Movement Kinematics of Prepotent Response Suppression in Aging During Conflict Adaptation

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Objectives. The purpose of the current study was to explore the role of adjustments in motor control and conflict adaptation in younger and older adults' prepotent response suppression.

Methods. Participants performed repeated pairs of key-presses on a piano-type keyboard as well as key-presses that conflicted with that prepotent pair. We used motion capture to assess cognitive and motor contributions to conflicting responses presented once, twice, or three times within single trials.

Results. Older adults performed the first conflicting response in a series as well as young adults but at a cost to prepotent response performance. Younger adults improved performance with increased conflict frequency, whereas older adults did not. Older adults spent less time planning and more time executing their conflicting responses, with the opposite pattern in younger adults.

Discussion. Overall, increasing the frequency of conflicting response presentation was detrimental to older but not to younger adults' prepotent response performance. In addition, the results indicate an age-related decline in conflict adaptation. The results are discussed in terms of current models of cognitive control.

Key Words: Aging—Conflict monitoring—Movement kinematics—Response suppression.

COGNITIVE control processes have been described as being responsible for the planning, coordinating, monitoring, and sequencing of other cognitive operations (e.g., Salthouse, Atkinson, & Berish, 2003). In the laboratory, cognitive control is often studied by asking participants to suppress prepotent or well-learned responses. Some tasks rely on responses that are prepotent because of a habitual tendency to respond in a certain way, such as reading a word in the Stroop task (Stroop, 1935). Other prepotent responses, like those in the Eriksen flanker task, arise because of a perceptual motor bias (Eriksen & Eriksen, 1974). Researchers can also create prepotent responses by training participants to expect particular response requirements. For example, in the motor sequencing literature, participants are trained to produce sequences of responses through repetition (see Koch, 2007). When overlearned, each response in the sequence acts as a cue for the next response in the sequence. Similarly, participants can be trained to associate individual pairs of key-presses through repetition. Completion of the first press in the associated pair becomes a prime for the prepotent expectancy of the second press from that pair (Trewartha, Endo, Li, & Penhune, 2009). Generally, presenting a stimulus that is incongruent with a prepotent response leads to increased error rates and/or reaction time.

In the cognitive aging literature, age-related deficits in prepotent response suppression are observed across a broad range of tasks, including the Stroop, stop signal (e.g., Pilar, Guerrini, Phillips, & Perfect, 2008), and Simon tasks (e.g.,

Van der Lubbe & Verleger, 2002). Theories to explain these age-related changes have been expressed in terms of inhibitory control (e.g., Hasher, Zacks, & May, 1999) and conflict-monitoring deficits (e.g., Braver & Barch, 2002).

Regardless of the specific cognitive mechanisms that allow prepotent response suppression, they must exert an influence on the motor control processes involved in executing the appropriate response. An important approach for exploring the nature of the relationship between cognitive processes and motor responses is to use kinematic analyses to delineate the contributions of movement preparation and execution to response suppression. For example, movements that are cued by a stimulus can be decomposed into meaningful components, such as planning and execution phases. Planning is defined as the latency to begin executing a movement and represents stimulus identification, response selection, and movement preparation/programming, whereas execution is the time from movement initiation to termination and is sometimes referred to as movement time (e.g., Bosman, 1993). Explanations of age-related prepotent response suppression deficits can benefit greatly from such analyses because there are known age-related changes in various kinematic measures of movement production (Haaland, Harrington, & Grice, 1993; Kennedy & Raz, 2005; Ketcham & Stelmach, 2001) that contribute to overall reaction time differences and to the ability to adjust control of movements in response to changing task demands (Ketcham, Seidler, Van Gemmert, & Stelmach, 2002; Seidler, 2006).

The reduced ability of older adults to adjust movement parameters in response to changing task demands suggests that age-related cognitive changes influence motor control. In a recent experiment, we explored kinematic measures of prepotent response suppression in younger and older adults (Trewartha et al., 2009). Participants were trained to make prepotent pairs of key-presses and then were tested on violations of the prepotent pair in which the second key-press conflicted with the expected response. These violations were embedded within a random sequence of key-presses, making them difficult to detect. Although prepotent response suppression led to increased planning time on the conflicting responses for both age groups, the younger adults compensated by shortening the time spent executing those key-presses. Older adults had slower planning time and were unable to modify movement execution in the face of prepotent response suppression. Thus, younger adults increased movement execution speed to successfully suppress prepotent responses. It is unclear, however, whether older adults' prepotent response suppression deficit was due to deficiencies in conflict detection or in the ability to adjust movement parameters. Thus, the motivation for the current study was to shed light on this issue by reducing the need for participants to rely on conflict detection mechanisms. This was accomplished by embedding conflicting responses within strings of repeated key-press pairs and by systematically varying the proportion of conflicting responses. In this context, any age-related differences in the pattern of planning and execution time during prepotent response suppression would largely be attributable to motor control processes.

The effects of increased exposure to conflict have been explored using the flanker (Gratton, Coles, & Donchin, 1992), Simon (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002), and Stroop tasks (Kerns et al., 2004), revealing that the interference effect is smaller on conflict trials that were preceded by other conflict trials. This finding has been referred to as the "Gratton effect" or conflict adaptation effect (e.g., Verbruggen, Notebaert, Liefooghe, & Vandierendonck, 2006). These types of findings have motivated the development of the conflict-monitoring theory of cognitive control (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001). Exploring conflict adaptation effects in the elderly participants would help clarify the nature of age-related deficits in prepotent response suppression. However, research on this topic has been relatively sparse. For younger adults, increasing the proportion of congruent items in the Stroop task increases the interference effect. Put another way, if participants are more frequently exposed to conflict, the interference effect is reduced (e.g., Lowe & Mitterer, 1982). In the elderly participants, the limited studies are mixed with some evidence, suggesting that older adults benefit less from increasing the proportion of incongruent trials (e.g., West & Baylis, 1998) but other research showing

evidence of age equivalence in conflict adaptation (e.g., Mutter, Naylor, & Patterson, 2005; West & Moore, 2005). These inconsistencies in the literature highlight the need to use alternative paradigms to explore the general effects of increasing exposure to conflict on cognitive control in the elderly participants and provide motivation for delineating cognitive and motor contributions to conflict adaptation. To this end, we modified our previous paradigm (Trewartha et al., 2009) to test whether repeated exposure to conflict changes the relative proportion of time spent planning and executing conflicting responses in young or elderly participants.

In the current study, we embedded conflicting responses within strings of repeated pairs of key-presses rather than random sequences. This modification effectively reduced the complexity of the task such that there were only two possible responses in each series: a prepotent well-learned pair or a conflicting pair. We reasoned that this would reduce the demands placed on the conflict-monitoring system, allowing us to isolate age-related differences in movement planning and execution during prepotent response suppression. Second, we explored whether manipulating the frequency with which participants encountered conflict would affect their ability to adjust movement execution parameters. We manipulated conflict frequency by including one-, two-, or three-conflicting key-presses within each 10-key-press conflict trial. Consistent with a conflict adaptation effect, it was predicted that participants would perform better with repeated exposure to conflicting key-presses within a trial. Finally, we predicted that the decreased need for conflict detection mechanisms, combined with increased exposure to conflicting responses, would equally affect older and younger adults' performance.

MATERIALS AND METHODS

Participants

Twenty younger (19–36 years old, $M = 24.95$, $SD = 5.21$) and 20 older adults (60–75 years old, $M = 68.2$, $SD = 4.72$) gave informed consent to participate in this study, which was approved by Concordia University's Human Research Ethics Committee. Participants were right handed, free from physical and neurological conditions affecting finger or hand movements, had less than three years of musical experience, and had not been practicing in the past ten years. Each participant completed four neuropsychological tests: the WAIS Digit Symbol Substitution (Wechsler, 1981), the Extended Range Vocabulary test (Form V2; Educational Testing Service, 1976), the Halstead–Reitan Trail Making Test, Parts A and B (Reitan, 1992), and the Stroop test (adapted from Spreen & Strauss, 2001). All participants performed as expected for their age group based on previous literature (Table 1).

Table 1. Means and Standard Errors of the Neuropsychological Tests and the t-Test Results of the Age Group Comparisons for Each Test

Neuropsychological test	Young Adults	Older Adults
WAIS Digit Symbol**	87.40 (4.31)	71.70 (3.79)
ERVT*	9.24 (1.09)	12.28 (0.90)
Trails Difference Scores**	24.60 (3.40)	49.75 (6.99)
Stroop Interference Score*	0.394 (0.03)	0.670 (0.13)

Note: Mean scores are presented with standard error in parentheses for the number of items completed (maximum: 133) in 2 min on the WAIS Digit Symbol Substitution subtest, the number of correct items, with a penalty for errors, on the ERVT, the difference in time (s) to complete Versions B and A of the Trail Making test (Trails), and the difference between the seconds per item completed on the Congruent and Incongruent versions of the color Stroop test. ERVT = Extended Range Vocabulary Test; WAIS = Weschler Adult Intelligence Scale.

$*p < .05; **p < .01$.

Apparatus

Participants made sequences of key-presses using the four fingers of their right hand on a piano-type keyboard while seated in front of a 17″ flat–screen monitor. Four dark gray 3″ × 3″ boxes oriented horizontally on the screen represented each of their fingers in a left-to-right manner. Each box, and finger, also corresponded to one of four consecutive keys on the keyboard on which pieces of Velcro were affixed to act as tactile cues to aid participants in remaining on the correct keys (see Figure 1). The boxes on the screen changed color one at a time to cue which finger/key the participant should press. The keyboard measured accuracy, whereas a 3D motion capture system (VZ3000; Phoenix Technologies Inc., Burnaby, Canada) obtained the movement data. The stimulus presentation software was custom written in C# on version 1.1 of the Microsoft.NET framework and also collected timing data of the motion capture frames and stimulus presentation for offline synchronization.

Procedures

Participants performed 10-key-press trials without performance feedback. The task instructions were to follow along as each box lights up and fully press down on the corresponding key with the corresponding finger as quickly and accurately as possible. Stimulus duration was 400 ms, with a 400-ms interstimulus interval (ISI) and a 3,000-ms pause between each trial. Participants performed three conditions: The first was a block of six random sequences using all four fingers that acted as a baseline of the ability to react to and follow along with the stimuli. The second condition was a homogeneous "repeated-only" condition in which 15 trials were presented involving the repetition of the same pair of key-presses five times in every trial. This induced a prepotent pair of key-presses that could be used to create conflicting pairs in subsequent blocks. The final condition consisted of nine heterogeneous blocks of 20 trials each that contained both repeated-only and conflict

trials (see Figure 1 for examples). There were a total of 120 repeated-only trials in these blocks that were identical to those in homogeneous condition except that they occurred in blocks also containing conflict trials. The 60 remaining trials were conflict trials. Each conflict trial included a conflicting key-press pair consisting of the first press of the repeated pair, followed by an unexpected alternate second key-press. These conflicts were embedded within trials of repeated pairs, and conflict frequency was manipulated by including one, two, or three conflicts in each trial. There were 20 trials of each conflict frequency randomly dispersed among the nine heterogeneous blocks with the constraint that each conflict trial would be separated by one, two, or three repeated-only trials. The serial position of the conflicts within each trial was also randomized to ensure that the locations of conflicting responses were not predictable. The particular key-press combination that was used as the prepotent pair was counterbalanced across participants.

Data Analyses

The data were separated into the following key-press pairs: (a) random; (b) repeated only in the homogeneous condition; (c) repeated only in the heterogeneous condition; (d) repeated responses within conflict trials; and (e) conflicting key-presses, separated into one, two, or three conflicts. The dependent variables were calculated only for the second key-press in each pair as the first key-press acted as the prime for the prepotent response. For the random sequences, all key-presses were included.

A response was considered accurate if the correct key was pressed while the stimulus was on the screen or within the ISI. Planning and execution time were calculated on unfiltered data using analysis tools developed in Matlab 2008b (described by Trewartha et al., 2009). Briefly, full key-presses were identified as local minima (i.e., troughs) among samples that were more than 2 *SD*s below the baseline in the vertical (*z*) dimension. Movement initiation was calculated using a backward search for the point at which the slope was greater than −0.05 mm/ms for each key-press. The amount of time from stimulus presentation to movement initiation was defined as the planning time, whereas the time from movement initiation to the trough defined execution time (Figure 2). Together, the kinematic measures provide an estimate of reaction time and are only presented for correct responses. For all three dependent measures, key-press types were averaged across trials within participant and across participants within age groups for comparison. (Due to the frequency of conflict manipulation, there are more data points for the repeated responses than the conflicting responses. To test whether the unequal number of data points affected the results, all analyses were conducted a second time using a random subset of the repeated responses to equate the number of data points in
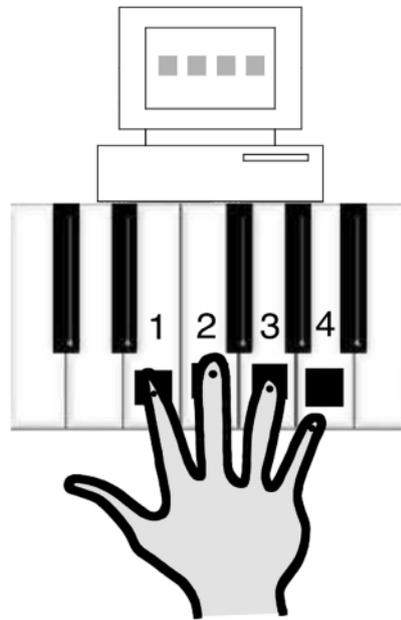
Examples of key press sets from each condition

	Conditions					
	Homogeneous		Heterogeneous			
	Random (6 trials)	Repeated Only (15 trials)	Repeated Only (120 trials)	1-Conflict (20 trials)	2-Conflicts (20 trials)	3-Conflicts (20 trials)
	4 2 1 3 2 1 4 1 2 3	3 4 3 4 3 4 3 4 3 4	3 4 3 4 3 4 3 4 3 4	3 4 3 4 3 1 3 4 3 4	3 4 3 4 3 1 3 4 3 2	3 2 3 4 3 2 3 4 3 1

Note: Repeated pairs are underlined and conflicts are in bold.

Figure 1. Illustration of the computer/keyboard set-up for the motor task (top panel). Participants placed each of the four fingers of their right hand on Velcro pads affixed to four consecutive keys on the keyboard. One light emitting diode marker was placed on each fingernail of the right hand, and nine motion capture cameras were oriented in a semicircle around the computer/keyboard set-up. Numbers on the keys are for illustration purposes only. The table (bottom panel) presents examples of the sequences used in each experimental condition.

each condition. There were no changes in the pattern of effects for any of the analyses. In the interest of including the full data, results are presented from the first analysis.)
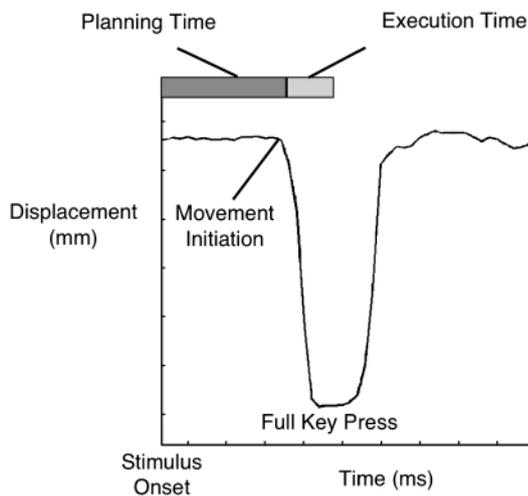
Figure 2. Illustration of the parsing of a single key-press into the kinematic time course variables of planning and execution time.

Results

Overall Conflict Effects

To explore, the overall effects of exposure to conflict younger and older adults' performance was compared on the seven different response types: random, repeated only-homogeneous, repeated only-heterogeneous, repeated with conflict, and conflicting responses in one-, two-, and three-conflict trials. Each dependent measure was subjected to a 2 (Age Group) × 7 (Response Type) analysis of variance (ANOVA).

For accuracy (top panel of Figure 3), this overall ANOVA revealed significant main effects of response type, $F(6, 33) = 14.24$, $p < .001$, $\varsigma_p^2 = 0.73$, and age group, $F(1, 38) = 4.3$, $p < .05$, $\varsigma_p^2 = 0.10$, and a significant interaction between age group and response type, $F(6, 33) = 3.15$, $p < .05$, $\varsigma_p^2 = 0.37$. Likewise, in planning time (center panel of Figure 3), there were significant main effects of response type, $F(6, 33) = 22.65$, $p < .001$, $\varsigma_p^2 = 0.84$, and age group, $F(1, 38) = 4.38$, $p < .05$, $\varsigma_p^2 = 0.12$, and a significant interaction between age group and response type, $F(6, 33) = 3.31$,

$p < .05$, $\varsigma_p^2 = 0.42$. Finally, for execution time (bottom panel of Figure 3), there was a significant main effect of age group, $F(1, 38) = 4.43$, $p < .05$, $\varsigma_p^2 = 0.12$, and a significant interaction between age group and response type, $F(6, 33) = 4.07$, $p < .01$, $\varsigma_p^2 = 0.46$, but no main effect of response type ($p > 0.32$). In order to explore these interactions, pair-wise comparisons were conducted using a Bonferroni correction for each dependent variable.

First, in the homogeneous block, younger adults were better able to respond to a series of random key-presses than older adults in terms of accuracy, $t(19) = 3.17$, $p < 0.01$, and had shorter planning time, $t(19) = 3.91$, $p < 0.001$, but execution time did not differ between the groups ($p > 0.27$). Importantly, there were no differences between the age groups for the repeated-only homogeneous responses on any of the dependent measures (all $p > 0.52$). Thus, despite age differences in performance of random sequences of key-presses, age equivalence was observed for performance of the prepotent responses (left side of each panel in Figure 3). With this in mind, comparisons were made among the repeated and conflicting responses in the heterogeneous blocks.

In order to assess the global effect of introducing conflicting responses in the heterogeneous blocks, within-group comparisons were made between the repeated-only responses in the homogeneous and heterogeneous conditions. Younger adults did not exhibit a difference for any of the dependent measures for this comparison (all $p > 0.25$) nor did the older adults (all $p > 0.95$). However, it appears from the center panel of Figure 3 that planning time differed between the groups for the repeated responses in the heterogeneous condition. A follow-up between-groups comparison of the repeated-only responses in the heterogeneous condition confirmed that older adults had longer planning time than younger adults, $t(19) = 3.31$, $p < 0.01$. Thus, the introduction of conflict trials in the heterogeneous condition compromised the age equivalence in prepotent response performance observed in the homogeneous block.

In order to assess the more local effects of responding to prepotent responses within conflict trials, repeated-only responses in the heterogeneous condition were compared with repeated responses in conflict trials within groups. Younger adults did not differ for these response types (all $p > 0.25$), whereas older adults were less accurate, $t(19) = 6.33$, $p < 0.001$, and spent more time planning, $t(19) = -4.47$, $p < 0.01$, repeated responses that occurred within conflict trials. No other comparisons were significant (all $p > 0.95$). This suggests that in addition to the global effect of conflict, older adults experienced greater local costs than younger adults on repeated responses in conflict trials.

Finally, within-group comparisons were made to explore conflicting response performance across different levels of conflict (averaged within one-, two-, and three-conflict trials) and with repeated-only responses in the heterogeneous blocks (see right side of all panels in Figure 3). Overall,

younger adults were less accurate for all levels of conflict relative to their repeated-only responses, $t(19) = 6.56$, $p < 0.001$, $t(19) = 5.23$, $p < 0.001$, and $t(19) = 5.10$, $p < 0.001$, respectively. They also spent more time planning the conflicting responses, $t(19) = -6.6$, $p < 0.001$, $t(19) = -8.79$, $p < 0.001$, and $t(19) = -8.49$, $p < 0.001$, respectively, but showed no differences in execution time (all $p > 0.64$). Older adults showed the same pattern of lower accuracy for all levels of conflict, $t(19) = -6.82$, $p < 0.001$, $t(19) = -7.94$, $p < 0.001$, and $t(19) = -7.09$, $p < 0.001$, respectively, and their planning time was longer compared with their repeated-only responses, $t(19) = -4.21$, $p < 0.01$, $t(19) = -3.66$, $p < 0.05$, and $t(19) = -3.30$, $p < 0.05$, respectively. However, the older adults also took longer to execute conflicting responses in all three trial types compared with their repeated-only responses, $t(19) = -4.49$, $p < 0.01$, $t(19) = -4.20$, $p < 0.01$, and $t(19) = -4.18$, $p < 0.01$, respectively. This pattern differed from the younger adults who did not differ in execution time for conflicting and repeated responses. In addition, comparisons among the levels of conflict revealed that younger adults improved their accuracy in two- and three-conflict trials compared one-conflict trials, $t(19) = 4.31$, $p < 0.01$, and $t(19) = 4.47$, $p < 0.01$, respectively. No other comparisons were significant (all $p > 0.18$), indicating that older adults did not improve conflicting response performance in trials with more than one conflict.

To summarize, despite age equivalence in performing prepotent responses in isolation, younger and older adults' performance differed on the repeated responses in the context of conflicting responses. For older adults only, conflicting responses interfered with performance on the repeated responses, both globally in the heterogeneous blocks as well as locally on the repeated responses within conflict trials. Moreover, although both groups performed worse on conflicting responses than prepotent responses, only younger adults improved their performance when more than one conflict was presented.

Conflict Adaptation

The improvement in younger adults' performance during trials with more than one conflict is consistent with a conflict adaptation effect. However, an alternative explanation is that the improvement was due to increases in the proportion of conflicting responses within conflict trials. A genuine conflict adaptation effect would be observed if participants' performance improved on conflicting responses that were preceded by previous conflicting responses within a trial. We explored this by comparing the conflicting responses in terms of their position within each type of conflict trial (Figure 4) unlike the previous analysis in which we averaged across conflicts in each trial. Conflicts were separated into the following response types: one-conflict only; first and second conflict in a two-conflict trial;
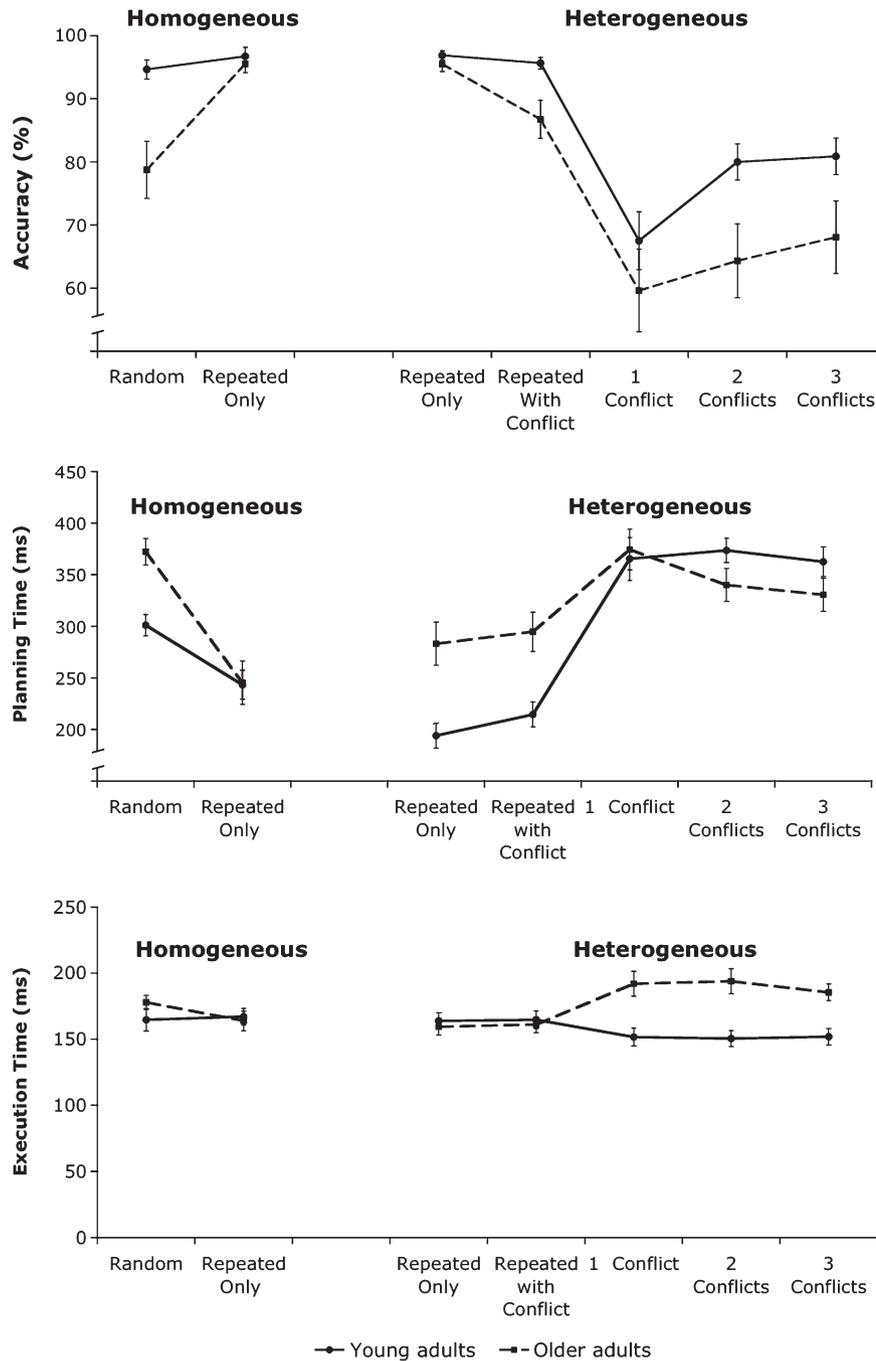
Figure 3. Younger and older adults' keyboard and motion capture data in the homogeneous and heterogeneous conditions. Averages are shown for all seven response types: random, repeated-only homogeneous, repeated-only heterogeneous, repeated with conflict, and conflicting responses averaged within one-, two-, and three-conflict trials. Panel (a) displays averaged accuracy, (b) displays averaged planning time, and (c) displays execution time. Error bars represent standard error of the mean.

and first, second, and third conflict in a three-conflict trial. Each dependent variable was compared using a 2 (Age Group) × 6 (Conflict Position) ANOVA. For accuracy, there was a significant main effect of response type, $F(5, 34) = 11.64$, $p < .001$, $\varsigma_p^2 = 0.24$, and a significant interaction between age group and response type, $F(5, 34) = 7.61$, $p < .001$, $\varsigma_p^2 = 0.17$, but no main effect of age group ($p > 0.07$).

For planning time, there were significant main effects of response type, $F(5, 34) = 5.32$, $p = .001$, $\varsigma_p^2 = 0.45$, and age group, $F(1, 38) = 4.11$, $p = .05$, $\varsigma_p^2 = 0.10$, and a significant interaction between age group and response type, $F(5, 34) = 2.74$, $p < .05$, $\varsigma_p^2 = 0.30$. There was also a significant main effect of age in execution time such that older adults spent more time executing conflicting responses than younger
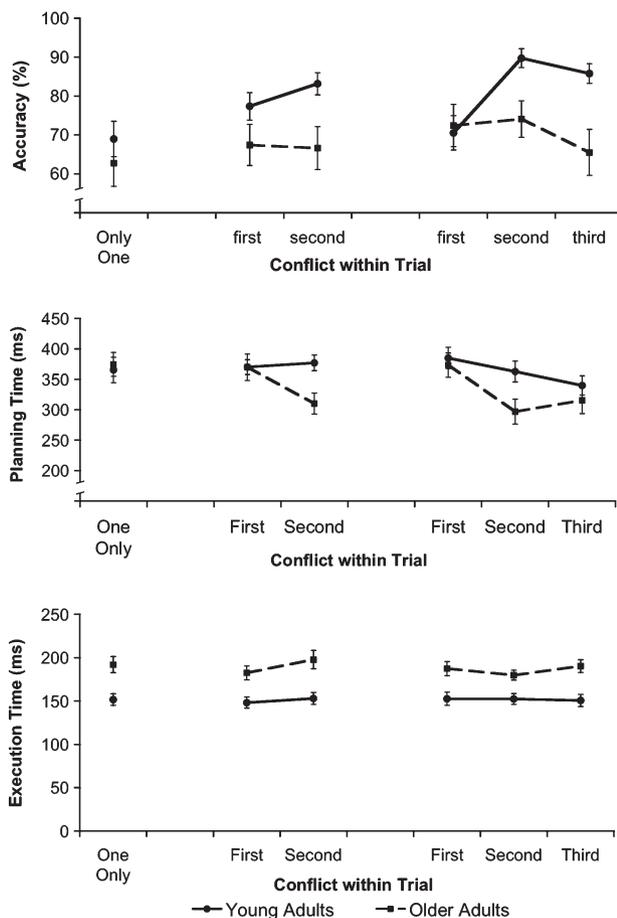
Figure 4. Conflict frequency data: Younger and older adults' keyboard and motion capture data for six different conflict positions. Namely, conflicting responses in the one-conflict trials; first and second conflicts in the two-conflict trials; and the first, second, and third conflict in the three-conflict trials. Panel (a) displays averaged accuracy, panel (b) displays averaged planning time, and (c) displays execution time. Error bars represent standard error of the mean

adults, $F(1, 38) = 18.57$, $p < .001$, $\varsigma_p^2 = 0.34$, but no other effects were significant (all $p > 0.67$).

Pair-wise comparisons revealed a conflict adaptation effect in the three-conflict trials for younger adults as they were significantly more accurate on the second and third conflicting response compared with the first, $t(19) = -5.95$, $p < .001$ and $t(19) = -4.48$, $p = .001$, respectively (right side of top panel in Figure 4). No other comparisons were significant for the younger adults (all $p > .065$). Older adults did not improve in accuracy on subsequent conflicts within trials, rather they were marginally less accurate on the third conflict in a three-conflict trial compared with the second, $t(19) = -3.12$, $p = .053$ (no other comparisons reached significance, all $p > .09$). Interestingly, in the two-conflict trials, older adults decreased planning time on the second conflicting response compared with the first, $t(19) = 3.40$, $p < .05$ (center of middle panel in Figure 4). Likewise, they decreased planning time on the second conflict in the three-conflict trial, $t(19) = 5.22$, $p < .001$, and marginally on the

third compared with the first conflict, $t(19) = 3.11$, $p = .055$ (right side of middle panel in Figure 4). No other comparisons were significant (all $p > .44$).

These analyses confirm that a conflict adaptation effect could account for improved accuracy of younger adults on trials with more than one conflict. Older adults did not improve in accuracy on the second or third conflict within a trial, suggesting an age-related decline in the ability to benefit from previous exposure to conflict.

Discussion

The goal of this study was to isolate the role of conflict adaptation from conflict detection processes in age-related prepotent response suppression deficits. To this end, we minimized the need for conflict detection by embedding conflicting key-presses in series of repeated pairs and manipulated the number of conflicts within each series. Two sets of findings emerged. First, although older adults performed conflicting key-presses as well as younger adults, their performance suffered on the prepotent responses. Moreover, on the conflicting responses, older adults exhibited shorter planning and longer execution times, whereas younger adults showed the opposite pattern. Second, the more fine-grained analyses of conflict frequency effects revealed that age equivalence in performance of a conflicting response was limited to the first conflict in a trial. Contrary to our prediction, only the younger adults improved performance with repeated exposure to response conflict. In fact, older adults became less accurate with repeated response conflict and showed reductions in planning time. Although reducing the need to rely on conflict detection allowed older adults to perform as well as young adults on the first conflict in a trial (cf. Trewartha et al., 2009), they failed to show a conflict adaptation effect for subsequent conflicts. Additionally, impaired performance on the prepotent responses suggests that even when conflict detection demands were minimized, older adults had difficulty regulating performance in response to changes in task context.

The finding that older adults were able to suppress the prepotent response during the first conflict in a series is consistent with observations that increased conflict saliency can benefit older adults' performance in the Stroop task (e.g., Borella, Delaloye, Lacerf, Renaud, & De Ribaupierre, 2009). In contrast, our previous experiment revealed that older adults exhibited prepotent response suppression deficits when conflicts were embedded within random sequences—a context in which conflict detection is challenging (Trewartha et al., 2009).

A possible explanation for this discrepancy is that the current paradigm has only two competing mental sets (i.e., the prepotent response or any conflicting response). In our previous experiment, there were at least three mental sets because prepotent and conflicting responses were performed within random sequences. In the task-switching

literature, global set-selection costs in reaction time, obtained by comparing blocks of task switching to blocks without switching, are often larger in older adults than local costs of switching tasks (e.g., Mayr, 2001). Consistent with this, we observed age equivalence on the first conflicting pair in a series, which represents a local switch from performing the prepotent pair. Additionally, global costs were only evident for older adults as their prepotent response performance was reduced in the heterogeneous compared with the homogeneous condition in which no mental set switch was required. Similar age-related changes in performance have been observed in the context of increased response choices (e.g., McDowd & Craik, 1988) and multiple stimulus-response mappings (Kolev, Falkenstein, & Yordonova, 2006).

An alternative explanation of the difference between the current findings and those of Trewartha and colleagues (2009) is that older adults benefited from greater conflict awareness induced by embedding conflicts within repeated pairs rather than random key-presses. Neurophysiological studies have dissociated mechanisms associated with conflict detection from those associated with conflict awareness (O'Connell et al., 2007). There is evidence that the amplitude of event-related potential components associated with both detection and awareness is reduced in later adulthood (e.g., Band & Kok, 2000; Mathewson, Dywan, & Segalowitz, 2005; cf. Mathalon et al., 2003). In the current study, conflict detection demands are minimal, so preserved conflict awareness could account for older adults' prepotent response suppression during the first conflict in a trial.

Despite improvements in performance on the first conflict in a series, older adults' performance suffered on the repeated responses in the heterogeneous condition consistent with evidence of age-related declines in interference resolution (e.g., Rekkas, 2006). Moreover, the current data revealed that older adults failed to adapt their performance based on previous exposure to conflict within trials. The conflict-monitoring hypothesis (Botvinick et al., 2001) predicts that encountering conflicts should trigger adjustments in cognitive control aimed at reducing the effects of future conflicts. Support for this prediction comes in the form of behavioral improvements during subsequent conflict (Gratton et al., 1992; Stürmer et al., 2002) and changes in neural activity associated with those behavioral improvements (e.g., Kerns et al., 2004; Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003). Given these findings and evidence of preserved conflict adaptation in the elderly participants (e.g., Mutter et al., 2005), we predicted that younger and older adults would improve with repeated exposure to conflict. We found support for conflict adaptation effects in younger adults' response selection accuracy as error rates were reduced during the second and third presentation of a conflict in each trial.

However, contrary to our prediction, the older adults' accuracy worsened across subsequent conflicts. In fact, they only performed as well as younger adults on the first

presentation of conflict in a trial. In addition, they shortened planning time on the second and third presentation of a conflict compared with the first presentation in a trial, but this did not benefit their overall performance. Shortened planning time, in the context of longer execution time, is consistent with evidence that older adults fail to inhibit prepotent responses and must rather rely on online movement corrections (Potter & Grealy, 2006). This pattern differs from our previous finding that older adults spent more time planning conflicting responses than younger adults (Trewartha et al., 2009). This is likely because our previous paradigm required participants to rely on conflict detection mechanisms that are less efficient in later adulthood (Nieuwenhuis et al., 2002). In the Potter and Grealy and our current study, conflict detection demands were minimized by only including responses that were either prepotent or conflicting. Given the speeded nature of these tasks, shorter planning time by older adults may reflect an impulsive response style due to uncertainty in mental set selection.

Overall, our findings are consistent with evidence of age differences in proportion congruent effects in the Stroop task (West & Baylis, 1998; cf. Mutter et al., 2005), suggesting that conflict adaptation in our paradigm may rely on similar mechanisms. Likely, the prepotent responses in our paradigm are less well learned and thus more susceptible to interference than the prepotent responses in a Stroop task. Nevertheless, younger adults maintained prepotent response performance while also showing a robust conflict adaptation effect. Older adults had more difficulty maintaining the prepotent response representation during a condition in which it must also be suppressed.

The age-related performance decline across repeated conflicts may also be explained in terms of a deficiency in managing competing mental sets (e.g., Mayr & Liebscher, 2001) and is consistent with evidence that older adults exhibit a deficiency in adjusting cognitive control (e.g., Nessler, Friedman, Johnson, & Bersick, 2007). Such an age-related deficiency could be explained in the context of the dual mechanisms of control account (Braver, Gray, & Burgess, 2007). This theory proposes that cognitive control is accomplished by both proactive anticipatory biasing of attention prior to stimulus presentation and reactive stimulus-driven adjustments in control. In the current study, participants may have maintained a mental set of the prepotent response and, upon encountering the first conflict in a trial, used stimulus-driven reactive control to respond accurately. The observation of age invariance of the first conflict in a series is consistent with evidence of preserved reactive control in later adulthood (see Braver et al., 2007). The initial exposure to the first conflict in a series could update working memory with an additional mental set (i.e., a conflicting response), and the interference introduced by proactively maintaining more than one anticipatory bias in working memory could burden older adults' ability to rely on proactive control. The fact that older adults failed to

benefit from repeated exposure to conflict is consistent with proactive control deficits in later adulthood (see Braver et al., 2007). Thus, the current data are consistent with the idea that an age-related deficit in maintaining more than one mental representation in working memory may be exacerbated when participants frequently shift between mental.

In summary, under conditions of high conflict saliency, older adults can perform conflicting responses as well as young adults but only for the first conflict in a series. This is potentially due to a preservation of a reactive mode of cognitive control in later adulthood. However, in contrast to younger adults, increasing conflict frequency, rather than benefiting older adults' performance, exacerbates the interference between the well-learned and conflicting representations. Moreover, older adults' performance suffered on the prepotent response in the heterogeneous condition where participants must frequently switch between prepotent and conflicting responses. Interference between the proactive anticipation of the prepotent response and a conflicting response led to age-related performance declines. Therefore, the current study provides evidence that declines in the ability to simultaneously regulate more than one mental representation could contribute to reduced conflict adaptation in later adulthood.

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