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Age and Cognitive Stress Influences Motor Skill Acquisition, Consolidation, and Dual-Task Effect in Humans

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Abstract

This study examined motor skill learning using a weight-bearing and cognitive-motor dual-task that incorporated unexpected perturbations and measurements of cognitive function. Forty young and 24 older adults performed a single-limb weight bearing task with novel speed, resistance, and cognitive dual task conditions to assess motor skill acquisition, retention and transfer. Subjects performed a cognitive dual task: summing letters in one color/orientation (simple) or two colors/orientations (complex). Increased cognitive load diminished the rate of skill acquisition, decreased transfer to new conditions, and increased error rate during an unexpected perturbation; however, young adults had a dual-task benefit from cognitive load. Executive function predicted 80% of the variability in dual-task performance. Although initial learning of a weight-bearing cognitive-motor dual-task was poor, longer-term goals of improved dual-task effect and retention emerged.

Keywords

Dual-task; Aging; Perturbation; Executive Function

INTRODUCTION

In order to function in the community, individuals must be able to perform simultaneous motor and cognitive tasks. It is common to perform a cognitive task, like thinking of a grocery list, while navigating a changing environment in a crowded store. In older adults, a diminished capacity to perform simultaneous tasks can lead to injury; notably when exposed to an unexpected environmental event.

We developed a novel method to elicit unexpected conditions during an upright standing weight bearing task (Madhavan et al., 2009; Madhavan & Shields, 2009; Tseng et al., 2017) and recently added a cognitive challenge. Unlike gait, which offers unique over ground

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challenges (Montero-Odasso, Muir, & Speechley, 2012; Mortaza, Abu Osman, & Mehdikhani, 2014), our experimental method enables us to safely assess feed forward movement control (visual-motor tracking task) and reflexive feedback control (0-200 milliseconds) after unexpected conditions, in a standing weight-bearing position.

The ability to correctly perform both a cognitive attention-demanding task and a motor task depends, in part, on the complexity of the task. Motor tasks that can be performed efficiently require decreased processing resources. When performance of a dual-task is poorer than performance of a single-task, the effect is described as a “dual-task cost” (Nordin, Moe-Nilssen, Ramnemark, & Lundin-Olsson, 2010; Somberg & Salthouse, 1982; L. Yang, Liao, Lam, He, & Pang, 2015). When dual-task performance exceeds single-task performance, the effect is described as a “dual-task benefit” (Beilock, Carr, MacMahon, & Starkes, 2002; Goh, Sullivan, Gordon, Wulf, & Winstein, 2012; Yu & Huang, 2017). It is well accepted that movement accuracy during cognitive task performance is impaired in older adults, requiring increased cognitive resources to perform a previously automatic task (Whitman et al., 1999; Wong, Masters, Maxwell, & Abernethy, 2008; Woollacott & Shumway-Cook, 2002). This was classically observed by Lundin-Olsson and co-authors; older individuals would stop walking when asked a question, not having the ability to perform both a cognitive and a motor task simultaneously (Lundin-Olsson, Nyberg, & Gustafson, 1997). However, modest improvements in spatio-temporal parameters of gait after dual-task training (Fritz, Cheek, & Nichols-Larsen, 2015; Wajda, Mirelman, Hausdorff, & Sosnoff, 2016); (Bedard & Song, 2013; Song, Im, & Bedard, 2015), suggest that adaptive plasticity persists in older adults, and that dual-task training may offer a unique rehabilitation strategy. No previous study has assessed whether dual task training modulates responses to an unexpected event (perturbation) in an upright weight bearing task.

The influence of cognitive load on our ability to control movement during unexpected events is important in a changing environment. Cognitive load training during unexpected perturbations of the upper extremity (Cheng, Pratt, & Maki, 2013; Taylor & Thoroughman, 2007) does not provide us with an assessment of the somatosensory, vestibular, and visual integration utilized during standing upright conditions. Studies of cognitive load on standing-slip platforms are informative but offer challenges because of the change in an individual’s CNS central set following the first slip condition (Bhatt, Yang, & Pai, 2012; Nnodim, Kim, & Ashton-Miller, 2015; P. J. Patel & Bhatt, 2015; Pavol, Runtz, Edwards, & Pai, 2002; Zettel, McIlroy, & Maki, 2008). Thus, the novelty of our approach is that we evaluate a dual-task strategy during a novel weight-bearing task that requires visual, vestibular and somatosensory integration and that can reproducibly and safely deliver unexpected perturbations.

We coupled a visual discrimination task with our visuomotor task to create the dual-task condition. We chose this strategy because learning is enhanced if similar central resources are used in the motor and the cognitive tasks (Goh et al., 2012; Hemond, Brown, & Robertson, 2010) and because of the historical precedent of successful learning from visual discrimination tasks (Im, Bedard, & Song, 2016; Song & Bedard, 2013, 2015). Because several cognitive domains are necessary for motor task performance, we included tests for executive function and working memory (McCabe, Roediger, McDaniel, Balota, &

Hambrick, 2010), (N. P. Gothe et al., 2014; Muir, Gopaul, & Montero Odasso, 2012). Because it is natural to emphasize motor skill deficits during dual task movement, we also assessed cognition to ascertain if there are key cognitive deficits associated with motor performance (Azadian, Torbati, Kakhki, & Farahpour, 2016; Mirelman et al., 2011; Silsupadol, Siu, Shumway-Cook, & Woollacott, 2006).

Accordingly, we investigated the extent to which a cognitive task combined with a novel weight-bearing visual-motor task influences the acquisition, consolidation, and transfer of knowledge during expected and unexpected conditions in young and older individuals. We hypothesized that increased cognitive load would delay skill acquisition, consolidation, and transfer of knowledge, but would enhance longer term retention of motor performance during unexpected events. We also explored the association between cognitive function and motor task performance after dual task training.

METHODS

Subjects

Sixty-four subjects participated in this study after providing written informed consent approved by the University of Iowa Human Subjects Institutional Review Board. Subjects were 20-39 years old (“Young”; $n=40$) and 60-80 years old (“Older”; $n=24$). Exclusion criteria were self-reported history of knee ligament reconstruction, current or recent (<3 mo) knee pain, cardiovascular disease, known lower extremity osteoarthritis, rheumatoid arthritis, neurologic disease, known cognitive impairment (such as a diagnosis of dementia), or any movement impairment. All participants had normal corrected vision.

Experimental Design

Motor Task—Participants stood in a weight-bearing system that measured force and displacement at the knee during a game-based visuomotor task (Shields, 2006). Participants stood on one leg and maintained light fingertip contact on the test apparatus with one hand (< 2 N). This light-touch support was intended to reduce or eliminate balance challenge from the task but provide minimal biomechanical support. The user performed a single limb squat to move a projected line that indicated their instantaneous knee position (Figure 1). Participants matched the knee position line to a sinusoidal oscillating target line. During the experiment, task difficulty was hierarchically varied over 9 conditions via alterations of knee movement resistance (percent body weight) and task speed (frequency of the oscillating target line)(Tseng et al., 2017). The 9 conditions consisted of a combination of three target line speeds (0.2, 0.4, and 0.6 Hz), and three resistances (5%, 10%, and 15% body weight; Figure 1). The duration of each trial was 25, 12.5, and 8.3 seconds for movement rates of 0.2, 0.4, and 0.6 Hz respectively. One “trial” consisted of five sinusoidal cycles at each of the 9 task conditions.

The system also created an unexpected perturbation by rapidly decreasing the resistance of the brake to null, and then rapidly returning the resistance to pre-perturbation levels (Madhavan & Shields, 2009). The perturbation was given randomly during one of the five sinusoidal cycles for each of the 9 task conditions. The brake release always occurred when

the user completed the first 1/3 of the flexion (downward-going) phase of knee motion. No brake release was delivered as the knee moved into the extension phase of the knee. The duration of the brake release that caused the perturbation was 400, 250, and 200 milliseconds for the 0.2 Hz, 0.4 Hz, and 0.6 Hz target line frequencies, respectively.

The motor task was the same for all subjects in all groups (Figure 2). On Day 1, subjects performed 20 training trials at a speed of 0.4 Hz and a brake resistance of 10% body weight (BW). After every trial, subjects were given feedback of performance via a knee position percent error score. Subjects were offered one-minute rest breaks every 5 trials. Following training, subjects performed a test series of the 9 hierarchical visuomotor task conditions without feedback of percent error. Subjects were allowed rest breaks between task conditions if requested. After every 5 trials and after the final trial, subjects were asked to rate their perceived exertion on the Borg 15-pt scale (Gearhart et al., 2001; Lagally & Costigan, 2004). No subject rated their exertion to be greater than a 13 (“Somewhat hard”).

Cognitive Task—On the same screen as the projected motor task (target line), the letter “T” flashed for 0.5 seconds every 1.0 second (Figure 1). The letter was randomly selected from either upright or upside-down T’s, and from one of four colors (orange, yellow, pink or white). The cognitive task involved counting the number of pre-specified color(s) and orientation(s) of the letter on the screen. This method has been used by other researchers to provide an effective cognitive load as part of a cognitive-visuomotor task that alters the contextual environment in which learning is performed (Song & Bedard, 2015).

Subjects in the Young and Older age groups were divided into four sub-groups (Fig. 2). 10 young adults were assigned to each of two control groups (YCT1, YCT2) and two dual-task groups (YDT1, YDT2). Likewise, 6 older adults were assigned to each of two control groups (OCT1, OCT2) and two dual-task groups (ODT1, ODT2). During Day 1 training and testing, the control groups performed only the 9-condition visuomotor task. One intervention group (DT1) performed the 9-condition visuomotor task and simultaneously counted the number of upright orange T’s that flashed on the screen (simple cognitive task). The other intervention group (DT2) performed the 9-condition visuomotor task and simultaneously counted the total sum of the upright orange T’s and upside-down yellow T’s (complex cognitive task).

On day 2 (48 hours later), each group performed five training trials under their previous day 1 training condition, with feedback via a position error score. After a 1-minute rest they performed a “cross condition”: the DT1 and DT2 groups solely performed the 9-condition visuomotor task (no cognitive dual-task) and the CT1 and CT2 groups performed the simple and complex dual-tasks, respectively. After a 1-minute rest, subjects in each group performed a 9-condition block under their original day 1 training condition.

On test day 3 (7 days later), each group first performed a 9-condition block under their original day 1 training condition. After a rest, each group then performed a 9-condition block under the “cross condition” used on day 2. Finally, the groups performed a “complexity-crossed” 9-condition block: participants who previously performed the simple cognitive dual-task received the complex cognitive dual-task. Conversely, participants who

previously performed the complex cognitive dual-task received the simple cognitive dual-task.

Cognitive Testing—Cognitive domain testing was performed before visuomotor testing on the first test day via selected elements of the NIH Toolbox Cognition Battery (Release 10.2) (Heaton et al., 2014). Tests were administered via the computerized Assessment Center platform (“Assessment Center,” 2017) in the following order: Dimensional Change Card Sort (DCCS) Age 12+, Flanker Inhibitory Control and Attention Test Age 12+, and List Sorting Working Memory Test Age 7+. As we were interested in quantifying age-related differences in cognition, we examined the Unadjusted Scale Score for each measure. The List Sorting Working Memory test provides a general working memory capacity score, and has a strong reliability coefficient of 0.77 (Tulsky et al., 2014), moderate convergent validity of 0.58 and divergent validity of 0.27. The Dimensional Change Card Sort measures set shifting and task switching, and the Erikson Flanker test measures inhibition control and executive attention (Zelazo et al., 2014). Both tests have a re-test reliability coefficients > 0.85, and an age correlation of approximately –0.6 for the ages of 25-85 (Zelazo et al., 2014).

Physical Activity Assessment—The International Physical Activity Questionnaire Short Form (IPAQ-SF) was delivered on the last day of testing to estimate the physical activity of subjects in the past week. The seven day time frame of the questionnaire captures the testing duration presented in this methodology. Previous unpublished data from our laboratory demonstrated a moderate but significant correlation ($R=0.594$; $P < 0.05$) between IPAQ-SF score and mean activity in younger and older adults as rated by an Actigraph™ activity monitoring system.

Data Analysis

Custom LabView software was used to collect knee displacement data and axial force data at a 2000 Hz sampling rate. Data were then analyzed using DIAdem software (Version 12.0).

Student’s T-test was used to determine differences between Older Adults and Younger Adults for activity level and each cognitive metric. A two-way ANOVA was used to inspect for Age (Older, Younger) versus Group (CT, DT1, DT2) differences. Significant main effects of Age or Group were followed by Tukey’s post-hoc testing as indicated ($p < 0.05$).

A two-way ANCOVA was used to determine the difference in second day retesting (dependent variables: coherence and mean trial error) for factors of age (Younger, Older) and group (CT, DT1, and DT2) while accounting for final training performance during the first day of training. A significant interaction would indicate that imposition of cognitive load during dual-task testing influenced consolidation of motor learning differently between age groups. Main effects would identify an age and/or a group difference in consolidation of motor learning.

A split-plot ANOVA was used to determine the influence of blocks of age (younger and older adults), whole plots of randomly assigned group (CT, DT1, and DT2), and sub-plot of condition (condition 1 through 9). Dependent variables analyzed using this method were

coherence, mean trial error, knee flexion rate, perturbation error rate, and dual-task effect. Simple effects were examined by Tukey's post-hoc tests as required. Due to unequal sample sizes between younger and older age groups, the weighted means, or type III sum of squares, were used to determine statistical significance.

Correlations were obtained between cognitive variables (DCCS, Flanker, List Sorting) and performance variables (coherence and mean trial error) of the final test day. We also obtained the exponential fit to the decay in trial error and growth in coherence during first day training (skill acquisition). The Benjamini-Hochberg Method was used for multiple comparisons to ensure minimal loss of power and to reduce the effect of increased type II error.

Significance was determined by using critical value of 0.05. All statistical analysis was performed using SAS software (version 9.3).

RESULTS

Activity and Cognitive Characteristics

Self-reported activity levels were not different between young (mean=4210.17, SD=2959.47) and older individuals (mean=4815.69, SD=3556.28) ($t(62)=0.701$, $p=0.486$). However, cognitive assessment results were significantly different between ages (all p 's < 0.0001), with older adults earning lower cognitive performance scores than younger adults on List Sorting (mean $\pm$ standard deviation; young: 125.8 ± 7.8 , old: 113.5 ± 8.2), Flanker Test (young: 115.0 ± 5.9 , old: 106.2 ± 4.6), and Dimensional Change (young: 118.3 ± 8.8 , old: 107.0 ± 10.4).

Skill Acquisition and Consolidation

During the initial 20 acquisition trials of the visuomotor task, a lower error was achieved at increasing trial repetitions for increasing cognitive task complexity (Figures 3A,C; Day 1 Training). Control (CT as combined CT1 and CT2), simple cognitive task (DT1), and complex cognitive task (DT2) groups achieved a similar stable error in motor performance at trials 8, 12 and 17, respectively, indicating that no significant change occurred in the error beyond these points. Older adult groups (OCT, ODT1), with the exception of those performing the complex cognitive (ODT2) task, achieved a stable error level by the 8th trial (Figure 3B), and stable coherence level by the 12th trial (Figure 3D). Younger and older groups achieved similar final training performance except for older subjects performing the complex cognitive task (ODT2), who demonstrated 300% greater error (age $\times$ group: $F_{2,62}=9.83$, $p=0.0002$; post-hoc older age: group: $F_{2,21}=7.36$, $p=0.0003$, $\eta^2=0.41$) and 50% less coherence (age $\times$ group: $F_{2,62}=4.44$, $p=0.0157$; post-hoc older age: group: $F_{2,21}=5.53$, $p=0.0038$, $\eta^2=0.35$). Although not depicted, stratifying visuomotor performance by accuracy of the cognitive task revealed that when cognitive task error was high (more than ± 1 character count), visuomotor task error was higher compared to when cognitive task error was low (less than or equal to ± 1 character count error). During day 1 training, cognitive task error decreased from approximately 125% ([user count – actual count]/actual count) to approximately 10% (Figure 3A insert).

On Day 2 of testing, older individuals demonstrated less retention of learning compared to Day 1 final training (mean trial error: $F_{1,61}=14.52$, $p=0.0003$, $\eta^2=0.1923$; coherence: $F_{1,61}=15.23$, $p=0.0002$, $\eta^2=0.1998$), though within each age group (age*group $F_{1,61}=4.71$, $p=0.0126$, $\eta^2=0.1337$) retention of learning was similar across intervention groups (no significant post-hoc differences CT, DT1, DT2). Following five training trials on day 2, subjects performing a complex cognitive (DT2) task did not achieve the same level of performance on the motor task as the control (CT) and simple cognitive task (DT1) groups (coherence: $F_{2,62}=9.64$, $p=0.0002$, $\eta^2=0.2151$; trial error: $F_{2,62}=9.64$, $p=0.0002$, $\eta^2=0.2151$) (Figure 3A; Day 2 Reacquisition).

Transfer of Learning

During a 9-condition block of varied speed and resistance, the relative effect of altering motor task conditions was similar regardless of cognitive task (CT, DT1, DT2) within each younger (interaction: coherence $F_{16,322}=0.63$, $p=0.8569$, trial error $F_{16,322}=0.94$, $p=0.5910$) and older adult (interaction: coherence $F_{16,167}=1.29$, $p=0.2069$, trial error $F_{16,167}=1.62$, $p=0.0692$) group. There was a progressive increase in error (Figure 4A) and decrease in coherence (Figure 4C) with increasing resistance and velocity. For younger adults, error was, however, on average 1.1 degrees of knee flexion lower in the control group (YCT) compared to those performing a simple (YDT1) and complex (YDT2) cognitive task (group: coherence $F_{3,62}=15.92$, $p<0.0001$, $\eta^2=0.059$; trial error $F_{3,62}=17.94$, $p<0.0001$, $\eta^2=0.097$). Within the older group, there was an approximate 93% increase in error ($F_{2,203}=11.07$, $p<0.0001$, $\eta^2=0.0781$) and 65% decrease in coherence ($F_{2,203}=13.02$, $p<0.0001$, $\eta^2=0.0821$) at 0.6 Hz compared to 0.2 and 0.4 Hz (Figures 4 B,D). Older adults in the control (OCT) and simple cognitive (ODT1) task groups had similar error and coherence on new motor task conditions, while those performing the complex cognitive task (ODT2) consistently experienced greater error ($F_{2,21}=8.69$, $p=.0018$, $\eta^2=0.277$) and decreased coherence ($F_{2,21}=8.25$, $p=.0023$, $\eta^2=0.1081$).

Unexpected Events

Error rate and knee flexion rate were analyzed during the period after the release of the brake and before volitional reaction time (0-200 milliseconds after brake release (Figure 5). Main effects revealed that for younger and older adults, the unexpected release of the brake increased error rate ($F_{8,489}=33.70$, $p<0.0001$, $\eta^2=0.1990$) and knee flexion rate ($F_{8,489}=35.6$, $p<0.0001$, $\eta^2=0.286$) when task resistance and task velocity increased. Interestingly, post-hoc results show that older adults experienced slower knee flexion rates when exposed to the unexpected event as compared to younger adults (age $\times$ condition $F_{8,489}=2.84$, $p<0.0001$, $\eta^2=0.023$) at the highest task resistance and velocity. Unexpected release of the brake triggered greater error rate ($F_{2,62}=5.05$, $p=0.0093$, $\eta^2=0.035$) for the dual-task conditions (DT1 and DT2) for both younger and older adults as compared to control conditions (age $\times$ group: $F_{2,62}=1.52$, $p=0.2277$).

Dual Task Effect

Younger adults who trained with a cognitive task (YDT1, YDT2) demonstrated a dual-task *benefit*, where the dual-task effect for error ($F_{3,362}=29.93$, $p<0.0001$, $\eta^2=0.1859$; Figure 6A) and coherence ($F_{3,362}=27.49$, $p<0.0001$, $\eta^2=0.1685$; Figure 6C) indicated improved

performance under the dual-task condition. Conversely, older adults showed a dual-task *cost* for all groups (OCT1, OCT2, ODT1, ODT2), where generally performance was improved under the single-task condition regardless of whether or not they trained with a concurrent cognitive task. (Figures 6B,D). However, when training with only the motor task and then performing a complex cognitive task (OCT2), the older group demonstrated significantly higher dual-task cost compared to all other groups (coherence: $F_{8,179}=16.49$, $p<0.0001$, $\eta^2=0.1546$; trial error: $F_{8,179}=14.44$, $p<0.0001$, $\eta^2=0.1587$).

One week following the first training session, dual-task trained younger subjects (YDT1, YDT2) continued to have a lower magnitude of dual-task effect ($F_{8,362}=3.65$, $p=0.0004$, $\eta^2=0.0594$) when compared to subjects who trained without the dual-task (medium speed and resistance), though the control groups (YCT1, YCT2) demonstrated the dual-task benefit (Figures 7A,C). At the other 8 conditions, however, dual-task cost was similar across groups (post hoc, $p>0.05$). Interestingly, the older adults demonstrated a different trend. Older adults exposed to a complex cognitive task, be it during training or day 2 testing (OCT2, ODT2), had a higher dual-task cost compared to those exposed to a simple cognitive (OCT1, ODT1) task ($F_{8,179}=9.11$, $p<0.0001$, $\eta^2=0.1190$). This difference was maintained not only at the trained condition, but carried over to all resistances and velocities (group $\times$ condition: trial error: $F_{24,179}=0.38$, $p=0.9965$; coherence: $F_{24,179}=0.67$, $p=0.8798$) (Figures 7B,D). Older adults also demonstrated similar dual-task cost within each group across all conditions (trial mean: $p=0.2800$; coherence: $p=0.1827$).

Cognition and Motor Performance Correlations

Correlations were performed to determine the relationship between motor performance and cognition (Table 1). Working memory capacity was only able to explain 28.3% and 33.7% of the variability of the rate of learning for error and coherence on day 1 for the control group younger adults. Working memory capacity was not correlated with rate of learning for any dual-task groups or the older adult control groups. Executive function (Flanker test), however, explained between 71.9 and 89.5 percent of the variability in final day, trained condition motor performance of both younger and older adult dual-task trained groups. Executive function did not correlate with final performance of the control groups in either age group.

DISCUSSION

The major findings of this study were: 1) a cognitive load, added to a novel weight bearing visuomotor task, increased the learning time for young and old adults; 2) the cognitive load did not affect consolidation of the learned task; 3) the cognitive load decreased the capacity to transfer the learned visuomotor task to new conditions (resistance and velocity); 4) the cognitive load increased the error rate during the time immediately after the unexpected event (0-200 milliseconds) in both younger and older adults; 5) the cognitive load improved dual-task effect; and 6) executive function explained approximately 80% of the variability when training dual-task visuomotor performance.

Skill Acquisition and Consolidation

The ability to improve a motor task regardless of a simultaneous cognitive task has been examined by several previous studies (Malone & Bastian, 2010; M. Patel, Kaski, & Bronstein, 2014; Taylor & Thoroughman, 2007, 2008). In this study, all but one group demonstrated acquisition of the visuomotor task (exception was older adults who performed a simultaneous complex cognitive task (ODT2)). As cognitive task difficulty increased, however, the rate of learning slowed in the older adults performing a complex cognitive task; learning slowed so much that they achieved no significant motor improvement over the twenty training trials. Similarly, some studies have found that older adults are not able to achieve the same level of performance during dual-tasks as younger adults, even with extra practice (McDowd & Craik, 1988; Strobach, Frensch, Muller, & Schubert, 2012; Tsang & Shaner, 1998). It is likely, though, that the level of concurrent task difficulty continues to be influential on the capacity to reduce error during a single session of practice.

Previous dual-task learning studies have shown improved (An et al., 2014; Goh et al., 2012; Kim, Han, & Lee, 2014; Raisbeck, Regal, Diekfuss, Rhea, & Ward, 2015) and impaired (K. Gothe, Oberauer, & Kliegl, 2007; Makizako et al., 2012) performance. Here we showed no effect on consolidation of motor performance regardless of cognitive task complexity. This is interesting, considering our study employed motor and cognitive tasks that share central processing resources (visuomotor), which is posited to facilitate consolidation of learning (Goh et al., 2012). This differential finding may be related to the fact that in our study, the processing of both the cognitive and motor task was continuous over a period of time. Goh and others (2012) examined the benefit of central process-sharing between motor and cognitive tasks during the discrete time period related to planning of movement or the execution of reaching. Additional potential sources of variation in such studies include sleep duration/quality and motor cortex activation during training, both of which may influence consolidation. In addition, an “optimal” difficulty level may exist for cognitive tasks to enhance motor task consolidation. In the present study, it is unknown whether such an “optimal” level may have been achieved.

Although the emphasis of this study is on the motor learning and performance, some observations regarding the cognitive task may be identified. For most participants, both motor and cognitive task error started high and then declined simultaneously. This supports that attention is delivered to *both* visuomotor and visuo-cognitive tasks equally, as opposed to decreasing error in one domain before the other (Song & Bedard, 2013; Song et al., 2015). The exception to this equivalent cognitive-motor interference is that older adults performing the complex visuo-cognitive task (ODT2) significantly reduced cognitive task error by the end of training, though motor error and variability remained high. This may indicate that when older adults are presented with a difficult cognitive task, priority is differentially allocated to the cognitive task vs the motor task. This, however, would make the assumption that the difficult visuo-cognitive task would be achieved with 100% accuracy (0% cognitive task error) if presented without the context of the simultaneous motor task. Due to the emphasis on motor effects, baseline testing of the visuo-cognitive task alone, however, was not performed in this study. If this is indeed the case, it may constitute a major factor in the limited motor learning demonstrated by this group. The possible cognitive task

prioritization is interesting, as previous studies have shown that when not specifically directed to focus on one task or the other, subjects will adopt a “posture-first” strategy, focusing on the motor task rather than the cognitive task (Nnodim et al., 2015; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Sun & Shea, 2015). Our results may align with the concept that task prioritization is flexible, and may depend on the context of tasks (eg. instruction, task complexity, postural reserve, and hazard estimation) (Howard, Perry, Chow, Wallace, & Stokic, 2017; Kelly & Shumway-Cook, 2014; Yogev-Seligmann, Hausdorff, & Giladi, 2012). In this experiment, we allowed all subjects to have light touch on the testing frame and the rack and pinion system constrained movement to the sagittal plane. This may have provided sufficient postural support to eliminate fear of instability or falling, decreasing the need for postural protection strategies. Hence, participants may have been more at liberty to concentrate on the complex cognitive task.

Transfer of Learning

Few studies have attempted to quantify the transference of a motor skill that was acquired under a cognitive-motor dual task. In this study, when tested under 8 novel conditions, younger individuals continued to scale performance of new task conditions by resistance and velocity in a similar fashion to previous subjects who did not train using the visuomotor task (Tseng et al., 2017). However, an altered transfer was noted as the error and coherence curves shifted downward and upward, respectively. Younger adults showed a similar pattern of transfer (no group by condition interaction), though greater error and lower coherence were noted at each condition for those performing a dual-task compared to a single task. Older adults, on the other hand, showed a flattening of the resulting difficulty curve, with similar performance at the three resistances during the 0.2 and 0.4 Hz frequencies (conditions 1-6). This indicates that transfer was diminished for all older adult groups, though greater error and lower coherence indicated diminution of transfer for older adults performing a simultaneous complex cognitive task. Our findings in older adults are similar to a previous upper extremity reaching study, showing that transfer of visually rotated reaching decreases as the distance of the new reaching position deviates from the trained position (Bedard & Song, 2013).

This is a novel finding due to the need of older and younger individuals alike to vary the speed of movement to meet situational demands at a variety of task resistance levels. Interestingly, training of an upper extremity coordination task (spooning beans between cups; “feeding”) results in improvement in an unrelated upper extremity task (fastening buttons with the non-dominant hand; “dressing”) (Schaefer & Lang, 2012). Although the mechanism and neural basis of transfer in these studies were not determined, it does reveal that dual-task training may provide improvements not only in the trained task, but to motor tasks using similar effectors. Further, the transfer of one movement to a completely different movement using the same limbs may indicate that by starting a rehabilitation program with a more isolated repeated movement such as a single limb squat, task transfer may yield improvements in gait and other functional movements necessary for accomplishing activities of daily living.

Unexpected Events

During one of the five cycles of each trial, a force perturbation was elicited by rapidly reducing the resistance to null for less than a second. All age groups demonstrated a systematic increase in knee flexion rate with increase in resistance and frequency of the motor task, whereas error rate was most affected by resistance and higher rates of movement. This increase in error and knee flexion rate was similar to untrained task performers (Tseng et al., 2017), though shifted toward null as would be expected with improvements due to learning. One previous study showed that when an auditory stimulus was presented before, during, or after a force perturbation overlying an adapted reaching motion, no difference existed in the feedback response of the reaching motion, regardless of presentation (Taylor & Thoroughman, 2007). Here, however, we show that error rate was increased under all conditions when a complex cognitive task (DT2) was simultaneously performed. This finding is notable because it is generally believed that any reflex responses to perturbations bypass the central executive (Matthews, 1991), indicating that even when cognitive task demand is high, there should not be a more severe error when exposed to an unexpected event. Our findings are congruent with observations that static balance studies showed declines in visual working memory as postural demand increased (Elaine Little & Woollacott, 2014). They are also similar to postural perturbation studies that showed a diminished EEG response (N1) to perturbation during a dual-task, resulting in greater postural sway (Little & Woollacott, 2015).

Dual-Task Effect

Dual-task effect is the difference between dual-task and single-task performance (Nordin et al., 2010; Somberg & Salthouse, 1982; L. Yang et al., 2015), and allows insight into the capability of an individual to reduce central processing resources and/or stages of the motor task. When dual-task performance is poor compared to single-task, there is a dual-task cost; when dual-task performance is more accurate compared to single-task, there is a dual-task benefit. A movement that would be more efficient, allowing no interference from a cognitive task would result in a dual-task effect of null, or no difference in motor performance regardless of the presence of a cognitive task. We show that 48 hours after training, younger adults who trained with a dual-task (YDT1, YDT2) have a dual-task benefit, where the effect is near null and crosses the baseline of improved performance during dual-tasking. Younger adults who trained without a cognitive task (YCT1, YCT2), however, continue to demonstrate a dual-task cost. Older adults show a similar cost between groups, with the exception of an elevated cost in control subjects asked to perform with a difficult cognitive task (OCT2). This is similar to previous studies (Canning, Ada, & Paul, 2006; Y. R. Yang, Chen, Lee, Cheng, & Wang, 2007) where dual-task cost was significantly greater for all older aged groups, indicating that the decreased ability to automatize the visuomotor task resulted in similar dual-task cost when the cognitive task was simple. Comparing performance on similar tasks between groups in our study, however, revealed that when CT2 individuals performed the complex cognitive task, they performed similarly on the motor task as those who were trained with the complex cognitive task. Perhaps the simple cognitive task continued to allow enough central resources for the CT1 older adults to perform similarly to the dual-task trained group with poorer dual-task cost. Conversely, the

complex cognitive task created a high enough central processing demand to detract from the motor task regardless of previous exposure.

When younger subjects who trained on the dual task (YDT1, YDT2) returned 7 days later, they demonstrated a dual-task effect near null. Control subjects (YCT1, YCT2), on the other hand, performed *better* on the dual-task condition compared to their trained single-task condition now showing a dual-task benefit. Older adults again revealed a different dual-task cost compared to younger adults, where those exposed to the simple cognitive task, whether during training or testing (OCT1 and ODT1), had improved efficiency of processing compared to those exposed to the complex dual-task (OCT2 and ODT2). Interestingly, the OCT2 group was able to generalize learning to improve performance, unlike the ODT2 group, who did not improve dual-task performance. It appears that while simple cognitive task performers could continue to improve with repeated exposure to the task, high attentional task demands prevented complex task performers from improving their motor performance. These results might be influenced due to training order, as single-task trained subjects performed nine conditions of the visuomotor task without a cognitive task, followed by nine conditions of a dual-task. Another possible explanation may be the benefit of hybrid training (Silsupadol et al., 2006; Song et al., 2015; Strobach, Frensch, Soutschek, & Schubert, 2012). Although inconsistent results exist in the literature, it may be that for younger adults, training first with a single-task and then being exposed to several trials of a dual-task (nine conditions on the second day), is optimal. For older adults, however, maintaining a lower level of cognitive load while training and testing motor performance reduces dual-task cost of the motor task with longer-term training. In the present study, the older DT1 group who performed a complex cognitive task (instead of simple or no cognitive task) far out-performed the older DT2 group who performed only the simple cognitive task (instead of complex or no cognitive task) (data not shown). This suggests that training with a low cognitive load not only enhances central processing, but prepares the older adult for performing under heavier cognitive load. Certainly, it may also be that with a substantial cognitive load, older adults need substantially greater practice (Strobach, Frensch, Soutschek, et al., 2012), or that the capacity to reduce central processing of a coordination or weight-bearing movement may be impaired with older age.

Cognition and Motor Performance

Discrepancies in older and younger adult dual-task capability may be due to differences in neural substrate activation. Although dual-task performance for younger and older adults may activate similar brain regions (Al-Yahya et al., 2015; Erickson et al., 2007a, 2007b; Godde & Voelcker-Rehage, 2017; N. P. Gothe et al., 2014), older adults employ compensations by distributing activation throughout the frontal cortex (Erickson et al., 2007b; Hartley, Jonides, & Sylvester, 2011; Reuter-Lorenz & Lustig, 2005). This increases activation of the sensorimotor cortex (Heuninckx, Wenderoth, & Swinnen, 2008), including the temporal and occipital lobes (Bogost, Burgos, Little, Woollacott, & Dalton, 2016). The frontal cortex is identified as a major contributor to dual-task performance due to involvement in both motor planning (Poldrack et al., 2005) and rule-set shifting (McCabe et al., 2010). Other key contributors include the cerebellum (Lang & Bastian, 2002; Wu, Liu, Hallett, Zheng, & Chan, 2013) and dorsal pre-motor cortex (Goh, Lee, & Fisher, 2013).

Many of these substrates also play a role in executive function and working memory capacity, which also declines with older age (Tulsky et al., 2014; Zelazo et al., 2014). In the past decade, evidence has begun to accumulate regarding the relationship of motor performance and cognition.

In this study, we correlated cognitive performance measures of working memory capacity and executive function to motor learning and performance of the single motor and cognitive-motor tasks. Here we found that the greatest predictor of delayed retesting of trial error was the Flanker Test executive function measure of attention and inhibitory control. Working memory capacity only explained ~30% of the variability in the rate of learning, for the young control adults only. The working memory test used in this study incorporates both auditory and visual working memory capacity: this may allow auditory system compensation during cognitive testing, while only visual working memory capacity is employed during the visuo-cognitive and motor testing. Working memory capacity has been correlated to single-task motor learning in younger adults (Bo & Seidler, 2009), though its role is more complex in older adults (Anguera, Reuter-Lorenz, Willingham, & Seidler, 2010, 2011). This suggests that the relationship between aging, cognitive load, and working memory capacity is much more complex than for younger adults learning a motor task without concurrent tasks.

Executive function had a much stronger relationship, accounting for 72-90% of the variability of error during dual-tasks for older and younger adults. Executive function moderately predicted final day coherence, though only for young adult controls, simple cognitive task performers, and older adults performing a complex cognitive task. Improvements in motor function attributed to executive function were much lower in one previous study of older adults (N. P. Gothe et al., 2014), accounting for only approximately 6% of the variance. This may be due, however, to clumping generalized gross motor adaptations rather than precisely measuring movement error as in this study.

It is interesting that executive function correlated to coherence and error differently. A previous dual-task gait training study in 228 healthy, older adults determined that executive function predicted change in swing time, though not gait speed for dual-task walking (Hausdorff, Schweiger, Herman, Yogev-Seligmann, & Giladi, 2008). They explain this finding by positing that different components of functional movement may be controlled by systems that are differentially affected by executive function. This may indeed be the case in our study as well, where matching the rate of movement may be controlled by different central networks than error of movement.

CONCLUSION

Our results demonstrate that even in a healthy population of older adults, differences exist in dual-task learning compared to younger adults. Dual-task performance with a complex cognitive task eliminated the ability of older adults to improve motor performance, while a simple task only slowed the rate of learning for all age groups. Older adults had a reduced capacity to transfer a learned movement to new conditions of resistance and movement rate compared to young adults; little transfer occurred when older adults performed a complex

cognitive task. Dual-task cost was greatest for older adults who were exposed to a simple cognitive load. Finally, executive function of attention and inhibitory control accounted for ~80% of error of final performance, possibly supporting its use as a prognostic factor for motor learning.

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Experimental Setup

Figure 1. Experimental setup.

Top left: schematic of the standing frame, monitor, and rack and pinion knee resistance / force measurement system. Top right: representative example of user generated line (dashed) and target line (solid line) of the five-cycle sinusoid task. Bottom right: nine speed $\times$ resistance combinations of the testing paradigm. Training is performed under condition 1 (medium speed and medium resistance).

Figure 2. Experimental Design.

Testing conditions presented for four training groups on three different days (Day 1, Day 2, and Day 3). Testing flow begins at the top of each column (Day 1), continuing to the bottom of the same column (Day 3). Each group (CT1, CT2, DT1, DT2) contains 10 younger adults and 6 older adults.

Figure 3. Skill Acquisition and Retention Full Trial Analysis.

Twenty training trials on day 1, and 5 training trials 48 hours later were performed without distraction (closed circle: Control), a simple cognitive task (open circle: Dual-Task 1), and a complex cognitive task (open triangle: Dual-Task 2). Mean and standard deviation of the absolute value of trial mean (A,B), and Coherence (C,D) is presented. # = Older adults in the dual-task 2 group experienced greater error and lower coherence compared to all other groups on day 1, and in both younger and older adults on day 2. & = Older adults with higher error or lower coherence from younger adult for similar training group ($p < 0.05$).

Figure 4. Transfer of Learning: Full Trial Variables.

Trial Error (A,B) and Coherence (C,D) for younger (A,C) and older (B,D) adults, performing only the motor task (control, closed circle), and simultaneous motor, and simple (open circle) and complex (open triangle) cognitive tasks. The left side depicts each individual combination and the right side depicts the mean of three trials of each resistance and velocity. * = younger controls perform differently than dual-task groups. ^ = condition of resistance or velocity is significantly different from the others. # = older dual-task 2 group

different from other older groups. #* = indicates dual-task 2 group only different from the control group.

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Figure 5. Transfer of Learning: Non-Volitional Feedback Variables.

Knee flexion rate (A,B) and error rate (C,D) 50-200 ms following an unexpected force perturbation for younger (A,C) and older (B,D) adults, performing only the motor task (control, closed circle), and simultaneous motor, and simple (open circle) and complex (open triangle) cognitive tasks. The left side depicts each individual combination and the right side depicts the mean of three trials of each resistance and velocity. ^ = condition of resistance or velocity is significantly different from the others. ^* = condition different from each condition

with the same symbol. #* = dual-task 2 group only different from the control group. & = all older adult groups different from the younger adult groups.

Figure 6. Dual-Task Cost: Day 2.

Younger (A,C) and Older (B,D) adults performed both a single motor (closed symbol) and dual cognitive-motor (open symbol) tasks. Presented is the difference in motor performance between single and dual-task conditions at each resistance and velocity. ###** = dual-task groups different from control groups. ** = CT2 group different from all other groups. *** = both CT2 and CT1 different and different from dual-task groups. ^* = different from other conditions with the same symbol.

Figure 7. Dual-Task Cost: Day 3.

Young (A,C) and Older (B,D) adults performed both a single motor (closed symbol) and dual cognitive-motor (open symbol) tasks. Presented is the difference in motor performance between single and dual-task conditions at each resistance and velocity. ###** = dual-task groups different from control groups. #* = CT1 and DT1 different from CT2 and DT2. * = CT1 different from DT2. ^* = different from other conditions with the same symbol.

**Table 1-
Motor Task and Cognitive Test Performance Correlations.**

Bold and asterisk values indicate significant correlation using a critical value of 0.05.

Cognition Measure	Dependent Variable	Age Group	Patient Group	R-squared	p-value	BH adjusted p's
Working Memory (List Sorting)	Decay Exponent fit to <i>Trial Error</i> during 20 Training Trials	Younger Adults	Control	0.283	0.017*	0.0035*
			DT1		0.512	0.3840
			DT2		0.206	0.1030
		Older Adults	Control		0.905	0.9050
			DT1		0.422	0.2638
			DT2		0.622	0.5702
	Growth Exponent fit to <i>Coherence</i> during 20 Training Trials	Younger Adults	Control	0.337	0.005*	0.0004*
			DT1		0.242	0.1311
			DT2		0.554	0.4617
		Older Adults	Control		0.085	0.0354*
			DT1		0.701	0.6718
			DT2		0.541	0.4283
Executive Function (Flanker)	Final Day <i>Trial Error</i> on Trained Condition (Medium Speed and Resistance)	Younger Adults	Control		0.591	0.5171
			DT1	0.755	0.024*	0.0070*
			DT2	0.760	0.0236*	0.0059*
		Older Adults	Control		0.484	0.3428
			DT1	0.719	0.032*	0.0120*
			DT2	0.895	0.004*	0.0002*
	Final Day <i>Coherence</i> on Trained Condition (Medium Speed and Resistance)	Younger Adults	Control	0.327	0.008*	0.0010*
			DT1	0.475	0.027*	0.0090*
			DT2		0.471	0.3140
		Older Adults	Control		0.357	0.2083
			DT1		0.137	0.0628
			DT2	0.889	0.014*	0.0023*