001$, $\eta_p^2 = .52$], indicating that trials following an error ($M = 1.46 \mu V$) generated more negative-going MFNs than did those after a correct response ($M = 4.10 \mu V$). The main effect of response compatibility was significant [$F(1,42) = 10.92$, $p < .002$, $\eta_p^2 = .21$], showing that, relative to compatible responses ($M = 3.31 \mu V$), incompatible responses ($M = 2.27 \mu V$) were more negative-going. However, age group interacted

marginally with correctness [$F(2,42) = 2.40$, $p < .10$, $\eta_p^2 = .10$], as did age group and response compatibility [$F(2,42) = 2.95$, $p < .06$, $\eta_p^2 = .12$]. To determine the source of these interactions, planned comparisons, in the form of subsidiary ANOVAs, were performed.

For the young adults, posterror relative to postcorrect trials were significantly more negative-going [$F(1,15) = 8.86$, $p < .009$, $\eta_p^2 = .37$]. The main effect of response compatibility was marginally significant [$F(1,15) = 3.82$, $p < .07$, $\eta_p^2 = .20$]. Importantly, however, the correctness $\times$ response compatibility interaction [$F(1,15) = 7.77$, $p < .01$, $\eta_p^2 = .34$] was reliable. As verified by post hoc tests, the interaction indicated that, in comparison with postcorrect, compatible-response trials, posterror, incompatible-response trials (i.e., two sources of conflict were combined) showed a reliable increase in MFN magnitude but postcorrect, incompatible-response trials and posterror, compatible-response trials (i.e., only a single source of conflict was present) did not. (See Table 4.)

For older adults, the main effects of correctness [$F(1,13) = 39.78$, $p < .0001$, $\eta_p^2 = .75$] and response compatibility [$F(1,13) = 14.56$, $p < .002$, $\eta_p^2 = .53$] indicated, respectively, greater negative-going activity on posterror trials than on postcorrect trials and on incompatible-response trials than on compatible-response trials. The response compatibility $\times$ correctness interaction ($F = 1.38$) was not reliable, suggesting that, unlike for young adults, MFN magnitude was not differentially enlarged on dual-conflict as opposed to single-conflict trials (Figure 3; Table 4).

For children, in contrast with older adults but similar to young adults, the main effect of response compatibility was not significant ($F < 1$), suggesting that children did not show reliable MFNs when only a single source of response-incompatibility conflict was present. However, the main effect of correctness [$F(1,14) = 7.90$, $p < .01$, $\eta_p^2 = .36$] indicated increased MFNs on posterror relative to postcorrect trials, an effect that was of similar magnitude for lower conflict (compatible-response) and highest conflict (incompatible-response) trials (response compatibility $\times$ correctness interaction $F < 1$).

Table 4
Mean ($\pm SE$) MFN Amplitudes Collapsed Across the Nine Sites From the ANOVA for Postcorrect and Posterror Trials Under Compatible- and Incompatible-Response Conditions

	Compatible		Incompatible		Grand Mean	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Young adults (<i>n</i> = 16)						
Postcorrect	3.5	0.9	3.4	0.8	3.4	0.8
Posterror	2.4	0.8	0.7	0.9	1.6	0.7
Grand mean	2.9	0.8	2.0	0.8		
Older adults (<i>n</i> = 14)						
Postcorrect	5.2	0.9	3.6	0.8	4.4	0.9
Posterror	1.7	0.9	-0.8	1.0	0.5	0.8
Grand mean	3.5	0.8	1.4	0.8		
Children (<i>n</i> = 15)						
Postcorrect	4.7	0.9	4.5	0.8	4.6	0.8
Posterror	2.4	0.9	2.3	1.0	2.4	0.8
Grand mean	3.5	0.8	3.4	0.8		

In sum, young adults showed more negative-going pre-RT and MFN components only when two sources of conflict were combined (posterror, incompatible responses) but not when a single source of conflict was present. By contrast, only older adults showed reliable increases in pre-RT and MFN magnitudes when the only source of conflict was response incompatibility on postcorrect trials. However, if the single source of conflict was posterror, both older adults and children exhibited increased pre-RT and MFN amplitudes. Older adults and children also produced more negative-going pre-RT and MFN activities when posterror and response-incompatibility conflicts were combined. However, except for the pre-RT activity in older adults, these effects did not differ quantitatively from those observed for single-source conflict trials, suggesting a less differentiated pattern of ERP activity in these groups than in young adults.

DISCUSSION

The primary aim of the present investigation was to determine whether developmental and age-related differences in the upregulation of cognitive control and the detection of response conflict would occur when engendered by response override (i.e., incompatible responses) and posterror-induced forms of conflict. Indeed, developmental and age-related behavioral differences were most prominent when participants had to simultaneously recover from an error and deal with incompatible-response conflict on the current trial—that is, when conflict was augmented to the highest level (see also Nessler, Friedman, et al., 2007). Consistent with the behavioral data, the cognitive control processes reflected by pre-RT activity and response conflict detection indicated by the MFN showed clear developmental and age-related alterations, discussed below.

When response incompatibility was the only source of conflict, children and young adults showed performance decrements of similar magnitude. However, in stark contrast to the behavioral results of two earlier studies (Davies et al., 2004; Santesso et al., 2006), children, relative to young and older adults, showed an accuracy decrease on compatible trials when only a single, posterror source of conflict was present. Moreover, when confronted with a second, incompatible-response source of conflict on posterror trials, children, relative to young adults, not only demonstrated decreased accuracy but also failed to slow their RTs. Hence, whereas the executive processes that deal with situations in which response override is necessary appear to be relatively mature in 9- and 10-year-old children, those employed to overcome posterror conflict appear to be still developing.

The behavioral results for older adults also indicated deficiencies in the executive processes recruited to manage conflict, but differed from those found in the children. Independent of the type of conflict, when only a single source of conflict was present (postcorrect, *incompatible responses*; posterror, compatible responses), older adults, relative to young adults, showed greater RT slowing. An aspect of the slowing may have reflected increased recruit-

ment of control, which appeared to successfully avert a decrease in accuracy. However, the magnitude of RT slowing on incompatible, posterror trials (when a second source of incompatible-response conflict was present) was not sufficient to avoid a larger accuracy decrement than that for the young (see also Nessler, Friedman, et al., 2007). Thus, whereas older adults appeared able to deal with posterror conflict on compatible-response trials and incompatible-response conflict on postcorrect trials, they showed clear deficiencies when posterror and incompatible-response conflicts were combined.

The performance decrements in children and older relative to young adults were accompanied by differences in pre-RT and MFN components. For young adults, there was no reliable difference in upregulating control (pre-RT activity) or response conflict detection (MFN) when a single source of conflict (postcorrect, incompatible; posterror, compatible) was compared with a condition with presumably little or no conflict (postcorrect, compatible). Then again, when demand was heightened by the combination of two sources of conflict (posterror, incompatible), the upregulation of control (pre-RT activity) and the amount of conflict detected (MFN) were increased. By contrast, children appeared to upregulate control (pre-RT activity) and detect increased amounts of conflict (MFN) when only a single source of conflict was present (posterror, compatible-response trials). In addition to showing increments in upregulating control and conflict detection on these single-conflict trials, older adults also demonstrated increases in these processes in the other single-conflict condition—that is, postcorrect, incompatible responses.⁴ In other words, both children and older adults showed relatively undifferentiated executive processes on low- as well as high-demand trials, whereas only young adults appeared to respond differentially, depending on the level of cognitive demand. However, older adults did produce evidence (at least at a trend level) of increments in the upregulation of control (pre-RT) when two sources of conflict, relative to a single source, were combined.

Nonetheless, the relatively undifferentiated pattern of upregulating cognitive control and response-conflict detection in older adults may be interpretable within the recently formulated framework that distinguishes between proactive and reactive cognitive control (Braver, Gray, & Burgess, 2007; Paxton, Barch, Racine, & Braver, 2008; see also Velanova et al., 2007). This distinction refers to findings in situations characterized by increased cognitive demand that older adults do not appear to maintain a tonic, proactive task set (e.g., procedural rules for dealing with a given set of stimulus–response contingencies). Maintaining a proactive set would serve to prepare older adults for processing in a fast and efficient manner in order to inhibit and override prepotent responses (DePisapia & Braver, 2006). Moreover, a proactive strategy would be beneficial in a situation where the rules for responding are constant over an entire block of trials (as in the present study). Specifically, for compatible blocks, young adults appeared able to utilize a proactive control strategy, which was maintained even following an error, as suggested by the lack of pre-RT and MFN differences between post-

error and postcorrect trials under the compatible-response condition (Figure 3, two top-left rows). Similarly, a proactive control strategy appeared to be used successfully during incompatible-response blocks, as long as posterror conflict was not present. By contrast, in the incompatible-response condition, on posterror relative to postcorrect trials, young adults showed more negative-going pre-RT activity, beginning well before the behavioral response. Because an error on the previous trial presumably triggers an increase in cognitive control on the subsequent one, neural activity associated with such upregulation could have begun quite early. In line with a decrease in accuracy, young adults also produced greater MFN magnitudes on these trials (Tables 3 and 4; Figure 3). These data suggest that, when incompatible responses were required, proactive control was not sufficient to overcome the heightened conflict associated with an error on the previous trial, and reactive control (in the form of negative-going pre-RT activity) became necessary.

This reasoning would suggest that both children and older adults engaged a more reactive-control strategy, even at relatively low levels of response conflict, as evinced by their more negative-going pre-RT activity on posterror, compatible-response trials (children, older adults) and postcorrect, incompatible-response trials (older adults). This type of reactive strategy may be less efficient than a proactive one (Paxton et al., 2008), as attested to here by the performance deficits observed in children and older adults. Moreover, these results are consistent with interpretations made in earlier studies (Friedman et al., 2008; Lustig et al., 2006; Milham et al., 2002; Reuter-Lorenz & Mikels, 2006; Velanova et al., 2007) that older, relative to young, adults appear to recruit executive processes at lower levels of cognitive demand (i.e., in an undifferentiated manner). Older adults experience detrimental alterations in prefrontal neurocognitive mechanisms (Raz & Rodrigue, 2006; West, 1996), which may necessitate the recruitment of control processes, even at low levels of cognitive demand in these participants (Friedman et al., 2008; Reuter-Lorenz & Mikels, 2006).

By contrast with older adults, the prefrontal networks of 9- and 10-year-old children are most likely still developing (Bunge & Zelazo, 2006; Dempster, 1992; Rubia et al., 2006). Given the present results, what appears to be maturing is the ability to selectively recruit and use efficiently putative prefrontal control processes under posterror conflict conditions (see also Bunge et al., 2002). Committing an error on the previous trial, unlike response-override conditions, might create a situation that engenders greater response conflict. Therefore, in comparison with young adults, 9- and 10-year-old children might need to engage greater amounts of cognitive control when posterror processing provides the only source of conflict. Although no previous ERP or fMRI studies speak to this point, a recent behavioral investigation appears to support the undifferentiated recruitment of executive processes in children observed here (Davidson, Amso, Anderson, & Diamond, 2006). The authors used a task-switching paradigm in which low-demand pure blocks of the same task were compared with high-demand mixed blocks, in which

participants had to switch between two tasks. They observed that the RT increment and accuracy decrement on a more difficult task (e.g., press right when the stimulus is on the left) relative to an easier task (e.g., press right when the stimulus is on the right) in pure blocks was large and reliable in children as old as 13 years of age but not in young adults. In young adults, this difference was found only in mixed blocks of trials, for which cognitive demand was at its highest level. Here again, whereas young adults appeared to titrate their control in line with cognitive demand, children did not appear to do so.

A second aim of the present study was to assess developmental and age-related alterations in the error-monitoring system as reflected by ERN amplitude. Unlike in prior research, the error-monitoring system appeared to be relatively mature in the children and maintained in older adults (Davies et al., 2004; Falkenstein et al., 2001; Ladouceur et al., 2007; Mathalon et al., 2003; Santesso et al., 2006; West, 2004). In accord with our results, Eppinger, Kray, Mock, and Mecklinger (2008) have very recently reported the absence of age-related changes in ERN amplitude when performance differences between young and older adults have been controlled. Interestingly, Eppinger et al. also measured ERN activity using a pre-stimulus baseline highly similar to that used here. On the other hand, they were the first to observe age-equivalent ERN magnitudes among many previous reports of age inequality in ERN magnitude. Additionally, the visual impressions gleaned from the present Figure 1 suggest ERN reductions (although not statistically significant) in children and older adults relative to young adults. Thus, it is perhaps premature, at this time, to attempt to assign functional significance to this infrequently reported result.

Nonetheless, according to one theoretical stance, error monitoring and detection are specific instances of the operation of a general conflict-monitoring system (Botvinick et al., 2001; Botvinick et al., 2004). To the extent that this is true, ERN amplitude might be modulated by variables, such as response compatibility, analogously to the MFN. Indeed, for older adults only, both the ERN on postcorrect, erroneous trials and the MFN on postcorrect, correct trials were more negative-going when incompatible as opposed to compatible responses were required (Figure 1). This finding confirms the results of earlier investigations (Bartholow et al., 2005; Nessler, Friedman, et al., 2007), suggesting that, in addition to error processing, the ERN may also be influenced by response conflict.

To conclude, the present study is unique in examining the upregulation of cognitive control and response conflict detection under response-override and posterror conditions in children, young adults, and older adults. For children, the executive processes that upregulate control and detect conflict following an error do not yet appear to have reached young adult levels. For older adults, although the deficits in cognitive-control processes observed on posterror trials were less marked than those for children, they also showed deficiencies in managing incompatible-response conflict. Older adults and children appeared to revert to reactive control strategies even under these presumably low-conflict conditions, whereas young adults

appeared to utilize a more efficient proactive control strategy. On these bases, the efficiency with which cognitive control is applied and conflict is detected under the highest demand conditions are still developing in 9- and 10-year-old children and may be altered in older adults.

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REFERENCES

- BARTHOLOW, B. D., PEARSON, M. A., DICKTER, C. L., SHER, K. J., FABIANI, M., & GRATTON, G. (2005). Strategic control and medial frontal negativity: Beyond errors and response conflict. *Psychophysiology*, **42**, 33-42. doi:10.1111/j.1469-8986.2005.00258.x
- 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. doi:10.1037/0033-295X.108.3.624
- BOTVINICK, M. M., COHEN, J. D., & CARTER, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences*, **8**, 539-546. doi:10.1016/j.tics.2004.10.003
- BRAVER, T. S., GRAY, J. R., & BURGESS, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 76-106). Oxford: Oxford University Press.
- BUNGE, S. A., DUDUKOVIC, N. M., THOMASON, M. E., VAIDYA, C. J., & GABRIELI, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, **33**, 301-311.
- 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.
- 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. doi:10.1016/j.neuropsychologia.2006.02.006
- DAVIES, P. L., SEGALOWITZ, S. J., & GAVIN, W. J. (2004). Development of response-monitoring ERPs in 7- to 25-year-olds. *Developmental Neuropsychology*, **25**, 355-376. doi:10.1207/s15326942dn2503_6
- DEMPSTER, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review*, **12**, 45-75. doi:10.1016/0273-2297(92)90003-K
- DEPISAPIA, N., & BRAVER, T. S. (2006). A model of dual control mechanisms through anterior cingulate and prefrontal cortex interactions. *Neurocomputing*, **69**, 1322-1326. doi:10.1016/j.neucom.2005.12.100
- EPPINGER, B., KRAY, J., MOCK, B., & MECKLINGER, A. (2008). Better or worse than expected? Aging, learning, and the ERN. *Neuropsychologia*, **46**, 521-539. doi:10.1016/j.neuropsychologia.2007.09.001
- FALKENSTEIN, M., HOHNSEIN, J., HOORMANN, J., & BLANKE, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography & Clinical Neurophysiology*, **78**, 447-455. doi:10.1016/0013-4694(92)90062-9
- FALKENSTEIN, M., HOORMANN, J., & HOHNSEIN, J. (2001). Changes of error-related ERPs with age. *Experimental Brain Research*, **138**, 258-262.
- FIEHLER, K., ULLSPERGER, M., & VON CRAMON, D. Y. (2005). Electro-physiological correlates of error correction. *Psychophysiology*, **42**, 72-82. doi:10.1111/j.1469-8986.2005.00265.x
- FRIEDMAN, D., NESSLER, D., JOHNSON, R., JR., RITTER, W., & BERSICK, M. (2008). Age-related changes in executive function: An event-related potential (ERP) investigation of task-switching. *Aging, Neuropsychology, & Cognition*, **15**, 1-34. doi:10.1080/13825580701533769
- GEHRING, W. J., & FENCSEK, D. E. (2001). Functions of the medial frontal cortex in the processing of conflict and errors. *Journal of Neuroscience*, **21**, 9430-9437.
- GEHRING, W. J., GOSS, B., COLES, M. G. H., MEYER, D. E., & DONCHIN, E. (1993). A neural system for error detection and compensation. *Psychological Science*, **4**, 385-390. doi:10.1111/j.1467-9280.1993.tb00586.x
- GEHRING, W. J., & WILLOUGHBY, A. R. (2002). The medial frontal cortex and the rapid processing of monetary gains and losses. *Science*, **295**, 2279-2282. doi:10.1126/science.1066893
- GURLAND, B., GOLDEN, R. R., TERESI, J. A., & CHALLOP, J. (1984). The SHORT-CARE: An efficient instrument for the assessment of depression, dementia and disability. *Journal of Gerontology*, **39**, 166-169.
- HAJCAK, G., McDONALD, N., & SIMONS, R. F. (2003). To err is autonomic: Error-related brain potentials, ANS activity, and posterior compensatory behavior. *Psychophysiology*, **40**, 895-903. doi:10.1111/1469-8986.00107
- HOGAN, A. M., VARGHA-KHADEM, F., KIRKHAM, F. J., & BALDEWEG, T. (2005). Maturation of action monitoring from adolescence to adulthood: An ERP study. *Developmental Science*, **8**, 525-534. doi:10.1111/j.1467-7687.2005.00444.x
- HOLROYD, C. B., & COLES, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, **109**, 679-709. doi:10.1037/0033-295X.109.4.679
- HUTTENLOCHER, P. R., & DABHOLKAR, A. S. (1997). Developmental anatomy of prefrontal cortex. In N. A. Krasnegor, G. R. Lyon, & P. S. Goldman-Rakic (Eds.), *Development of the prefrontal cortex: Evolution, neurobiology, and behavior* (pp. 69-83). Baltimore: Brookes Publishing.
- JENNINGS, J. R., & WOOD, C. C. (1976). The ϵ -adjustment procedure for repeated-measures analyses of variance. *Psychophysiology*, **13**, 277-278. doi:10.1111/j.1469-8986.1976.tb00116.x
- JOHNSON, R., JR., BARNHARDT, J., & ZHU, J. (2003). The deceptive response: Effects of response conflict and strategic monitoring on the late positive component and episodic memory-related brain activity. *Biological Psychology*, **64**, 217-253. doi:10.1016/j.biopsycho.2003.07.006
- JOHNSON, R., JR., BARNHARDT, J., & ZHU, J. (2004). The contribution of executive processes to deceptive responding. *Neuropsychologia*, **42**, 878-901. doi:10.1016/j.neuropsychologia.2003.12.005
- JOHNSON, R., JR., HENKELL, H., SIMON, E., & ZHU, J. (2008). The self in conflict: The role of executive processes during truthful and deceptive responses about attitudes. *NeuroImage*, **39**, 469-482.
- KERNS, J. G., COHEN, J. D., MACDONALD, A. W., III, CHO, R. Y., STENGER, V. A., & CARTER, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science*, **303**, 1023-1026. doi:10.1126/science.1089910
- 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. doi:10.1111/j.1467-7687.2007.00639.x
- LUSTIG, C., HEAD, D., JANES, W. E., & BUCKNER, R. L. (2006). *Frontal-parietal responses to increased demand across the lifespan: Evidence from task switching*. Paper presented at the Cognitive Aging Conference, Atlanta.
- MASAKI, H., FALKENSTEIN, M., STÜRMER, B., PINKPANK, T., & SOMMER, W. (2007). Does the error negativity reflect response conflict strength? Evidence from a Simon task. *Psychophysiology*, **44**, 579-585. doi:10.1111/j.1469-8986.2007.00522.x
- MATHALON, D. H., BENNETT, A., ASKARI, N., GRAY, E. M., ROSENBLUM, M. J., & FORD, J. M. (2003). Response-monitoring dysfunction in aging and Alzheimer's disease: An event-related potential study. *Neurobiology of Aging*, **24**, 675-685. doi:10.1016/S0197-4580(2002)900154-9

- MAYEUX, R., STERN, Y., ROSEN, J., & LEVENTHAL, J. (1981). Depression, intellectual impairment, and Parkinson disease. *Neurology*, **31**, 645-650.
- MILHAM, M. P., ERICKSON, K. I., BANICH, M. T., KRAMER, A. F., WEBB, A., WSZALEK, T., & COHEN, N. J. (2002). Attentional control in the aging brain: Insights from an fMRI study of the Stroop task. *Brain & Cognition*, **49**, 277-296. doi:10.1006/brcg.2001.1501
- MORRIS, S. E., YEE, C. M., & NUECHTERLEIN, K. H. (2006). Electrophysiological analysis of error monitoring in schizophrenia. *Journal of Abnormal Psychology*, **115**, 239-250. doi:10.1037/0021-843X.115.2.239
- NESSLER, D., FRIEDMAN, D., JOHNSON, R., JR., & BERSICK, M. (2007). ERPs suggest that age affects cognitive control but not response conflict detection. *Neurobiology of Aging*, **28**, 1769-1782. doi:10.1016/j.neurobiolaging.2006.07.011
- NESSLER, D., JOHNSON, R., JR., BERSICK, M., & FRIEDMAN, D. (2007). The temporal trajectory of age-related decreases in executive function: ERP and behavioral evidence. *Journal of Cognitive Neuroscience*, **19**(Suppl.), 235.
- OLDFIELD, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, **9**, 97-113. doi:10.1016/0028-3932(71)90067-4
- PAXTON, J. L., BARCH, D. M., RACINE, C. A., & BRAVER, T. S. (2008). Cognitive control, goal maintenance, and prefrontal function in healthy aging. *Cerebral Cortex*, **18**, 1010-1028. doi:10.1093/cercor/bhm135
- PERRIN, F., PERNIER, J., BERTRAND, O., & ECHALLIER, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography & Clinical Neurophysiology*, **72**, 184-187.
- RABBITT, P. M. (1966). Errors and error correction in choice-response tasks. *Journal of Experimental Psychology*, **71**, 264-272. doi:10.1037/h0022853
- RAZ, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik & T. A. Salthouse (Eds.), *Handbook of aging and cognition* (2nd ed., pp. 1-90). Mahwah, NJ: Erlbaum.
- RAZ, N., GUNNING-DIXON, F. M., HEAD, D., DUPUIS, J. H., & ACKER, J. D. (1998). Neuroanatomical correlates of cognitive aging: Evidence from structural magnetic resonance imaging. *Neuropsychology*, **12**, 95-114. doi:10.1037/0894-4105.12.1.95
- RAZ, N., & RODRIGUE, K. M. (2006). Differential aging of the brain: Patterns, cognitive correlates and modifiers. *Neuroscience & Biobehavioral Reviews*, **30**, 730-748. doi:10.1016/j.neubiorev.2006.07.001
- REUTER-LORENZ, P. A., & MIKELS, J. A. (2006). The aging mind and brain: Implications of enduring plasticity for behavioral and cultural change. In P. B. Baltes, P. A. Reuter-Lorenz, & F. Rösler (Eds.), *Lifespan development and the brain: The perspective of biocultural co-constructivism* (pp. 255-276). Cambridge: Cambridge University Press.
- RIDDERINKHOF, K. R., VAN DER MOLEN, M. W., BAND, G. P. H., & BASHORE, T. R. (1997). Sources of interference from irrelevant information: A developmental study. *Journal of Experimental Child Psychology*, **65**, 315-341. doi:10.1006/jecp.1997.2367
- RUBIA, K., SMITH, A. B., WOOLLEY, J., NOSARTI, C., HEYMAN, I., TAYLOR, E., & BRAMMER, M. (2006). Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. *Human Brain Mapping*, **27**, 973-993. doi:10.1002/hbm.20237
- SANTESSO, D. L., SEGALOWITZ, S. J., & SCHMIDT, L. A. (2006). Error-related electrocortical responses in 10-year-old children and young adults. *Developmental Science*, **9**, 473-481. doi:10.1111/j.1467-7687.2006.00514.x
- SCHEFFERS, M. K., HUMPHREY, D. G., STANNY, R. R., KRAMER, A. F., & COLES, M. G. H. (1999). Error-related processing during a period of extended wakefulness. *Psychophysiology*, **36**, 149-157. doi:10.1017/S0048577299980307
- SEGALOWITZ, S. J., & DAVIES, P. L. (2004). Charting the maturation of the frontal lobe: An electrophysiological strategy. *Brain & Cognition*, **55**, 116-133. doi:10.1016/S0278-2626(03)2900283-5
- 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. doi:10.1111/j.1469-8986.1986.tb00696.x
- SHARBRUGH, F., CHATRIAN, G. E., LESSER, R. P., LÜDERS, H., NUWER, M., & PICTON, T. W. (1990). *Guidelines for standard electrode position nomenclature*. Bloomfield: American EEG Society.
- SOWELL, E. R., PETERSON, B. S., THOMPSON, P. M., WELCOME, S. E., HENKENIUS, A. L., & TOGA, A. W. (2003). Mapping cortical change across the human life span. *Nature Neuroscience*, **6**, 309-315. doi:10.1038/nn1008
- TAYLOR, S. F., STERN, E. R., & GEHRING, W. J. (2007). Neural systems for error monitoring: Recent findings and theoretical perspectives. *Neuroscientist*, **13**, 160-172.
- ULLSPERGER, M. (2006). Performance monitoring in neurological and psychiatric patients. *International Journal of Psychophysiology*, **59**, 59-69. doi:10.1016/j.ijpsycho.2005.06.010
- VAN VEEN, V., & CARTER, C. S. (2006). Conflict and cognitive control in the brain. *Current Directions in Psychological Science*, **15**, 237-240. doi:10.1111/j.1467-8721.2006.00443.x
- VELANOVA, K., LUSTIG, C., JACOBY, L. L., & BUCKNER, R. L. (2007). Evidence for frontally mediated controlled processing differences in older adults. *Cerebral Cortex*, **17**, 1033-1046. doi:10.1093/cercor/bhl013
- WATT, N. F. (1976). *Two-factor index of social position: Amherst modification (An adaptation of Hollingshead and Redlich, 1958)*. Unpublished manuscript.
- WECHSLER, D. (1991). *The Wechsler intelligence scale for children* (3rd ed.). San Antonio, TX: Harcourt.
- WECHSLER, D. (1997). *Wechsler adult intelligence scale* (3rd ed.). New York: Harcourt.
- WEST, R. L. (1996). An application of prefrontal cortex theory to cognitive aging. *Psychological Bulletin*, **120**, 272-292.
- WEST, R. L. (2004). The effects of aging on controlled attention and conflict processing in the Stroop task. *Journal of Cognitive Neuroscience*, **16**, 103-113. doi:10.1162/089892904322755593

NOTES

1. Two flankers were presented to the left and two were presented to the right of the central arrow, which participants were instructed to ignore. The flankers were congruent (i.e., pointed in the same direction), incongruent (i.e., pointed in the opposite direction—a representation of the incorrect response), or neutral (diamond shapes) with respect to the direction of the central arrow. In each block, the probability of each type of flanker was 33%. Although we included flanker type in formal analyses of the ERP data, this variable did not produce developmental or age-related effects and did not influence the magnitude of the ERP components under investigation. Therefore, for clarity of presentation, we focus only on response compatibility effects associated with postcorrect and posterror trials.

2. Postcorrect trials were used because there were too few errors following an erroneous response. The mean number ($\pm SD$) of trials entering the averages for compatible-correct, compatible-incorrect, incompatible-correct, and incompatible-incorrect were, respectively, for young adults, 263 (± 46), 37 (± 20), 229 (± 52), 44 (± 22); for older adults, 288 (± 34), 25 (± 12), 263 (± 56), 25 (± 16); for children, 226 (± 51), 37 (± 18), 197 (± 44), 41 (± 14).

3. The mean number ($\pm SD$) of trials entering the four postcorrect and posterror averages (postcorrect, compatible; postcorrect, incompatible; posterror, compatible; posterror, incompatible) were, respectively, for the young adults, 264 (± 46.0), 229.3 (± 52.0), 36.0 (± 19.8), 44.0 (± 22.0); for older adults, 289.6 (± 35.0), 260.4 (± 53.0), 25.1 (± 13.0), 27.0 (± 15.7); for children, 220.9 (± 48.0), 195.9 (± 45.6), 39.8 (± 16.6), 41.8 (± 13.4).

4. It is important to note that the age differences occurring prior to RT would not have been observable had a pre-RT rather than a prestimulus baseline been used.

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