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Dual-Task Performance Reveals Increased Involvement of Executive Control in Fine Motor Sequencing in Healthy Aging

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The purpose of the current study was to examine the role of executive control in fine motor sequencing using a motor-cognitive dual-task paradigm. Younger and older adults performed a sequential tapping task separately and concurrently with a semantic judgment task (Experiment 1) and a mental arithmetic task (Experiment 2). Experiment 1 established that under low cognitive load, older adults were slower and less accurate in sequential tapping than younger adults. Load was manipulated in Experiment 2, and across mental arithmetic difficulty levels, older adults were less accurate in sequential tapping when performing mental arithmetic than younger adults. At the highest difficulty level, both groups suffered performance costs. In line with gross motor research, these findings suggest a role for executive functions in fine motor performance in old age.

Key Words: Dual task—Executive Function—Fine motor sequencing.

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HEALTHY aging is associated with declines in both motor (Ketcham & Stelmach, 2001; Krampe, 2002) and cognitive control functions (Kramer & Madden, 2008; Verhaeghen & Cerella, 2002). In addition, motor and cognitive functions appear to become more strongly correlated with increasing age, suggesting an increased interdependence between the two domains (Baltes & Lindenberger, 1997; Li & Lindenberger, 2002). Other evidence of this interdependence comes from motor-cognitive dual-task research. The majority of such evidence involves simultaneous gross motor and cognitive task performance, showing in many cases greater dual-task costs (DTCs) for older adults compared with younger adults (for review, Woollacott & Shumway-Cook, 2002). This pattern has been interpreted to mean that motor performance requires more cognitive resources in old age. The coordination of simultaneous task performance has been considered a component of the executive system (Baddeley, 2002), which shows age-related decline (Kramer & Madden). The involvement of executive control in gross motor performance has recently been shown using measures of gait and balance (Mendelson, Redfern, Nebes, & Jennings, 2010; Yogev-Seligmann, Hausdorff, & Giladi, 2008). Fewer studies have explored the possibility of age-related increases in executive involvement during fine motor performance (e.g., Albinet, Tomporowski, & Beasman, 2006). Therefore, our goal was to examine the role of executive control in fine motor performance using a motor-cognitive dual-task paradigm.

In both gross and fine motor dual-task research, several factors have been suggested to account for age differences in dual-task performance (Krampe, 2002; Woollacott & Shumway-Cook, 2002). Some of the factors that have been implicated include a general slowing, declines in executive function, type of tasks combined, and physiological arousal. In the case of executive function, it is well documented that executive control processes may be invoked during motor tasks when adaptive online control is needed (Ble et al., 2005; Krampe; Woollacott & Shumway-Cook; Yogev-Seligmann et al., 2008). Kahneman (1973) maintained that all individuals have a limited capacity to process information and that they should be able to process two tasks at once as long as the two tasks do not exceed the individual's limited capacity or processing resources. If the tasks demands exceed an individual's capacity, then performance on one or both tasks can deteriorate (Kahneman). Given what is known about declines in executive and motor processes, it is not surprising that age differences are predicted in cognitive-motor dual tasks.

Despite this prediction, a growing number of walking and postural control studies have found that results vary depending on the tasks combined and the cognitive load of the component tasks (i.e., Huxhold, Li, Schmiedek, & Lindenberger, 2006; Li, Lindenberger, Freund, & Baltes, 2001; Lövdén, Schäefer, Pohlmeyer, & Lindenberger, 2008). For example, in a study of mildly challenging dual-task treadmill walking, younger and older adults showed cognitive dual-task facilitation and motor DTCs, which were more pronounced in older adults (Fraser, Li, DeMont, & Penhune, 2007). A follow-up experiment that included a cognitive load manipulation demonstrated that both age groups incurred costs in both domains and were negatively affected by the increase of cognitive difficulty (Li, DeMont, Penhune, Fraser, & Abbud, 2008). Interestingly, the younger adults were able to adjust their stride length to accommodate the increase in cognitive demands (Abbud, Li, & DeMont, 2009). The changing pattern of DTCs across experiments suggests that the choice of

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Table 1. Descriptive Statistics of the Samples.

	Experiment 1		Experiment 2	
	Younger	Older	Younger	Older
Age	23.10 (3.16)	67.67 (4.33)	21.10 (2.15)	70.37 (4.96)
Years of Education	15.95 (2.09)	14.81 (4.18)	14.95 (0.89)	15.11 (3.26)
Digit Symbol	88.60 (13.82)*	73.85 (18.23)*	69.90 (19.10)*	56.42 (14.19)*
Trails B-A	24.42 (12.68)*	59.81 (32.92)*	27.50 (15.81)*	46.47 (30.75)*
Digits Forward	7.35 (1.04)*	6.48 (1.08)*	7.15 (1.09)	6.68 (1.11)
ERVT	—	—	7.93 (4.46)*	13.03 (4.94)*
WAIS math-raw	—	—	13.30 (2.92)	13.95 (2.90)
WAIS math-scaled	—	—	10.35 (2.08)	10.63 (2.81)

Notes: Mean values and standard deviations (in brackets) presented. Years of education = total number of years of formal education; Digit Symbol value based on the total number of symbols correctly completed in 120 s; Trails B−A = time to complete Trails test A minus the time to complete Trails test B; Digits forward value based on the total number of items recalled. ERVT and WAIS math subtest were administered in Experiment 2. ERVT = extended range vocabulary test; WAIS = Wechsler Adult Intelligence Scale III.

*$p < .05$ for age group comparisons.

tasks and the cognitive load of the tasks chosen can have a large impact on the resulting pattern of performance. An added dimension of walking dual-task research is the influence of postural threat (Brown, Shumway-Cook, & Woollacott, 1999). It has been argued that older adults might adopt a "posture-first" principle, prioritizing walking and balance above all other tasks in order to avoid a fall (Woollacott & Shumway-Cook, 2002).

The potential confound of postural threat influencing age differences in dual-task performances is removed in fine motor dual-task research. In addition, motor measures (particularly fine and complex motor measures) have been shown to be as accurate as standard cognitive measures in delineating cognitively normal versus cognitively impaired older adults (mild cognitive impairment and mild Alzheimer's disease; Kluger et al., 1997). This close relationship between cognitive tasks and fine motor tasks in aging has been explored with the dual-task paradigm (Crossley & Hiscock, 1992). Using a within-subjects manipulation of cognitive load, Crossley and Hiscock compared young, middle-aged, and older adults on their performance of a simple tapping task with a concurrent cognitive load. At the highest level of cognitive difficulty, there were no age differences in cognitive performance, but older adults had larger decrements in simple tapping rates in comparison with younger and middle-aged adults. This simple tapping study demonstrates age differences in fine motor dual-task performance that increase with cognitive load. Would the same be true in the dual-task performance that involves a fine motor sequence? Or would the increased complexity of sequential tapping increase the overall cognitive load and increase age differences? One study that directly contrasted simple and sequential tapping with a cognitive load (speech production) found age group differences in DTCs only for sequential tapping (Kemper, Herman, & Lian, 2003). This finding suggests that sequential tapping places an added load on older adults in comparison with simple tapping.

The few published studies on aging and dual-task fine motor performance suggest that increasing the complexity of the motor task is more detrimental to older adults than young. However, the literature does not indicate if a similar pattern will emerge when cognitive complexity is varied. The current study was designed to address this gap in the literature. Our approach was to manipulate cognitive complexity in cognitive-sequential tapping task pairings in order to examine the possibility of increasing executive involvement in fine motor performance. Given the evidence for increased age-related involvement of executive functions in the gross motor literature, we began with the prediction that there would be age-related increases in motor DTCs. Such a finding would extend the existing body of research on the increasing role of cognition in motor performance.

Experiment 1

Method

Participants.—Twenty younger adults (20–31 years) and 21 older adults (60–75 years) participated in the experiment. Younger adults were recruited through Concordia Psychology's undergraduate participant pool and the older adults were recruited from a preexisting participant database. Younger adults received class credits for their participation, and older adults received a small honorarium. All participants were right handed, fluent in English, had normal or corrected vision, had never suffered a stroke, and were screened for medical conditions (e.g., Parkinson's disease, severe arthritis) and medications that would affect their movement. Individuals who reported hearing difficulties or who wore a hearing aid were excluded. The Forward Digit Span and the Digit Symbol Substitution Test of Wechsler Adult Intelligence Scale III (WAIS; Weschler, 1997), as well as the Trail Making Test (A & B; Spreen & Strauss, 1998), were administered to assess short-term memory, processing speed, and task switching, respectively. All participants were within a normal range for their age on these tests. Descriptive statistics for each group are presented in Table 1. All procedures were approved by the Concordia University Human Research Ethics Committee.

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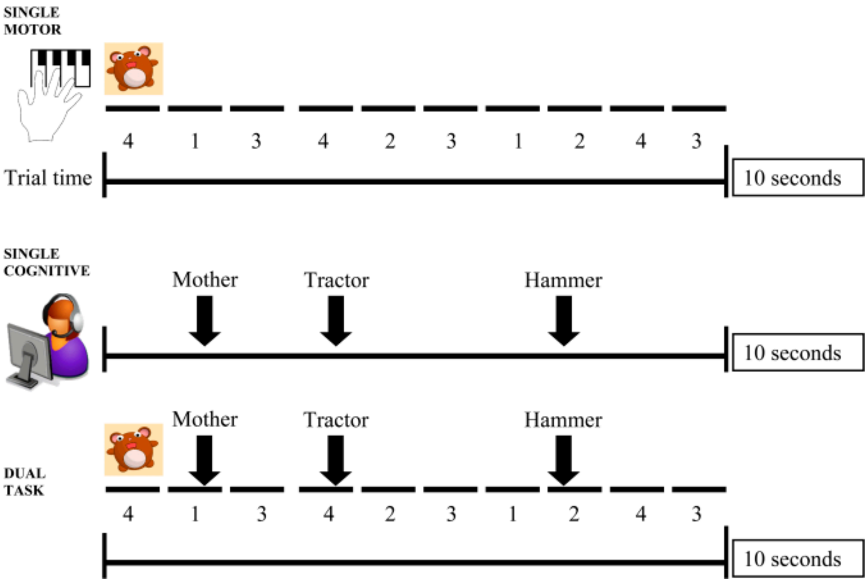

Figure 1. Graphic of the trials: single motor, single cognitive, and dual task. Dashed lines represent taps. Numbers under the dashed lines represent the key the participant had to tap. The fingers that corresponded to the keys were index = 1, middle = 2, ring = 3, and pinkie = 4. The solid line represents the time line of each trial (10 s). Arrows represent the word stimuli that were presented auditorially (i.e., mother, tractor, hammer). *Note.* Word stimuli were presented at random intervals during the trial and a trial could contain one, two, or three words.

Materials.—Fine motor task. The fine motor task was a modified version of the multifinger sequence task (MFST) used in Fraser, Li, and Penhune (2009). The MFST is a serial reaction time (RT) task, in which a visual stimulus presented in one of four squares on a computer screen and participants tap in response to the stimulus with the four fingers of their right hand on four keys of a piano-like keyboard. The visual stimuli were presented repetitively in fixed 10-tap sequence (4-1-3-4-2-3-1-2-4-3) or in random 10-tap sequences. For the purposes of the current dual-task experiment, only the repeating sequence type was used. For each tap in the repeating sequence, the intertap interval was set at 1,000 ms, in which the stimulus stayed on the screen for 600 ms and disappeared for 400 ms. Therefore, the duration of a motor trial was 10 s. In the previous experiment (Fraser et al., 2009), age equivalence in the performance of the sequence was achieved after 10 presentations of the sequence; therefore, for the current experiment, 14 trials were presented during practice to ensure age equivalence prior to the test phase. Thirty trials were presented in each of the four test runs. For both the practice and the test sessions, participants completed half of the motor trials in isolation (single-task block) and half with the semantic task (dual-task block). An example of each trial type (single motor, single cognitive, and dual task) is presented in Figure 1.

The visual stimulus in the sequence consisted of a 4.5-cm^2 cartoon animal (i.e., “Rolly the Hamster”) that was programmed in C-Sharp and shown on a 19-inch Dell desktop monitor. Each stimulus was displayed in one of four horizontally presented colored 5-cm^2 frames that stayed on the screen for the total duration of each trial. The participants responded to the stimuli on an M-Audio O2 Midi Controller piano keyboard. Participants were instructed to “catch the animal” by placing the four fingers of their right hand (i.e., index, middle, ring, and pinkie) on four marked keys, and the keyboard recorded the accuracy and RT of each key press.

Cognitive task: semantic judgments. For this task, participants were presented auditorially with word stimuli at random time intervals and they were asked to judge if the word they heard was living (e.g., mother) or nonliving (e.g., chair). Word stimuli used in the current experiment were the same as those presented in Fraser and colleagues (2007). The trial time structure mimicked the motor trials, such that each trial lasted 10 s (see Figure 1). Furthermore, all participants had a practice session in which they judged 30 words and four test sessions that contained 60 words each. Half of the words were presented in isolation (single-task block) and half were presented with the fine motor task (dual-task block). Each list included an equal number of living and nonliving words to judge. The digitized words consisted of two-syllable high-frequency distinct nouns (written frequency less than or equal to one word per million; Kuçera & Francis, 1967) and were spoken in a female voice. To minimize the predictability of the presentation of the words, a trial could contain one, two, or three words. The minimum interstimulus interval (ISI) for each word presentation was 1,500 ms and the maximum was 7,000 ms. An algorithm programmed with Matlab software (The MathWorks, Inc., Natick, MA) produced ISIs that would result an equal distribution of the words across each 10-s trial (equal numbers of words

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presented at the beginning, middle, or end of the trial). The words presented in the practice lists were not reused in the test lists. All test words were presented twice with a minimum separation of two lists. The word stimuli were randomly ordered within each list and presented with customized software, C-Sharp, through a Dell Inspiron 1300 laptop. Participants heard the words through a Plantronics (Santa Cruz, CA) DSP-300 headset that also recorded vocal RTs. Speech recognition software (Microsoft Speech API) identified participants' responses ("yes" for living words or "no" for nonliving words), and they were subsequently scored as correct or incorrect with Matlab software.

Procedure.—The testing took place in the Adult Development and Aging laboratory at Concordia University. After informed consent, all participants underwent a task familiarization session. For the motor task, participants imitated simple forward (1-2-3-4-1-2-3-4-1-2-3-4) or backward (4-3-2-1-4-3-2-1-4-3-2-1) 12-element sequences to familiarize them with the keyboard and visual stimuli. For the semantic task, participants performed the word repetition baseline where they had to repeat 30 words that were presented auditorially. To ensure adequate hearing for the test phase, participants needed to score 90% or more on the word repetition baseline. All participants met this criterion.

Participants then had practice in each of the conditions: single task (semantic), single task (motor), and dual task (semantic and motor). They completed seven trials per condition. Once they practiced the tasks, they completed four counterbalanced test runs of single motor, single semantic, and dual task. For each test run, there were 15 trials per condition. For both the practice and the test sessions, participants completed half of the motor trials in isolation (single-task block) and half with the semantic task (dual-task block). For both the practice and the test runs, participants were instructed that both tasks were equally important and that they should try to respond quickly and accurately. After the test session, participants completed the Digit Symbol, the Trail Making tests, the Digits Forward test, and a demographics questionnaire. Participants were debriefed and received course credit (younger) or an honorarium (older) for their time. The entire session lasted approximately 90 min.

Statistical analyses.—Four dependent variables were calculated: accuracy and RT for the cognitive task and accuracy and RT for the motor task. For both the cognitive and the motor data, the mean correct RT (ms) for each trial type was calculated for each participant. The time window for valid motor responses had a 1,000-ms duration, which started 100 ms prior to the presentation of each stimulus, to allow for anticipated responses. Any correct tap within this time window was considered part of the mean RT. For the vocal RT data, RTs were calculated from the offset of the verbal stimuli and responses were excluded if they were ±3 *SD* from an individual's overall mean RT. Only a small proportion of the responses were considered outliers (M_{Older} = 0.02, *SE* = 0.001; M_{Younger} = 0.01, *SE* = 0.001). Accuracy for the cognitive task and the motor task were based on the number of correct responses (i.e., correct semantic judgments, correct taps) in all possible responses for each trial type (single and dual). For the cognitive accuracy, motor accuracy, and motor RT, the data were checked for outliers based on the group mean. No such outliers were found.

DTCs were calculated for each of the four dependent variables. In the case of RT, dual-task RTs were subtracted from single-task RTs for each individual. For accuracy, single-task accuracy was subtracted from dual-task accuracy on an individual basis. The resulting difference scores represent four DTC scores: DTC motor accuracy, DTC motor RT, DTC semantic accuracy, and DTC semantic RT. For each variable, planned contrasts (α = .05) were conducted to assess age differences in DTCs. All post hoc analyses used a Bonferroni corrected *p* value (*p* = .025).

Results and Discussion

Mean values for single- and dual-task performances are reported in Table 2.

Fine motor: MFST.—Accuracy. The *t* test revealed significant age differences in motor accuracy DTCs, $t(39) = 2.23$, $p = .032$, such that older adults had higher motor accuracy DTCs (*M* = 4.71%, *SE* = 1.73) than younger adults (*M* = 0.60%, *SE* = 0.53). Only older adults' accuracy DTCs were significantly different from zero, $t(20) = 2.72$, $p = .013$.

Reaction times.—The *t* test for motor RT DTCs resulted in a significant age difference, $t(39) = 2.39$, $p = .022$. Again, older adults had higher motor RT DTCs (*M* = 61.50 ms, *SE* = 11.47) than younger adults (*M* = 25.39 ms, *SE* = 10.20). After Bonferroni correction, both younger, $t(19) = 2.49$, p = .022, and older adults', $t(20) = 5.36$, $p < .001$, motor RT DTCs were significantly different from zero.

Cognitive: semantic judgment task.—Accuracy. The *t* test comparing younger and older adults on their cognitive accuracy DTCs was nonsignificant, $t(39) = 0.92$, $p = .362$. An additional analysis on the full sample revealed that the DTCs in accuracy were not significantly different from zero, $t(40) = 1.24$, $p = .222$. When split by age, neither younger, $t(19) = 1.28$, $p = .215$, nor older adults', $t(20)$ = 0.31, $p = .760$, accuracy DTCs were significantly different from zero.

Reaction times.—In line with the accuracy results, the *t* test comparing younger and older adults' vocal RTs DTCs was nonsignificant, $t(39) = 0.35$, $p = .728$. In this case, the *t* test comparing vocal RT DTCs to zero was significant for the whole sample, $t(40) = 2.65$, $p = .012$. However, when split by age, neither younger, $t(19) = 1.96$, $p = .065$, nor older,

Table 2. Mean Single- and Dual-Task Performance Values for Younger and Older Adults.

	Experiment 1		Experiment 2			
Cognitive task	Semantic judgments		Minus-1		Minus-7	
	Younger	Older	Younger	Older	Younger	Older
Accuracy						
Single	89.25	92.90	99.50	99.74	75.08	82.37
Dual	91.00	93.14	98.33	99.04	67.58	69.47
Reaction times						
Single	662.42	762.63	567.09	600.64	1584.96	1462.89
Dual	690.52	786.61	665.46	641.20	1647.08	1439.82
Fine motor task	Sequential tapping					
	Younger	Older	Younger	Older	Younger	Older
Accuracy						
Single	96.90	94.76	97.82	93.13	96.97	91.30
Dual	96.35	89.90	97.43	86.86	84.28	69.96
Reaction times						
Single	281.89	405.48	290.54	413.03	294.92	391.59
Dual	307.28	466.98	313.59	447.24	377.82	486.62

Notes: Accuracy values = percentage points (a value of 100 = all responses correct). Reaction time values in milliseconds. Although single-task sequential tapping requires only a response to the visual stimulus, results for Minus-1 and Minus-7 are reported separately in this table because they were presented separately in a Minus-1 or Minus-7 test run. There were no significant differences in single-task sequential tapping accuracy between Minus-1 and Minus-7, $t(38) = 1.59$, $p = .120$.

$t(20) = 1.73$, $p = .098$, adults' vocal RT DTCs were significantly different from zero.

Testing for trade-offs: within and across domains.—Within each domain (cognitive and motor), bivariate correlations between mean dual-task accuracy and speed (reciprocal of RT: 1/RT) were computed to test for speed-accuracy trade-offs. A negative correlation between speed and accuracy measures would be expected if participants were slowing to maintain accuracy levels or making more mistakes to maintain speed. For younger adults, the correlation between vocal accuracy and speed, $r(18) = -.01$, $p = .973$, was nonsignificant. The correlation between and motor accuracy and speed, $r(18) = -.46$, $p = .044$, was significant for younger adults; however, a close examination of the scatterplot for this correlation revealed that one participant was driving this finding. When this participant was removed, the negative correlation between motor accuracy and speed was no longer significant, $r(17) = .05$, $p = .831$. Older adults had significant positive correlations between motor accuracy and speed, $r(19) = .53$, $p = .015$, and vocal accuracy and speed, $r(19) = .43$, $p = .050$. This positive correlation suggests a relationship between speed and accuracy such that older individuals who were quick to respond also had high-accuracy scores and those who were slower to respond had lower accuracy scores.

To rule out cross-domain trade-offs, bivariate correlations were conducted between motor and cognitive accuracy DTCs, as well as motor and cognitive RT DTCs. A negative correlation between these DTCs would suggest that lower costs in one domain (i.e., cognitive) are associated with greater costs in the other domain (i.e., motor). For correlations between domains in accuracy, no significant trade-offs were found for younger, $r(18) = -.07$, $p = .773$, or older adults, $r(19) = -.03$, $p = .910$. Similarly, there were no significant correlations between domains in RT for younger, $r(18) = .22$, $p = .353$, or older adults, $r(19) = -.11$, $p = .648$.

Summary.—The results of Experiment 1 replicate the general findings of Crossley and Hiscock (1992) using a sequential tapping task. The lack of an age difference in DTCs in combination with the age differences in motor DTCs aligns well with the notion of an increasing role for cognition in fine motor performance. Beyond age differences in fine motor performances, Crossley and Hiscock demonstrated that these age differences increased when cognitive load increased. In the case of sequential tapping, additional support for age-related cognitive-motor interdependence should be found in conditions with greater cognitive load. In keeping with previous findings, we hypothesized that in Experiment 2, a high concurrent cognitive load would produce greater costs to sequential tapping than a lower cognitive load (for both age groups) and that this difficulty manipulation would have a greater impact on the older adults' dual-task performances than the young.

Experiment 2

Method

Participants.—Twenty younger adults (18–27 years) and 20 older adults (60–78 years) participated in the experiment. Recruitment and exclusion criteria were the same as in Experiment 1. In addition to the standardized tests administered in Experiment 1, all participants completed the Extended Range Vocabulary Test (ERVT; Educational Testing Service,

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1976), and the Math subtest of the WAIS III, to assess vocabulary and math abilities, respectively. Descriptive statistics of the sample are presented in Table 1. All procedures were approved by the Concordia University Human Research Ethics Committee.

Materials.—Fine motor task. The motor task was identical to that used in Experiment 1.

Cognitive task: mental arithmetic. The cognitive task in this experiment had two levels of difficulty. For the Minus-1 level, participants subtracted one from randomly ordered two-digit numbers presented over headphones. For the Minus-7 level, participants subtracted seven from each stimulus. Stimuli consisted of two-digit numbers ranging from 11 to 99, not including numbers ending with seven (e.g., 17, 27, 37 . . .) or zero (e.g., 10, 20, 30 . . .). Two lists composed of 30 stimuli were used during the practice session. Sixty new stimuli were randomly arranged into four lists to be used in the four conditions (single Minus-1, single Minus-7, dual Minus-1, and dual Minus-7). The ISI range used in the current study (ISIs: minimum 2,300 ms and maximum 5,500 ms) was based on the average response times found in Abbud and colleagues (2009) for Minus-7. As compared with Experiment 1, the ISIs were lengthened here to accommodate the more complex cognitive tasks. In all other respects, the delivery of cognitive stimuli was the same as in Experiment 1.

Procedure.—The testing took place in the Adult Development and Aging laboratory at Concordia University. After informed consent, all participants underwent the motor familiarization session described in Experiment 1. After the motor familiarization, all participants completed two practice blocks (15 trials each). In the first block, they completed a fixed order of Minus-1, single-task motor, and dual Minus-1; in the second block, they completed a fixed order of Minus-7, single-task motor, and dual Minus-7. Participants were instructed that both tasks were equally important and that they should try to respond quickly and accurately. Prior to the test runs, participants were asked to complete the Digit Symbol test.

Once they had practiced the component tasks, they completed four test runs of the single motor, single cognitive, and dual-task trials. Runs 1 and 2 were always the Minus-1 difficulty level and Runs 3 and 4 were always the Minus-7 difficulty level. Within each run, the order was fixed: for Runs 1 and 3, single cognitive was always presented first, and for Runs 2 and 4, single motor was always presented first. The dual-task condition was always at the end of a run. These four runs were counterbalanced (i.e., 1-2-3-4, 4-1-2-3, 3-4-1-2, etc.) so that the difficulty manipulation was evenly distributed across the test session (i.e., with some participants having Minus-1, Minus-1, Minus-7, Minus-7; others Minus-7, Minus-1, Minus-1, Minus-7, etc.). For each of the four test sessions, there were 30 fine motor trials, 15 performed alone (single-task motor) and 15 performed concurrently with mental arithmetic (sequential tapping & Minus-sequential tapping & Minus-7). After the first two test runs, participants completed the Trail Making Test (A & B) and the ERVT, followed by the two remaining test runs. Finally, the participants completed the Digits Forward and the arithmetic subtest of the WAIS. Participants were debriefed and received course credit (younger) or an honorarium (older) for their time. The entire session lasted 90–120 min.

Statistical analyses.—Accuracy and RTs were derived in the same way as Experiment 1. DTCs were calculated for each dependent variable in each domain (motor and cognitive) and difficulty level (Minus-1 and Minus-7). For the vocal RT data, responses were excluded if they were ±3 *SD* from each individual's overall mean RT. Only a small proportion of the responses were considered outliers (M_{Older} = 0.01, *SE* = 0.001; M_{Younger} = 0.01, *SE* = 0.002). For cognitive accuracy, motor accuracy, and motor RT, the data were checked for outliers ±3 *SD* from the group mean (younger and older) on single-task performances. One older adult was removed based on this criterion. Consequently, analyses were conducted on 20 younger and 19 older adults. Mixed factorial analyses of variance (ANOVAs; α = .05) were carried out using the four dependent variables (DTCs) with difficulty level (Minus-1 and Minus-7) as the within-subjects factor and age group (younger and older) as the between-subjects factor. All post hoc analyses used a Bonferroni corrected *p* value (.025).

Results and Discussion

Mean values for single- and dual-task performances are reported in Table 2, and DTCs for each domain are presented in Figure 2.

Fine motor: MFST.—Accuracy. Figure 2A depicts the motor accuracy DTCs for both difficulty levels. The analysis revealed a main effect of difficulty level, $F(1,37) = 44.33$, $p < .001$, $\eta^2 = .545$, such that the Minus-7 had higher costs (*M* = 17.00%, *SE* = 2.20) than Minus-1 (*M* = 3.30%, *SE* = 1.00). In addition, there was a main effect of age group, $F(1,37) = 7.11$, $p = .011$, $\eta^2 = .161$, where older adults had higher DTCs in motor accuracy (*M* = 13.80%, *SE* = 2.00) than younger adults (*M* = 6.50%, *SE* = 1.90). The interaction was not significant, $F(1,37) = 0.46$, $p = .503$. The younger adults' motor accuracy DTCs were not significantly different from zero, $t(19) = 0.55$, $p = .590$, for Minus-1 but were significantly different from zero for Minus-7, $t(19) = 4.93$, $p < .001$. For both difficulty levels, older adults' motor accuracy DTCs were significantly different from zero, Minus-1: $t(18) = 3.41$, $p = .003$; Minus-7: $t(18) = 5.85$, $p < .001$.

Reaction times. Figure 2B displays the motor RT DTCs. The ANOVA for motor RT DTCs resulted in a significant

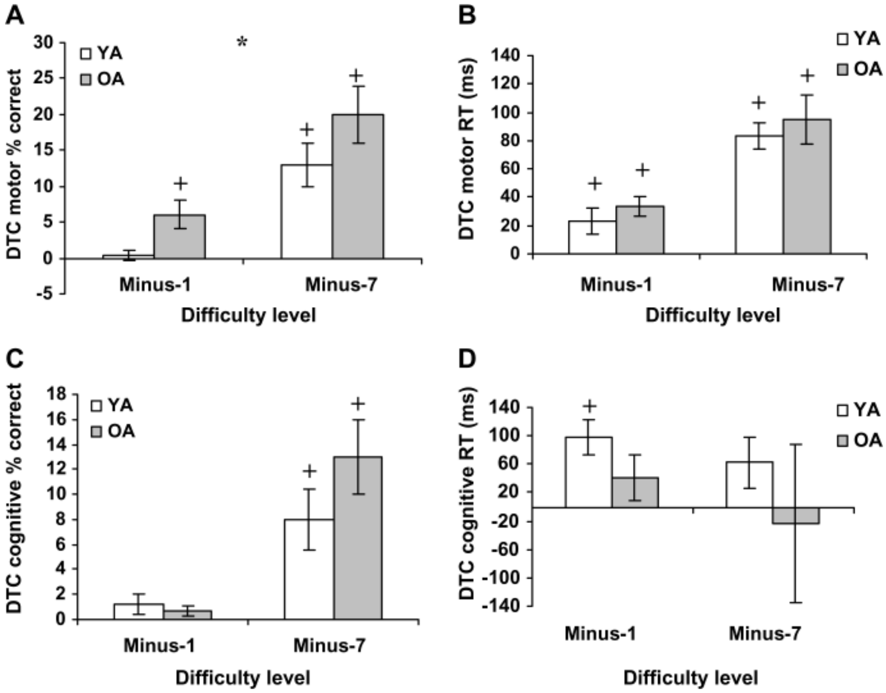

Figure 2. Experiment 2: (**A**) Mean dual-task costs (DTCs) in motor accuracy by difficulty level (Minus-1 and Minus-7). (**B**) Mean DTCs in motor reaction times (RTs) by difficulty level. (**C**) Mean DTCs in cognitive accuracy by difficulty level. (**D**) Mean DTCs in cognitive RTs by difficulty level. Error bars are ±1 *SE* of the mean. *Note.* * = significant age difference in DTCs; + = DTCs are significantly greater than zero.

main effect of difficulty, $F(1,37) = 39.48$, $p < .001$, $\eta^2 = .516$, where Minus-7 resulted in higher DTCs ($M = 88.96$ ms, $SE = 9.55$) than Minus-1 ($M = 28.63$ ms, $SE = 5.56$). The main effect of age, $F(1,37) = 0.89$, $p = .351$, and the interaction, $F(1,37) = 0.01$, $p = .960$, were nonsignificant. Analyses of the RT DTCs for the full sample confirmed that the DTCs for both difficulty levels were significantly different from zero, Minus-1: $t(38) = 5.13$, $p < .001$; Minus-7: $t(38) = 9.38$, $p < .001$.

Cognitive: mental arithmetic.—Accuracy. Figure 2C depicts the cognitive DTCs in accuracy for both difficulty levels. The mixed factorial ANOVA revealed a main effect of difficulty, $F(1,37) = 23.33$, $p < .001$, $\eta^2 = .387$, on the accuracy DTCs, such that DTCs were higher on Minus-7 trials ($M = 10.20\%$, $SE = 1.90$) than on Minus-1 trials ($M = 0.94\%$, $SE = 0.40$). Both the main effect of age, $F(1,37) = 1.49$, $p = .230$, and the interaction of difficulty and group, $F(1,37) = 2.33$, $p = .135$, were nonsignificant. Additional analyses on the full sample revealed that the DTCs in accuracy were significantly different from zero for both the Minus-1, $t(38) = 2.13$, $p = .039$, and the Minus-7, $t(38) = 5.22$, $p < .001$, conditions. When split by age, younger adults' DTCs in Minus-1 were not significantly different from zero, $t(19) = 1.47$, $p = .158$, but they were significantly different from zero in Minus-7, $t(19) = 3.10$, $p = .006$. Similarly, the older adults' DTCs were not significantly different from zero in the Minus-1 condition, $t(18) = 1.91$, $p = .072$, but were significantly different from zero in the Minus-7 condition, $t(18) = 4.30$, $p < .001$.

Reaction times. Figure 2D depicts the cognitive DTCs in RTs for both difficulty levels. There were no significant effects in the cognitive RT data. The DTCs in vocal RTs did not differ by difficulty level, $F(1,37) = 0.73$, $p = .398$, nor by age group, $F(1,37) = 1.32$, $p = .258$, and the interaction between difficulty level and group did not reach significance, $F(1,37) = 0.06$, $p = .816$. Pooling together both age groups, the DTCs in the Minus-1 condition were significantly different from zero, $t(38) = 3.42$, $p = .002$, but the DTCs in the Minus-7 condition were not, $t(38) = 0.37$, $p = .717$. When split by age, only younger adults' DTCs were significantly different from zero in the Minus-1 condition, $t(19) = 3.97$, $p = .001$, and neither age group had DTCs that were different from zero in the Minus-7 condition, Younger: $t(19) = 1.77$, $p = .092$; Older: $t(18) = 0.21$, $p = .837$.

Testing for trade-offs: within and across domains.—At each level of difficulty, the mean dual-task scores within each domain were tested for a speed-accuracy trade-off. A negative correlation between speed and accuracy measures would indicate a trade-off. Correlations between mean dual-task motor accuracy and speed in the Minus-1 condition were nonsignificant for both age groups, Younger: $r(18) = -.04$, $p = .884$; Older: $r(17) = .39$, $p = .104$. Both younger and older adults had a significant positive correlation between dual-task motor accuracy and speed in the Minus-7 condition, Younger: $r(18) = .52$, $p = .018$; Older: $r(17) = .62$, $p = .005$. For both age groups, the cognitive dual-task correlations between accuracy and speed were nonsignificant for all conditions, Minus-1: $r(37) = .26$, $p = .105$; Minus-7: $r(37) = .21$, $p = .202$. Across both age groups, the lack of a significant negative correlation indicates that there was no speed-accuracy trade-off within domain.

Using DTCs, cross-domain trade-offs (i.e., responding quickly in motor task but slowing in cognitive) were tested with bivariate correlations between the cognitive and motor DTCs. For correlations between motor and cognitive accuracy DTCs, neither younger, Minus-1: $r(18) = .15$, $p = .540$; Minus-7: $r(18) = .20$, $p = .398$, nor older adults, Minus-1: $r(19) = .03$, $p = .913$; Minus-7: $r(19) = -.24$, $p = .334$, demonstrated any significant cross-domain trade-offs. Similarly, there were no significant cross-domain trade-offs for correlations between motor and cognitive RTs for younger, Minus-1: $r(18) = -.22$, $p = .349$; Minus-7: $r(18) = .22$, $p = .354$, or older adults, Minus-1: $r(19) = .05$, $p = .846$; Minus-7: $r(19) = -.07$, $p = .774$.

Summary.—Similar to the simple tapping findings of Crossley and Hiscock (1992) and the sequential tapping findings of Kemper and colleagues (2003), tapping sequentially while performing a cognitive task had a greater impact on older adults' motor performances than younger adults. The younger adults were able to maintain their motor accuracy in the Minus-1 condition, whereas older adults demonstrated significant accuracy costs in both difficulty levels. Both groups slowed when sequentially tapping with a cognitive task but there was no age difference in the degree of slowing. In the cognitive measures, the pattern of results is similar for younger and older adults with the only exception being significant cognitive RT DTCs in the Minus-1 condition for the younger adults. The lack of speed-accuracy trade-offs and cross-domain trade-offs suggests that younger adults were not slowing to maintain performance on another measure. In the Minus-7 condition, the lack of significant cognitive RT DTCs in combination with significant motor DTCs for both age groups in both measures might indicate a prioritization of cognitive task under the highest cognitive load.

General Discussion

The primary goal of this study was to examine the role of executive control in fine motor performance using a motor-cognitive dual-task paradigm. This study extends previous work on dual-task simple tapping (Crossley & Hiscock, 1992) and complex tapping (Kemper et al., 2003) with age differences found primarily in fine motor performances. The first experiment combined a low-load semantic judgment task with sequential tapping and older adults were slower and less accurate than younger adults on the sequential tapping task. In the second experiment, in which cognitive load was manipulated, there were age differences in motor accuracy, with older adults demonstrating costs in both difficulty levels, whereas motor accuracy costs only emerged in the harder condition for younger adults. Because older adults demonstrate costs in sequential tapping even in the conditions of lowest load and these costs reliably emerge in motor accuracy performance, we propose that older adults require greater executive control processes in order to perform the sequential tapping task.

In both experiments, there was an asymmetry in the pattern of results, such that DTCs occurred mainly in the motor domain. This occurred despite differences in temporal predictability across the cognitive and motor tasks. Indeed, one might hypothesize that the less predictable cognitive task (that occurred at different time points during the trial) would be more affected by dual-task interference than the motor task that was presented in a more predictable fashion (one stimulus each second). Ultimately, across the different levels of cognitive load, the cognitive tasks interfered with the sequential nature of the tapping task and older adults were more affected by this interference than younger adults. The interference from the cognitive task affected the older adults' fine motor performance even in the easiest condition, and younger adults only faltered when task demands were too great. With the exception of the Minus-1 condition RT measure (cognitive and motor), all performance costs for younger adults were found in the harder Minus-7 condition. Perhaps mild cognitive loads taxed younger adults' coordinative processes (i.e., coordinating the performance of the two tasks). Whereas for older adults, all cognitive loads were sufficiently challenging that key press accuracy or response selection in the motor task was affected.

Given that the sequence we presented was repeated throughout the each block of trials, younger and older adults may have encoded the sequence of key presses into a single action plan (Tubau, Hommel, & Moliner, 2007). Findings with younger adults have demonstrated that execution of an action plan can be disrupted by visual and auditory verbal distracters. In addition, sequence learning and action plans have both been shown to involve the prefrontal cortex (Tubau et al.). The prefrontal cortex and the executive control processes it subserves are known to decline with normative aging (Verhaeghen & Cerella, 2002). Therefore, in the current experiment, because older adults relied more heavily on executive control functions for sequential tapping, they demonstrated greater performance costs than their younger counterparts. In support of this proposal, existing sequence learning research (Aizenstein et al., 2006) has found age differences in frontal activity during concurrent sequence learning, such that older adults show greater activity than younger adults in the left dorsolateral prefrontal cortex.

The results of the current experiment are also consistent with our previous findings in dual-task walking experiments, which used the same cognitive tasks (Fraser et al., 2007; Li et al., 2008). In particular, Fraser and colleagues (2007) found age differences only in walking performance

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when performing the semantic task, and Li and colleagues (2008) demonstrated maintenance of walking performance during the Minus-1 condition for younger adults but costs similar to older adults in the harder condition. Similarly, in Experiment 1, there was age equivalence in performance of the semantic task, and age differences emerged in sequential tapping. Furthermore, in Experiment 2, although younger adults slowed their sequential tapping in the Minus-1 condition, they maintained their accuracy when older adults demonstrated accuracy costs and both groups had similar costs in the Minus-7 condition. These similarities suggest that gait and sequential tapping may draw on similar executive control functions. The age-related dual-task effects reported by Crossley and Hiscock (1992) may have been a reflection of age-related reductions in general dual-task coordination processes rather than an indication that simple tapping requires executive control. Indeed, previous research suggests that simple tapping does not rely on executive functions (Hausdorff, Yogev, Springer, Simon, & Giladi, 2005). The similarity of the current pattern of results with that of previous walking research (Fraser et al., 2007; Li et al., 2008) suggests that executive functions might play a role in both walking and fine motor DTCs and that the previous walking findings were not primarily driven by postural threat. Although it is clear that postural threat influences attentional allocation (Brown et al., 1999), it has also been found that different degrees or levels of difficulty of postural threat (Lajoie, Teasdale, Bard, & Fleury, 1996) can modulate DTCs in older adults.

Conclusions

Taken together, the findings extend the research on aging and dual-task fine motor performance in demonstrating that concurrent sequential tapping costs are greater in older adults due to the disruption of a planned execution of taps at the executive processing level. Under low cognitive load, younger adults have a more proceduralized or automatic approach to the sequential tapping task that does not require executive control. In contrast, older adults demonstrate costs at every load level demonstrating the cognitive penetration of motor task performance (Teasdale, Bard, LaRue, & Fleury, 1993).

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