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RESEARCH ARTICLE

Effects of age and cognitive load on response reprogramming

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Abstract A dual-task paradigm was used to examine the effect of cognitive load on motor reprogramming. We propose that in the face of conflict, both executive control and motor control mechanisms become more interconnected in the process of reprogramming motor behaviors. If so, one would expect a concurrent cognitive load to compromise younger adults' (YAs) motor reprogramming ability and further exacerbate the response reprogramming ability of older adults (OAs). Nineteen YAs and 14 OAs overlearned a sequence of key presses. Deviations of the practiced sequence were introduced to assess motor reprogramming ability. A Serial Sevens Test was used as the cognitive load. A 3D motion capture system was used to parse finger movements into planning and motor execution times. Global response time analysis revealed that under single-task conditions, during prepotent transitions, OAs responded as quickly as YAs, but they were disproportionately worse than YAs during conflict transitions. Under dual-task conditions, YAs performance became more similar to that of OAs. Movement data were decomposed into planning and movement time, revealing that under single-task conditions, when responding to conflicting stimuli YAs reduced their movement time in order to compensate for delayed planning time; however, additional cognitive load prevented them from exhibiting this compensatory hastening on conflict transitions. We propose that age-related declines in response reprogramming may be linked to reduced cognitive capacity. Current findings suggest that cognitive capacity, reduced in the case of OAs or YAs under divided attention conditions, influences the ability to flexibly adapt to conflicting conditions.

Keywords Aging · Cognitive control · Fine motor performance · Response reprogramming

Introduction

Many everyday activities involve the ability to suppress responses that are inappropriate or no longer required. For example, one must resist the tendency to walk a straight path if an obstacle appears ahead. Generally, response suppression is necessary to flexibly adapt our behaviors to changing environments (Verbruggen and Logan 2009). Research in aging and response suppression indicates moderate to substantial declines across a variety of paradigms (McDowd and Shaw 2000). A less frequently studied aspect of response suppression involves the revision of a prepared action, or response reprogramming. In general, older adults have shown more difficulty reprogramming well-learned responses compared to younger adults. We have recently argued that age-related declines in reprogramming are attributable to aging of executive control mechanisms (Trewartha et al. 2009). However, because older adults may have less efficient cognitive control processes as well as diminished motor skills, the challenge remains to disentangle the concurrent contributions of cognitive and motor aging. In the current study, we used a dual-task paradigm to simulate the effects of reduced cognitive capacity in young participants and compared their performance with that of older adults. Based on the view

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that motor performance in old age is increasingly reliant on cognitive control processes, we expected that increased cognitive load would hinder younger adults' ability to reprogram their well-learned motor responses and further exacerbate the response reprogramming ability of older adults.

Aging and response suppression

Response suppression has been included as a component of several major theories of inhibition (e.g., Hasher et al. 1999) and executive function (e.g., Miyake et al. 2000) and in general entails the avoidance of a familiar or prepotent response. Among the tasks commonly used to investigate response suppression are the Stroop test (Stroop 1935) and the Hayling test (Burgess and Shallice 1996). In the Stroop test, the interference condition requires participants to name the color of the printed words, which are incongruent color names (e.g., GREEN printed in red ink). In the Hayling test, participants complete sentences by saying the sentence final word, but must not produce the expected completion. The evidence from a variety of response suppression paradigms indicates a decline in performance with aging (e.g., Andrés et al. 2008; Bielak et al. 2006; Earles et al. 1997; Kramer et al. 1994).

Response reprogramming is a related but less commonly studied aspect of response suppression. In this type of paradigm, participants are instructed to carry out a repeated motor response to predictable stimuli, but must occasionally revise their responses and reprogram new responses. Across a variety of reprogramming paradigms, older adults generally need more time to reprogram their motor movements compared to younger adults (e.g., Amrhein et al. 1991; Bellgrove et al. 1998). While at first glance response inhibition studies appear to engage similar processes, it is possible that response reprogramming requires even more cognitive control than simple suppression paradigms due to the additional need to activate a new motor program.

Motor and cognitive interactions in old age

The involvement of cognitive control processes in motor performance has been an important theme in aging research. The shared variance between cognitive and sensory/sensorimotor performances has been shown to increase with chronological age (e.g., Lindenberger and Baltes 1997). Correlational studies demonstrate that gait characteristics (variability, speed) and falls frequency are significantly correlated with higher-level cognitive functions such as Stroop interference (e.g., Hausdorff et al. 2005; Holtzer et al. 2006). Similar conclusions are found in experimental studies of dual-task performance whereby participants perform the motor and cognitive tasks separately and concurrently, and dual-task costs are calculated by comparing single- and dual-task scores. If cognitive control processes play a greater role in motor performance with aging, one would predict that a concurrent cognitive load would exacerbate the age differences observed in motor task performance. Accordingly, it has been shown that older adults frequently show greater dual-task performance costs compared to younger adults in studies of dual-task gait or balance (Li et al. 2001; Lindenberger et al. 2000; Woollacott and Shumway-Cook 2002; Yogev-Seligmann et al. 2008). Investigations of dual-task fine motor performance reveal parallel findings. For instance, Fraser et al. (2010) compared healthy younger and older adults on a visuomotor finger tapping task paired with a concurrent subtract sevens task. Overall, older adults showed greater motor dual-task costs than younger adults.

Executive control and motor reprogramming in old age

We have investigated the role of executive control processes on response reprogramming using a cued finger-sequencing task (Trewartha et al. 2009, 2011, 2013). Healthy younger and older adults are first trained on a specific pair of key presses to create a prepotent response. In the test phase, these prepotent response sequences are occasionally violated with unexpected changes (conflict transitions) to assess the efficiency of response reprogramming as compared to prepotent responses. To examine the joint contributions of cognitive control and motor processes, we have used motion tracking to decompose task performance into broadly cognitive (planning) and movement (execution) components. Planning time is measured from stimulus onset to movement initiation. Execution time is measured from movement initiation to termination of the key press. Across several data sets, both older and younger adults showed longer planning times when responding to conflict transitions as compared to prepotent transitions. Presumably, this delay reflects the reprogramming requirements of the conflict transitions. Importantly, on conflict transitions, only younger adults have shown faster execution times than on prepotent transitions, suggesting a form of compensatory hastening to recover from the delayed planning time. Under the most simple version of this paradigm, Trewartha et al. (2009) reported that older adults showed no difference between executing movements of prepotent and conflicting responses, suggesting that conflict processing declines with age. In a more complex version of the same paradigm with a variable number of transitions per trial, Trewartha et al. (2011) observed that older adults were differentially slowed during conflict transitions as compared to prepotent conditions, whereas younger adults continued to show the compensatory hastening effect.

We have interpreted our findings in the context of the age-related decline in cognitive control mechanisms such as working memory updating (e.g., Trewartha et al. 2013). However, it remains an open question as to whether age changes in basic motor processes also contributed to the older adults' inability to speed their movements when necessary. It has been well documented that advanced age is associated with general movement slowing in the context of reaching and grasping (Bennett and Castiello 1994; Carnahan et al. 1998) and continuous movements (Greene and Williams 1996). Fast twitch muscles are significantly reduced with advanced age (Lexell 1996), which affects voluntary strength and capability of full muscle activation in older adults (Yue et al. 1999), and muscle loss is one of the multiple factors that contribute to motor decline in healthy aging (Ketcham and Stelmach 2001).

Given that aging is associated with significant declines in motor functioning, it is difficult to dissociate the behavioral effects related to motor aging from those related to cognitive aging. To avoid this issue, our approach in the present work was to simulate the effects of cognitive aging in healthy young participants, who are presumably at peak motor functioning. We paired our previously used motor reprogramming task with a concurrent cognitive task requiring working memory updating. A comparison sample of older adults underwent the same protocol. We reasoned that if, under dual-task conditions, younger adults demonstrated reduced ability to flexibly adapt to conflicting conditions, this would support the interpretation that our previously observed age differences were due to reduced cognitive capacity more so than reduced motor abilities. We hypothesized that under full-attention conditions, younger adults would demonstrate longer planning times when facing conflicting stimuli, but faster executions of finger movements to compensate for longer planning times, as compared to highly practiced motor responses. We also hypothesized that with the addition of a concurrent working memory load, younger adults' ability to compensate for longer planning times would decrease. Finally, we expected older adults to show no evidence of compensatory hastening in either their single-task or dual-task motor performance.

Methods

Participants

Nineteen younger adults (19–29 years; female $n = 17$, male $n = 2$) and 14 older adults (63–74 years; female $n = 8$, male $n = 6$) were tested. To control for the effects of musical experience on task performance, all participants were selected to have less than 3 years of musical experience and no practice in the last 10 years. Participants were right-handed and were free from any medication, neurological disorder, or injury that could affect sensory, motor, or cognitive functioning. Young participants were recruited from the Concordia University Participant Pool and received course credits. Older participants were recruited from a preexisting senior participant database at Concordia University and received a small honorarium. All participants provided written informed consent prior to the testing session, in compliance with the Concordia University Human Research Ethics Committee.

Materials and apparatus

Neuropsychological measures

To assess whether groups differed on basic cognitive abilities, a battery of neuropsychological tests was administered. The Digit Symbol Substitution subtest of Wechsler Adult Intelligence Scale IV (Wechsler 2008) was used to measure processing speed, with the total number of correct items completed as the dependent measure. The Stroop test (adapted from Spreen and Strauss 2001), forms C and CW, was administered to assess controlled attention. The difference between the seconds per item completed on the Congruent and Incongruent conditions was used as a dependent measure. To assess task switching, the Comprehensive Trail Making Test (Reynolds 2002) was administered. The difference between the complex and simple task conditions was used as the dependent measure.

Cognitive task

For the concurrent cognitive task, we used the Serial Sevens Test (SST), a measure of attentional control with a relatively high processing load (Lezak et al. 2004). Serial subtraction has been commonly used as attention-demanding cognitive load in gait, balance, and aging studies (e.g., van Iersel et al. 2007; Springer et al. 2006; Yogev et al. 2005). The SST was given to our participants to occupy working memory and mimic age-related reductions in the cognitive capacity available for motor performance. In the current experiment, the SST was performed without auditory or visual cues, thereby placing continuous demands on working memory and updating. Throughout the experiment, participants completed two blocks of single cognitive tasks and one block in which they performed the cognitive and motor tasks concurrently (dual-task condition). Each cognitive block consisted of six trials. At the start of each trial, participants were told a randomly generated number between 86 and 99, and instructed to subtract 7 from the given number, and continue subtracting 7 from successive answers until told to stop. The duration of each trial was

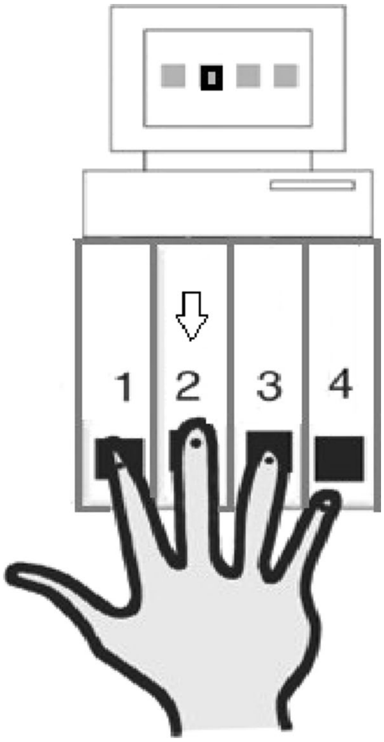

Fig. 1 Illustration of the computer–keyboard setup used for the motor task. In order to record the movements of the fingers, six motion capture cameras were placed in front of the computer–keyboard apparatus. The *arrow* and the *dark square* on the illustration indicate the correspondence between the *finger* and the *square*. *Numbers* on the keys are used for illustration purposes only

16 s, matching the duration of each motor sequence trial. Participants' responses were reported verbally and recorded by hand. Cognitive task performance was defined as the percentage of correctly subtracted responses per trial. The same cognitive task was performed under single- and dual-task conditions.

Motor sequence task

We used a very similar finger-sequencing paradigm to the one described by Trewartha et al. (2009) for both single- and dual-task conditions. Participants were instructed to reproduce sequences of key presses that were cued by visual stimuli presented on a computer monitor using four fingers of their right hand (Fig. 1).

A custom-built keyboard with four keys was used for this task. The keyboard was designed to mimic the physical characteristics (height, length, width, resistance, spacing) of a standard MIDI keyboard (Yamaha PSR-290). Pieces of Velcro were attached to the keys as tactile cues for finger positioning. The visual stimuli consisted of four squares ($3'' \times 3''$) that were displayed horizontally on the computer monitor ($17''$ flat screen). The squares mapped in a one-to-one manner onto each of four fingers (from left to right) and changed color from gray to pink to cue the participant to respond with a particular finger. Each visual cue was shown for 800 ms and replaced by the next cue, so that each trial (20 stimuli) lasted for a total of 16,000 ms. There was a pause between each trial of 3,000 ms.

A 3D motion capture system (VZ3000; Phoenix Technologies, Burnaby, British Columbia, Canada) was used to record the *x*-, *y*-, and *z*-positions of each finger with an acquisition rate of 50 Hz and one light-emitting diode (LED) marker attached to each relevant finger nail. The stimulus presentation software (Inquisit 3.0.4.0 Millisecond Software LLC. Seattle, WA) was used to send the stimulus triggers that were activated by each key press to a data acquisition (DAQ) card (NI USB-6221 BNC, National Instruments Inc.). A program written in C# on version 1.1 of the Microsoft.NET Framework was used to synchronize the motion capture data with the visual stimuli.

Motor task design and procedure

The motor sequence task consisted of a familiarization phase and an experimental phase. In the familiarization phase, the goal was to confirm that participants were comfortable with the apparatus and stimuli. In the experimental phase, the goal was to first build up the prepotent sequential response and then assess motor reprogramming when the sequences were perturbed. Accordingly, each motor performance block in the experimental phase was split into Learning and Test phases. To assess the effects of cognitive load, participants were presented with separate blocks of single- and dual-task trials.

Familiarization phase

The participants were first introduced to the motor apparatus by completing a simple 24-element fixed sequence (1, 2, 3, 4, 1, 2, 3…). To practice responding to unpredictable sequences, they then completed 10 trials of 10 random elements each. In keeping with Trewartha et al.'s (2009) procedures, participants had to achieve 85 % accuracy on the 10 random trials before advancing to the experimental phase. All participants met this criterion.

Experimental phase

Participants completed a block of single cognitive trials followed by a block of single motor trials, or vice versa. The order of the motor and cognitive single blocks was counterbalanced across participants. Following the single blocks, the dual-task condition was administered. Finally, another block each of single cognitive and single motor trials was administered to reduce the potentially confounding effects of practice and fatigue. The first trial of each block in the experimental phase was not scored to reduce the influence of transitioning from one task to another in the data.

Each motor block was subdivided into six Learning and six Test trials. In each Learning trial, participants were visually cued to produce repeated pairs of the same key presses (e.g., 2, 1, 2, 1…), totaling 20 stimuli per trial. Participants were assigned the same prepotent pairs for the entire experiment, and this assignment was counterbalanced across participants in each age group. The Test trials contained a mixture of prepotent and conflicting pairs. Conflicting response pairs started with the first key press of the overlearned pair (e.g., "2") followed by a conflicting cue (e.g., "3" instead of "1"). Within each conflict transition, the first stimulus was the same as in the prepotent transition, but the second stimulus was unexpected, thus when responding to the unexpected stimuli participants had to suppress their overlearned behavior. Each Test trial contained two pairs of prepotent transitions (e.g., 2, 1…2, 1…), two pairs of conflict transitions (e.g., 2, 3…2, 3…), and 12 random filler stimuli (e.g., 4). The position of filler stimuli was counterbalanced across trials.

General procedure

Participants first completed a written consent form and the battery of neuropsychological tests. They then completed the familiarization and experimental phases of the motor sequence task. They were allowed short breaks in between each block. Finally, participants were debriefed and given course credit or an honorarium. Each session lasted approximately 90 min.

Data analyses

Motor task preprocessing

The second key press of each pair was used to calculate the measurements for prepotent and conflict transitions. For each transition type, we calculated accuracy as the percentage of correct key presses out of the total number of key presses. If the key presses were made to the appropriate stimuli within the interstimulus intervals, then responses were considered correct. Global response times (RT) were defined as time from stimulus onset to the completion of the key press for correct responses. We further decomposed global RT into planning and execution times to better understand the relative contributions of cognitive (conflict detection, reprogramming) and motor (movement execution) processes.

The kinematic data were analyzed using a custom-written function in MATLAB (2007a, The MathWorks Inc., Natick, MA). To extract planning (stimulus onset to movement onset) and execution time (movement onset to minimum key depression) parameters from the motion capture data, we identified the finger movement initiations and key-press terminations using a peak identification algorithm. To control for individual and age differences, each participant's own performance was used as a baseline in all algorithms. The identification algorithm was based on the rate of change from the baseline in the vertical (z) dimension of the signal. To calculate the baseline, the data were centered around zero by means of low frequency removal and subtraction of a robust least squares fit of the data from the raw signal (see Trewartha et al. 2009).

For all cognitive and motor task variables, we used a 3 *SD* cutoff to define outliers within each age group. No such outliers were found. To analyze the cognitive accuracy data, we used a mixed factorial ANOVA with cognitive load (single-task vs. dual-task) and age group (young—YAs, older—OAs) as factors. To analyze motor task performance, four dependent variables (accuracy, global RT, planning time, and execution time) were subjected to a 2 × 2 × 2 cognitive load (single- vs. dual-task) × transition type (prepotent vs. conflict transitions) × age group (YAs vs. OAs) mixed factorial ANOVA design. Bonferroni corrections were applied to all post hoc contrasts. As done previously (Trewartha et al. 2009, 2011), we compared prepotent transitions during the learning phase with conflict transitions during the test phase, reasoning that the prepotent transitions from the learning phase represent optimal performance that is free of interference from conflicts. Planning times and execution times were calculated for the correct key presses only.

Results

The main goal of this study was to explore the involvement of executive control mechanisms in adaptation or reprogramming of fine motor responses. As a preliminary check, we examined the neuropsychological data for outliers. Performance on all neuropsychological tests was within age-normative ranges (see Table 1).

Cognitive accuracy

Mean values and standard deviations for single- and dual-task performance on the SST are shown in Table 2. The mixed factorial ANOVA comparing age group (younger adults vs. older adults) x attentional load (single-task vs. dual-task) revealed a significant main effect of attentional load, $F(1, 31) = 17.84$, $p < .001$, $\eta^2 = .365$ ($M_{\mathrm{YA}} = 4.68$, SEM = 3.78; $M_{\mathrm{OA}} = .37$, SEM = .28). There was a statistical trend toward a significant interaction between attentional load and age group, $F(1, 31) = 3.36$, $p = .077$,

Table 1 Means and standard deviations for background variables

	Younger adults	Older adults
Age (years)*	21.58 (2.32)	68.14 (3.96)
CTMT simple versus complex (s)*	5.61 (5.91)	4.45 (3.57)
Stroop interference (s/item)*	0.54 (0.22)	0.76 (0.18)
Digit symbol*	92.63 (15.55)	68.50 (14.66)

Values reflect mean scores per group with standard deviations shown in parentheses. Comprehensive Trail Making Test (CTMT) score is based on the difference between completion times (s) in the complex and simple task conditions; the color Stroop test score is based on the difference between the seconds per item completed on the Congruent and Incongruent conditions; Digit Symbol values of the Wechsler Adult Intelligence Scale (WAIS-IV) are based on the total number of symbols correctly completed in 120 s

* $p < .001$

$\eta^2 = .098$. The age group effect was not statistically significant, $p = .374$. Current results suggest that participants did not reach a performance ceiling or floor with respect to the total number of correctly subtracted numbers, meaning that the task was relatively difficult for both age groups and created adequate loading on working memory (see Table 2). Similar to other studies (e.g., Fraser et al. 2007, 2010), the dual-task effects were observed primarily in the motor task. This lack of an age group by attentional load interaction in the cognitive data allows for a clearer interpretation of any age effects in the movement data.

Key-press accuracy

We first confirmed that all participants were more than 85 % accurate on the motor task by the end of the practice phase. Participants' motor accuracy during simple practice ranged from 90 to 98 %, suggesting that all participants began the experimental phase at a relatively equal skill level. In the omnibus analysis of test phase accuracy scores (see Table 2), a significant main effect of cognitive load was observed, $F(1, 31) = 4.61$, $p = .04$, $\eta^2 = .13$, such that overall participants were more accurate on the motor task under single-task conditions ($M = .858$, SEM $= .026$) than dual-task conditions ($M = .794$, SEM $= .027$). All other main effects and interactions were nonsignificant ($ps \geq .135$). The lack of significant age effects or interactions in the motor accuracy data reflects the very accurate performance on the motor task overall, replicating earlier work (Trewartha et al. 2009).

Global response time

We next examined global response times to assess whether younger adults were more efficient than older adults at motor reprogramming overall. Mean values and standard deviations for single- and dual-task performance are shown in Table 2. We conducted an ANOVA using the mean reaction time (RT) in milliseconds. The age group x attentional load x transition type mixed factorial ANOVA revealed a significant main effect of attentional load, $F(1, 31) = 26.23$, $p < .001$, $\eta^2 = .458$, such that performance on the motor task was longer under dual-task conditions than under single-task conditions. A significant main effect of transition type was observed, $F(1, 31) = 106.13$, $p = <.001$, $\eta^2 = .774$, showing that reaction time for conflict transitions was longer than for prepotent transitions. A trend toward statistical significance was observed in the interaction of attentional load and transition type, F(1,

Table 2 Cognitive accuracy for the Serial Sevens task, motor accuracy, and motor task global response time during testing blocks for single-task and dual-task conditions for younger and older adults

Condition	Younger adults (*SD*)		Older adults (*SD*)	
Cognitive task accuracy (%)				
Single	79.39 (1.67)		76.55 (2.64)	
Dual	42.53 (1.33)		33.00 (1.86)	
	Prepotent	Conflict	Prepotent	Conflict
Motor task accuracy (%)				
Single	83.90 (0.05)	93.60 (0.04)	82.10 (0.06)	83.40 (0.04)
Dual	82.50 (0.04)	87.00 (0.05)	76.80 (0.05)	71.20 (0.06)
Motor task global RT (ms)				
Single	352.86 (22.94)	457.54 (10.68)	357.43 (26.72)	562.60 (12.45)
Dual	399.11 (24.12)	519.15 (15.84)	510.40 (28.09)	612.04 (18.45)

Accuracy for the Serial Sevens task and motor task = percentage of total correct responses. Motor task global response time in milliseconds. Standard deviations are shown in parentheses

31) = 3.31, $p = .078$, $\eta^2 = .097$. This two-way interaction was qualified by a significant interaction of attentional load, transition type, and age group, $F(1, 31) = 6.02$, $p = .020$, $\eta^2 = .163$. All other main effects and interactions were nonsignificant ($ps \geq .12$).

To explore the above three-way interaction, we conducted separate ANOVAs for the two attention conditions (single- and dual-task) with age group and transition type as factors. Under single-task conditions, a statistically significant main effect of age group was observed, $F(1, 31) = 6.59$, $p = .015$, $\eta^2 = .175$, showing larger response time for OAs ($M = 460.02$ ms, SEM = 16.21) than for YAs ($M = 405.20$ ms, SEM = 13.91). A significant main effect of transition type was observed, $F(1, 31) = 80.42$, $p = < .001$, $\eta^2 = .722$, showing that responses were slower for conflict ($M = 510.07$ ms, SEM = 8.20) than for prepotent transitions ($M = 355.15$ ms, SEM = 15.61). Importantly, the interaction of age group and transition type was also statistically significant, $F(1, 31) = 8.46$, $p = .007$, $\eta^2 = .214$, such that OAs had longer response times than YAs for the conflict transitions, $t(31) = -6.41$, $p = <.001$, whereas no age differences were found for the prepotent transitions, $t(31) = -.13$, $p = .898$. This indicated that despite age-equivalent baseline performance on the prepotent transitions, the presence of conflict was much more challenging for OAs than YAs.

Under dual-task conditions, we observed a statistically significant main effect of age group, $F(1, 31) = 15.96$, $p = <.001$, $\eta^2 = .34$, where OAs showed slower response times ($M = 561.22$ ms, SEM = 19.39) compared to YAs ($M = 459.13$ ms, SEM = 16.65). Similarly, the transition type main effect was also significant, $F(1, 31) = 37.51$, $p = <.001$, $\eta^2 = .547$, indicating that response time across prepotent transitions was faster ($M = 454.75$ ms, SEM = 18.51) than across conflict transitions ($M = 565.60$ ms, SEM = 12.16). However, no significant interaction was observed, $p = .615$.

The above results suggest that under single-task conditions, OAs were disproportionately worse than YAs when conflict transitions were presented despite responding as quickly as YAs during prepotent transitions. The absence of a significant age group x transition type interaction under dual-task conditions suggests that YAs response reprogramming performance became more similar to that of OAs. To further investigate the efficacy of motor reprogramming processes as a function of aging, the key-press data were decomposed into cognitive and motor components (planning and execution times) and examined separately.

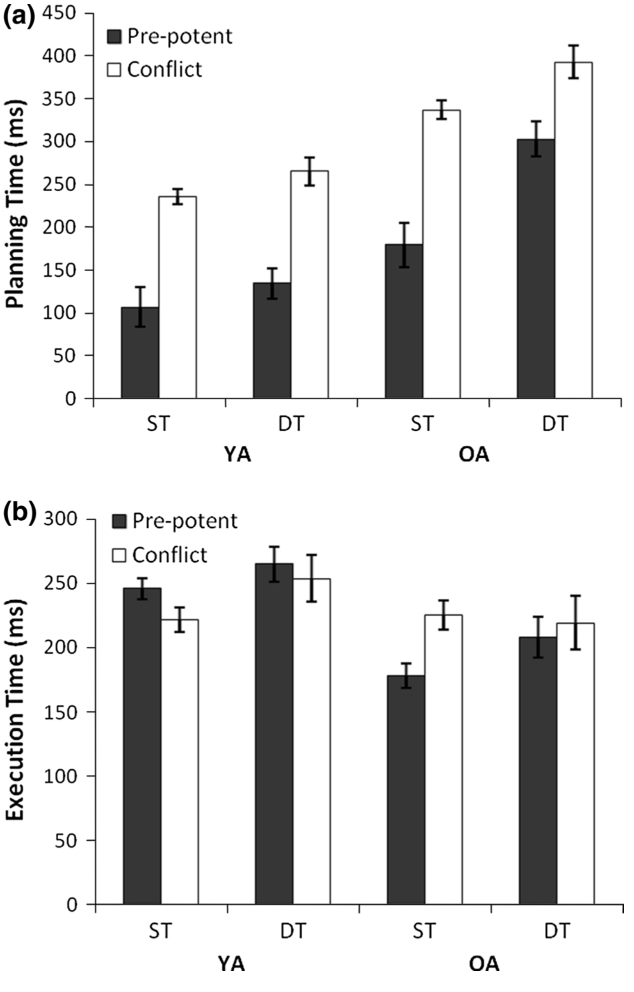

Fig. 2 Mean planning time (**a**) and execution time (**b**) of key presses for prepotent transitions during learning blocks and conflict transitions during test blocks for single-task and dual-task conditions per age group. *Error bars* represent ± 1 standard error of the mean. *ST* single-task, *DT* dual-task, *Acc* accuracy, *PT* planning time, *ET* execution time

Planning time

A similar ANOVA was conducted to evaluate the effects of age, cognitive load, and transition type on planning time (Fig. 2a). We expected OAs to exhibit longer planning times than YAs, and to be disproportionally affected by the cognitive load manipulation. As predicted, we observed a significant main effect of cognitive load, $F(1, 31) = 27.31$, $p < .001$, $\eta^2 = .468$, such that overall planning time was longer under dual-task conditions ($M = 273.90$ ms, SEM = 9.62) than single-task conditions ($M = 214.72$ ms, SEM = 9.27). Further, a significant main effect of transition type was observed, $F(1, 31) = 98.51$, $p < .001$, $\eta^2 = .761$, such that planning times were longer for conflict transitions ($M = 307.78$ ms, SEM = 8.18) than prepotent transitions ($M = 180.83$ ms, SEM = 11.37). Also as predicted, a significant interaction of cognitive load and age group was observed, $F(1, 31) = 7.24$, $p = .011$, $\eta^2 = .189$. Post hoc contrasts indicated that YAs were unaffected by cognitive load, $F(1, 18) = 3.28$, $p = .087$, $\eta^2 = .154$, whereas OAs were substantially affected, $F(1, 13) = 34.65$, $p < .001$, $\eta^2 = .727$, such that planning times were longer under dual-task ($M = 347.80$ ms, SEM = 15.92) than single-task conditions ($M = 258.13$ ms, SEM = 6.38). All other main effects and interactions were nonsignificant ($ps \geq .181$).

Execution time

A final ANOVA was carried out using the execution time data (Fig. 2b). Based on the assumption that a concurrent cognitive load would mimic the effects of cognitive aging in the YAs, we predicted that under dual-task conditions, YAs would be less able to hasten their execution times during conflict transitions, relative to their single-task performance. The analysis revealed a marginally significant main effect of cognitive load, $F(1, 31) = 3.43$, $p = .074$, $\eta^2 = .099$, such that execution times were longer under dual-task ($M = 236.27$ ms, SEM = 10.94) than under single-task conditions ($M = 217.89$ ms, SEM = 5.77). We also found a significant interaction of transition type and age group, $F(1, 31) = 8.19$, $p = .007$, $\eta^2 = .209$, which, importantly, was qualified by a significant interaction of cognitive load, transition type, and age group, $F(1, 31) = 6.25$, $p = .018$, $\eta^2 = .168$. All other main effects and interactions were nonsignificant ($ps \geq .25$). To examine the 3-way interaction, we conducted post hoc contrasts between transition types for each age group. Under single-task conditions, YAs' execution time for conflict transitions was significantly shorter than for prepotent transitions, $t(18) = 2.66$, $p = .016$, replicating previous work (Trewartha et al. 2009). Importantly, under dual-task conditions, YAs' execution times for conflict transitions and prepotent transitions were not significantly different, $t(18) = 0.85$, $p = .404$, as we had predicted.

Unlike the YAs, the analysis of the OAs execution time data revealed an inability to speed up their movements during conflict transitions even under single-task conditions. Instead, OAs exhibited significantly slower execution times on conflict transitions than on prepotent transitions, $t(13) = -3.69$, $p = .003$. Furthermore, in the dual-task condition, similar to YAs, OAs showed comparable execution times in conflict and prepotent transitions, $t(13) = -0.61$, $p = .553$.

Discussion

The primary purpose of this study was to investigate the role of executive control processes in response reprogramming using a dual-task paradigm. In our previous studies (Trewartha et al. 2009, 2011, 2013), we observed that younger adults, but not older adults, sped up their movement times to compensate for longer planning times when unexpected stimuli were encountered. To disentangle the relative contributions of cognitive and motor aging, we used a simulation approach to selectively limit the cognitive resources of younger adults available during motor task performance, while leaving motor capacity intact. The principle finding of this study is that under full-attention conditions, younger adults reduced execution time of their finger movements for conflict compared to prepotent transitions, but with the addition of a concurrent working memory load, this compensatory hastening effect was reduced. In contrast, older adults did not show any evidence of compensatory hastening. Together, our results suggest that age-related declines in response reprogramming are highly related to cognitive control resources and independent of declines in motor functioning in aging.

The current behavioral findings fit into the general pattern of results observed in our recent work (Trewartha et al. 2011, 2013), which showed compensatory hastening (faster execution time in conflict transitions than in prepotent transitions) for younger adults, but slower execution in the older adults on conflict transitions than on prepotent transitions. We note that our current findings differ slightly from those of Trewartha et al. (2009), where older adults spent the same amount of time executing movements for both prepotent and conflicting responses under single-task conditions. To determine how representative this currently observed slowing pattern was, we visually inspected the individual condition means of the older participants. We found only three participants who showed numerically longer execution times in the conflict transitions relative to prepotent transitions. The majority of our older participants seemed to follow the pattern observed in Trewartha et al. (2009). Moreover, there did not seem to be any systematic differences in those three participants in terms of their chronological age or neuropsychological profiles. Overall, these findings replicate well the older adult data from different versions of this paradigm in that in no cases did we observe systematic hastening in the same way as has been observed in multiple samples of younger adults (Trewartha et al. 2009, 2011, 2013).

Our present results complement recent findings from our group in which we combined the same kinematic measurement of response reprogramming with event-related potential (ERP) recordings (Trewartha et al. 2013). There, younger adults produced larger P3b amplitudes (central posterior P300 components) than older adults in response to the conflict transitions, and these amplitudes correlated with the magnitude of the hastening effect. In other literature, the P3b component has been associated with processes contributing to updating working memory (Polich 2007). On a behavioral level, the anticipated (prepotent) motor program must be rapidly revised, or updated, in order to correctly respond to conflict stimuli. Given that our concurrent cognitive task (SST) also requires memory updating (participants continually subtract 7 from the most recent product), the dual-task condition likely created competition for similar updating processes used during compensatory hastening in the motor task. To generalize these findings, future work may involve other concurrent updating tasks such as the n-back working memory task (Dobbs and Rule 1989).

The current study extends what is known about aging and response inhibition in several important ways. Beyond replicating other work that shows age-related declines in response inhibition (Kramer et al. 1994; Williams et al. 1999), ours is one of few studies employing motion tracking methods to isolate planning and motor execution times (Potter and Grealy 2006). In Potter and Grealy's study, prepotent grasping movements were occasionally interrupted by a requirement to revise the grasping trajectory. Those researchers reported disproportionately delayed planning time in older adults under conflicting conditions; however, they did not report any evidence of compensatory hastening, perhaps because the movements in their task were more novel than in ours.

Our findings also extend current knowledge about the interdependence of sensorimotor and cognitive functions in old age by identifying a potential source of cognitive–motor interference at the process level (i.e., working memory updating). Observations of age-related increases in dual-task costs during sensory or motor performance suggest that advanced age is associated with an increase in shared resources (e.g., Li and Lindenberger 2002; Schneider and Pichora-Fuller 2000). When faced with increased task complexity, such as concurrent task performance, older adults may experience competition for scarce resources, hence greater dual-task costs. Our findings implicate working memory updating as a candidate "scarce resource" that is shared across tasks in the current study. These results fit broadly with functional neuroimaging studies of coordinated movements (Heuninckx et al. 2005) and response inhibition (Nielson et al. 2002) that show age-related increases in recruitment of frontal lobe regions associated with cognitive control processes (for a review, see Seidler et al. 2010). At the same time, because cognitive control processes decline in healthy aging, the potential for compensatory cognitive recruitment during motor task performance is likely to be limited, as demonstrated behaviorally in the present study. Another possibility to consider in future work is that present results are due to the weakened connection or integration between cognitive and motor processing areas (Salek et al. 2011), rather than the age-related decline in frontal lobe functions.

In summary, the current results extend our understanding of the motor–cognitive interaction associated with aging and, more specifically, the processes underlying age differences in response reprogramming. Specifically, our results suggest that working memory updating processes contribute to motor reprogramming and successful compensatory hastening of movement times, in line with recent electrophysiological evidence (Trewartha et al. 2013). Taken together, the findings generally suggest that in addition to diminished neuromuscular capacity, age-related declines in response reprogramming may be strongly linked to reduced cognitive capacity.

Conflict of interest The authors declare that they have no conflict of interest.

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