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RESEARCH ARTICLE

# Memory-guided force control in healthy younger and older adults

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**Abstract** Successful performance of a memory-guided motor task requires participants to store and then recall an accurate representation of the motor goal. Further, participants must monitor motor output to make adjustments in the absence of visual feedback. The goal of this study was to examine memory-guided grip force in healthy younger and older adults and compare it to performance on behavioral tasks of working memory. Previous work demonstrates that healthy adults decrease force output as a function of time when visual feedback is not available. We hypothesized that older adults would decrease force output at a faster rate than younger adults, due to age-related deficits in working memory. Two groups of participants, younger adults (YA: $N = 32$, mean age 21.5 years) and older adults (OA: $N = 33$, mean age 69.3 years), completed four 20-s trials of isometric force with their index finger and thumb, equal to 25% of their maximum voluntary contraction. In the full-vision condition, visual feedback was available for the duration of the trial. In the no vision condition, visual feedback was removed for the last 12 s of each trial. Participants were asked to maintain constant force output in the absence of visual feedback. Participants also completed tasks of word recall and recognition and visuospatial working memory. Counter to our predictions, when visual feedback was removed, younger adults decreased force at a faster rate compared to older adults and the rate of decay was not associated with behavioral performance on tests of working memory.

**Keywords** Grip force · Motor control · Healthy aging · Visuomotor memory · Working memory

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## Introduction

Healthy aging is accompanied by changes in motor control that compromise dexterity as well as changes in cognition that can compromise daily activities such as driving, social interaction, and planning. In particular, precision gripping is an important task for activities of daily living, especially eating, writing, and self-care. Age-related changes in precision grip, such as reduced accuracy and increased variability during sustained force, may lead to reduced functional independence in older adults (Incel et al. 2009). Cognitive aging represents the gradual and ongoing change in cognition with advancing age. Cognitive aging affects many cognitive functions; however, the progression is uneven and highly variable across individuals and areas of cognition. For example, age-related deficits are significant in tasks involving working memory; however, tasks of implicit memory reveal only slight decrements (Craik 2000; Grady and Craik 2000). The goal of the present work was to compare performance on motor and cognitive tasks in healthy younger (YA) and older (OA) adults. Specifically, we sought to determine if performance on a motor memory task is related to performance on tasks of short-term memory span and visuospatial working memory.

In a seminal investigation of memory-guided grip force control in young adults, Vaillancourt and Russell reported that force output decays 0.5–1.5 s after visual feedback is removed (Vaillancourt and Russell 2002). This finding suggests that memory-guided force output may be dependent on the decay of visual information in short-term working memory. However, in a second experiment, Vaillancourt and Russell (2002) reported a similar period of force decay when the target amplitude is specified by the individual and not by visual feedback. The authors concluded that short-term motor memory decays after 0.5–1.5 s and, in turn, decreases the net activity of the motor neuron pool supporting the action. Thus, in the absence of visual feedback, participants initially rely on proprioceptive (Johansson and Cole 1992) and somatosensory (Johansson and Cole 1992; Johansson and Westling 1984; Marsden et al. 1983) feedback and then subsequently rely on stored internal representations to make adjustments (Vaillancourt and Russell 2002). In two recent investigations, our group evaluated memory-guided grip force control in individuals with Attention-Deficit/Hyperactivity Disorder (ADHD; Neely et al. 2016a) and Autism Spectrum Disorder (ASD; Neely et al. 2016b). We reported a steeper rate of force decay for both ADHD and ASD compared to age- and sex- matched controls. Further, the rate of force decay was associated with more severe social-communication abnormalities and reduced cognitive abilities in individuals with ASD (Neely et al. 2016b) and with ADHD-related symptoms and trait impulsivity in young adults with and without ADHD (Neely et al. 2016a). As a result, we suggested that the decay of force output in the absence of visual feedback could be related to deficits in short-term or visuospatial working memory; however, we did not explicitly measure memory in either study. Although motor memory has been examined in studies of continuous force production without visual feedback (Neely et al. 2016a, b; Poon et al. 2012; Vaillancourt et al. 2001; Vaillancourt and Russell 2002), no extant studies have investigated the relationship between memory-guided force and specific neuropsychological measures of short-term or working memory. The present investigation sought to address this gap by studying the association of age-related differences in working and short-term memory and memory-guided force control. Given that age-related deficits in working memory are well established in the cognitive aging literature (e.g., Park et al. 2002), we reasoned that older adults with greater memory impairment during the behavioral tests of word recall, word recognition, and visuospatial working memory would exhibit greater force decay in the absence of visual feedback.

The notion of a link between memory and the motor system is not novel. Working memory is paramount for the acquisition of many cognitive and motor skills (Adams 1971; Anderson 1982). Indeed, Seidler and colleagues consistently report that differences in visuospatial working memory (Anguera et al. 2010; Bo et al. 2009, 2011, 2012; Bo and Seidler 2009; Seidler et al. 2012) and non-visuospatial working memory (Bo et al. 2012; Seidler et al. 2012) are related to differences in motor learning. In the present study, younger and older adults completed 20-s trials of isometric force with their index finger and thumb, to a target equal to 25% of their maximum voluntary contraction. In the full-vision condition, participants received real-time visual feedback for the duration of the trial. In the no-vision condition, visual feedback was removed after 8 s and participants were instructed to maintain force production for the remaining 12 s. The between-groups comparison of force output in the full-vision condition provided a means to exclude fatigue and age-associated changes in motor control as explanations for force decay in the absence of visual feedback. For example, the number of spinal motor neurons begins to decrease after age 60 (Campbell et al. 1973; Tomlinson and Irving 1977) and cortical projections to spinal motor neurons may begin to decrease by age 50 (Eisen et al. 1996). Previous work reported that older adults have difficulty integrating visual feedback to guide force output (Baweja et al. 2015; Kennedy and Christou 2011), have reduced tactile sensitivity (Decorps et al. 2014), and elicit greater variability in the motor unit discharge rate (Enoka et al. 2003). Thus, if age-related differences in force production are observed in the full-vision condition, it may be due to age-associated changes in visuomotor control. The primary goal of the current study was to examine force output in the no-vision condition and its relation to neuropsychological measures of working and short-term memory. We hypothesized that if motor memory draws on the same cognitive systems as working and short-term memory, performance on behavioral tests of word recall, word recognition, and visuospatial working memory would be associated with performance on a memory-guided force task.

## Methods

### Participants

Young adults (YA), ages 18–25, and healthy older adults (OA), ages 60–85, were recruited through the Participants Across the LifeSpan (PALS) Database and local flyers in the Centre County Region. As shown in Table 1, the mean age of the YA group ($N = 32$, 16 females) was 21.5 years (SD 1.8 years). The mean age of the OA group ($N = 33$, 20 females) was 69.3 years (SD 6.5 years). Participants were excluded if they reported a musculoskeletal disorder, history of head injury, color blindness, or neurologic/seizure disorder. OA were excluded if they

**Table 1** Participant characteristics

| Variables | Group | | Significant group differences |
|---|---|---|---|
| | OA | YA | |
| Sample size | 33 | 32 | |
| Females | 20 | 16 | |
| Age, years | 69.27 (6.47) | 21.53 (1.80) | **OA > YA, F(1,64) = 1621.69, *p* < 0.001** |
| Years of education | 17.16 (2.49) | n/a | |
| GDS | 0.53 (0.72) | n/a | |
| MVC, Newtons | | | |
| Right pinch | 24.33 (10.72) | 45.06 (14.69) | **OA < YA, F(1,64) = 42.40, *p* < 0.001** |
| Left pinch | 25.73 (11.20) | 40.83 (13.63) | **OA < YA, F(1,64) = 23.88, *p* < 0.001** |
| Visospatial working memory | | | |
| Accuracy (%) | 67.64 (9.20) | 78.36 (8.76) | **OA < YA, F(1, 64) = 23.14, *p* < 0.001** |
| Reaction time (ms) | 950.13 (186.13) | 851.63 (259.35) | OA = YA, F(1, 64) = 3.11, *p* = 0.083 |
| Recognition | | | |
| Accuracy (%) | 89.58 (5.88) | 87.89 (10.73) | OA = YA, F(1, 64) = 0.63, *p* = 0.431 |
| Reaction time (ms) | 1269.30 (252.03) | 1007.41 (261.21) | **OA > YA, F(1, 64) = 16.93, *p* < 0.001** |
| Word recall | | | |
| Immediate (accuracy) | 10.84 (2.29) | 11.00 (2.16) | OA = YA, F(1, 64) = 0.075, *p* = 0.785 |
| Delayed (accuracy) | 9.21 (2.74) | 9.25 (2.75) | OA = YA, F(1, 64) = 0.003, *p* = 0.955 |

Values are means and standard deviations (in parentheses). Significant differences noted in bold font

scored below 27 on the Mini-Mental State Examination, indicating cognitive impairment (Folstein et al. 1975), and if they scored above 5 on the Geriatric Depression Scale (Yesavage et al. 1982). No participants were taking medications known to affect motor control at the time of testing, including antipsychotics, or anticonvulsants (Reilly et al. 2008). As noted in Table 1, OA reported an average of 17.16 SD 2.49 years of education. In terms of the highest level of education achieved for the YA: 7 individuals had a high school degree or equivalent, 14 had some college or post-high school education, 10 were college graduates, and 1 had an advanced graduate or professional degree.

## Procedure

The experimental task was part of a larger battery of experimental and standardized measures that took place in one 2.5 h session. After a complete description of the study, written informed consent was obtained from each participant. The Institutional Review Board at The Pennsylvania State University approved all procedures and they were consistent with the Declaration of Helsinki. All participants received monetary compensation for their participation in the study. During the laboratory session, participants completed neuropsychological measures to assess cognitive function, including working memory, and motor measures to assess manual dexterity, strength, and force production.

## Neuropsychological measures

Participants completed a battery of cognitive and motor measures to assess inhibitory control, memory, and manual dexterity. Verbal memory was assessed using two separate word recall tasks and a word recognition task adapted from the California Verbal Learning Task (Delis et al. 2000). In the immediate recall task, 16 concrete-object words (e.g., tangerines, jacket) were presented on the monitor one at a time using E-Prime (E-Prime 2.0, Psychology Software Tools, Inc., Sharpsburg, PA). Each word was shown for 3000 ms with a 1500 ms inter-stimulus interval, during which a fixation cross was displayed. Participants were instructed to say each word aloud as it appeared. After the last word, participants were given 4 min to complete a verbal recall of the words (i.e., immediate recall). Twenty minutes later, participants were given 4 min to complete a verbal recall of the words (i.e., delayed recall). Immediately following the delayed recall session, participants completed a word recognition task wherein concrete-object words were displayed on a computer screen one at a time. Participants indicated whether each word had been shown previously ("old") or if the word was "new". Participants completed 32 trials in the word recognition task.

Participants completed a visuospatial working memory task adapted from Saults and Cowan (2007). In this task, participants compare two patterns of colored squares that are identical in size and shape; however, the arrangement and selection of colors within the patterns is different. Each visual stimulus was presented independently. The trial timeline was as follows: centrally presented fixation cross for 200 ms, presentation of first visual stimulus for 1050 ms, a blank screen for 1400 ms, presentation of second visual stimulus for 1050 ms, and last, a blank screen for 2500 ms. During the last 2500 ms, participants indicated whether the two visual stimuli were identical or different. Participants were instructed to respond as quickly and accurately as possible. Trial-by-trial feedback was presented to the participant with response time in milliseconds and accuracy rate over all completed trials.

### Motor measures

The Purdue Pegboard Test was used to evaluate fine motor control and bimanual coordination (Buddenberg and Davis 2000). This task includes three subtests wherein participants must place metal pegs into holes as quickly as possible using their dominant hand, their non-dominant hand, or both hands simultaneously (Espe-Pfeifer and Wachsler-Felder 2000). Each subtest was scored based on the number of pins placed in 30 s. A fourth test requires the assembly of a pin, two washers, and a metal collar at each hole on the pegboard and is scored based on the number of pieces placed in 1 min. Participants completed each subtest two times and were provided with an opportunity to practice each subtest once to confirm understanding of the task instructions.

Precision grip strength was assessed by obtaining each participant's maximum voluntary contraction (MVC) using a pinch grip dynamometer (Lafayette Hydraulic Gauge, Lafayette, IN). The average of three 5-s trials determined each participant's MVC in Newtons.

### Grip force task

The precision grip task studied here has been employed in previous investigations to understand how visuomotor control of grip force is impaired in Autism Spectrum Disorders (Mosconi et al. 2015; Wang et al. 2015), attention deficit hyperactivity disorder (Neely et al. 2016b), Parkinson's disease (Vaillancourt et al. 2001) atypical parkinsonian disorders (Neely et al. 2013), and essential tremor (Neely et al. 2015; Poon et al. 2011). Visual stimuli were presented on a 102 cm (40-inch) Samsung television screen with resolution 1920 × 1080 and a 120 Hz refresh rate. Participants were seated upright in a chair (JedMed Straight Back Chair, St. Louis, MO) with a horizontal distance of 127 cm from the screen. The forearm of the dominant arm rested in a relaxed position at approximately 100° of flexion on an adjustable non-tilting hospital table. The room was dimly lit to limit glare and reflection on the screen. As shown in Fig. 1a, participants used their thumb and index finger to press against two ELFF-B4 model load cells constructed from piezoresistive strain gauges (Measurement Specialties, Hampton, VA). Force data was collected by Coulbourn Instruments Type B V72-25B amplifiers at an excitation voltage of 5 V. The force signal was transmitted via a 16-bit A/D converter and digitized at 62.5 Hz. The A/D board units were transformed to Newtons using a calibration factor derived from known weights. The voltage range was −10 to 10 V, and the A/D board was able to detect force levels as low as 0.0016 N. The summed output from the load cells was presented to the participant on the television screen. Voltage data acquisition, voltage-to-force transformation, and stimuli presentation were all conducted using customized programs written in LabVIEW (National Instruments, Austin, TX).

During the task, participants viewed two horizontal bars: a red/green force bar that moved up with increasing force and down with decreasing force, and a static white target bar. The target bar was set at 25% of each participant's MVC. The onset and offset of force production were cued by a color change of the moveable force bar. Green served as the go cue and red as the stop cue. Participants were instructed to produce force as quickly and as accurately as possible at the time of the color change from red to green and to keep the green bar at the target force level for the duration of the 20-s trial, until offset of force was cued. As shown in Fig. 1b, each run started and ended with 10 s of rest and included four 20-s trials of force with 10 s of rest in between each trial. During full-vision (FV) trials, the moveable force bar was visible for the duration of the trial, providing real-time visual feedback about performance. As shown in Fig. 1c, during the no-vision (NV) trials, the force bar disappeared for the last 12 s of the trial. Participants were instructed to continue producing force at the target level until the trial ended. Participants completed one run of four 20-s FV and one run of four 20-s NV trials. Task order was counterbalanced across participants. All participants completed a brief practice session to become familiar with the timing and force output requirements of the task.

### Analysis of neuropsychological and motor measures

We calculated percent accuracy as the outcome variable for visuospatial working memory, and word recognition tasks. For the immediate and delayed recall tasks, number of

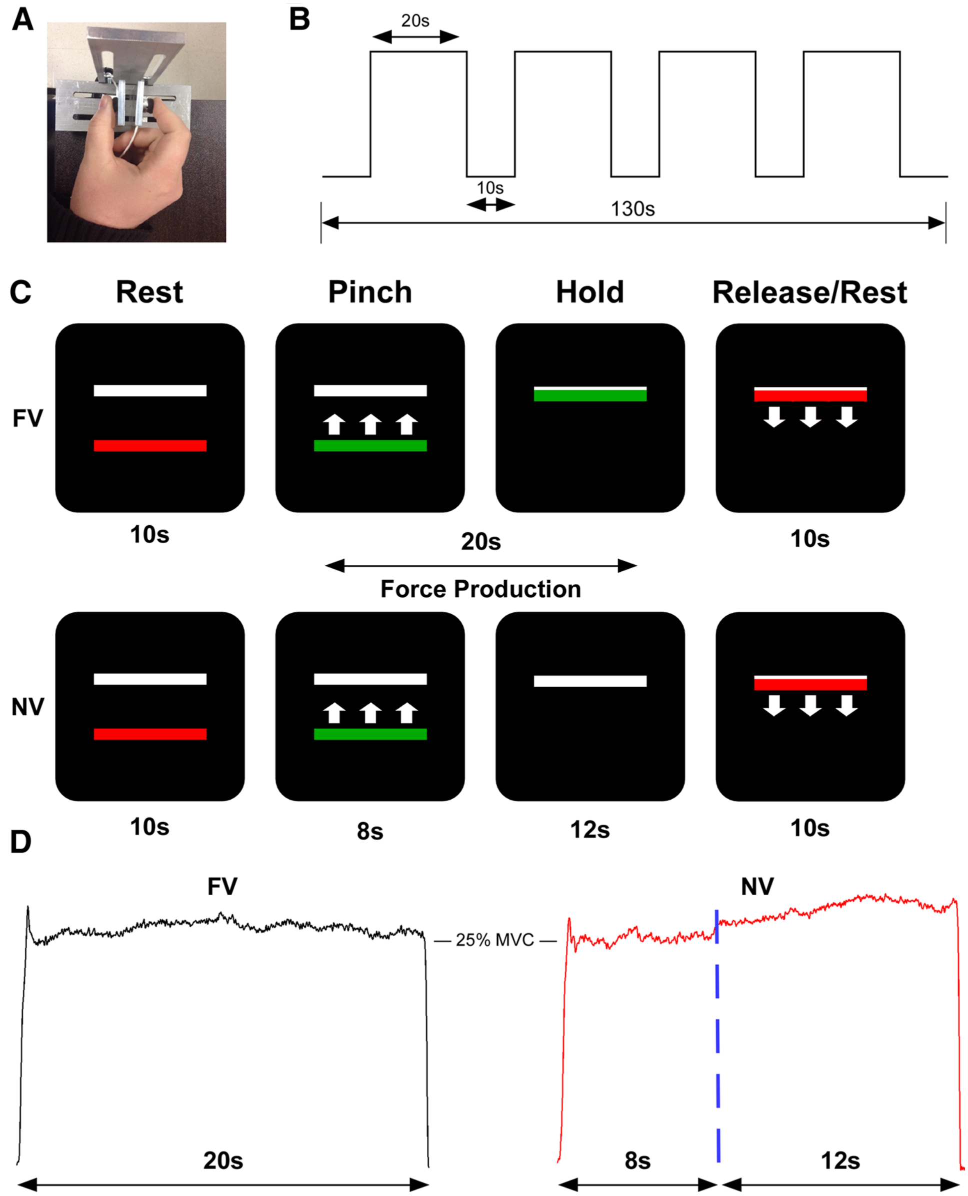


**Fig. 1** Healthy young ($N = 32$) and older ($N = 33$) adults completed 20-s trials of isometric force with their index finger and thumb to produce 25% of their maximum voluntary contraction. **a** The precision grip apparatus. **b** The experimental timeline for the full-vision (FV) and no-vision (NV) conditions. **c** The visual display for the FV and NV conditions. **d** Raw force output from one trial for an exemplar healthy older adult participant during the FV and NV conditions. *Hatched blue line* represents when visual feedback was removed

correct words (i.e., raw score) was the outcome variable. In addition, we calculated reaction time (RT) in the visuospatial working memory, and word recognition tasks. Manual dexterity was determined using the average of two trials of each subtest was obtained for the Purdue Pegboard Test. Similarly, hand and precision grip strength was determined by averaging the three trials to determine each participant's maximum voluntary contraction (MVC) in Newtons.

### Analysis of grip force output

The force time series data was digitally filtered using a tenth-order Butterworth filter with a 15 Hz low-pass cut-off frequency. Visual inspection of force output was performed and four time-points were determined for each trial: onset of force, beginning and end of force production, and offset of force. The 10-s periods of rest between each trial were removed from data analysis. The remainder of the data was averaged into 80-one second epochs to account for the four 20-s trials of force. Mean force was calculated for each 1-s epoch. All calculations were conducted with custom algorithms in MATLAB. Since the primary goal of this study was to evaluate group differences in force production when visual feedback was not available, we examined the last 12-s of each 20-s trial, which represents the time in which visual feedback was removed in the NV condition. Mean force was averaged across the four trials for each participant.

## Results

### Group differences in neuropsychological and motor measures

Table 1 reports the results for Univariate analyses of variance (ANOVA) for group (YA, OA) that were conducted to evaluate differences on the word recall-immediate, word recall-delayed, word recognition, Purdue Pegboard, and strength tasks. Briefly, YA were stronger than OA as measured by the pinch grip dynamometer test and YA out-performed older adults on all subtests of the Purdue Pegboard Task. YA were more accurate, but not faster than OA on the visuospatial working memory task. In contrast, no differences in accuracy were revealed for the word recognition task; however, OA were slower to respond compared to YA. Last, group differences in accuracy were not observed for the immediate or delayed verbal recall tasks.

### Grip force control

Figure 2 displays the mean force output for each group as a function of time, for each visual condition, in the last 12 s of the trial. Mean force output was submitted to a mixed model ANOVA for vision (FV, NV) by time (12-1-s epochs) by group (OA, YA). Within-subjects effects are reported with Huynh–Feldt correction to attenuate the violation of the assumption of sphericity. The results of this analysis revealed main effects of vision, $F(1.00, 63.00) = 34.49$, $p < 0.001$, $\eta_p^2 = 0.35$, time, $F(2.00, 127.70) = 29.82$, $p < 0.001$, $\eta_p^2 = 0.32$, and group, $F(1, 63) = 20.01$, $p < 0.001$, $\eta_p^2 = 0.24$, as well as interactions for vision by group, $F(1.00, 63.00) = 12.55$, $p = 0.001$, $\eta_p^2 = 0.17$, vision by time, $F(2.22, 140.09) = 37.46$, $p < 0.001$, $\eta_p^2 = 0.37$, and vision by time by group, $F(2.22, 140.09) = 5.20$, $p = 0.005$, $\eta_p^2 = 0.08$. To examine interactions involving vision, we next proceeded with separate mixed model ANOVAs for time (12-1-s epochs) by group (OA, YA) for each visual condition. In the FV condition, this analysis yielded an effect of group, $F(1, 63) = 8.25$, $p = 0.006$, $\eta_p^2 = 0.12$, such that OA (25.24% MVC SD 0.06%) produced more force than YA (24.82% MVC SD 0.06%) across the last 12 s of FV trials. No additional main effects or interactions were observed.

In the NV condition, the results demonstrated an effect of time, $F(1.79, 112.77) = 37.92$, $p < 001$, $\eta_p^2 = 0.38$, and group, $F(1, 63) = 17.84$, $p < 0.001$, $\eta_p^2 = 0.22$, and an interaction of time by group, $F(1.79, 112.77) = 4.03$, $p = 0.024$ $\eta_p^2 = 0.06$. As shown in Fig. 2, independent *t* tests for mean force at each 1-s epoch revealed group differences at every epoch (all ps < 0.001), demonstrating that OA produced more force than YA for the last 12 s of NV trials. We calculated the slope of the regression line for each participant to confirm that the decay of force output was steeper for YA (−0.27 SD 0.25) compared to OA (−0.15 SD 0.21) [$t(63) = -2.19$, $p = 0.032$].

Standard deviation of force was submitted to a mixed model ANOVA for vision (FV, NV) by time (12-1-s epochs) by group (OA, YA). The results of this analysis revealed a main effect of time, $F(11, 2.09) = 4.04$, $p = 0.018$, $\eta_p^2 = 0.6$, and interactions of vision by group, $F(1, 63) = 12.26$, $p = 0.001$, $\eta_p^2 = 0.16$, and time by group, $F(11, 131.62) = 2.73$, $p = 0.002$, $\eta_p^2 = 0.41$. To examine the vision by group interaction, we next proceeded with separate mixed model ANOVAs for time (12 1-s epochs) by group (OA, YA) for each visual condition. The results for the FV condition demonstrated an interaction for time by group [$F(2.56, 160.52) = 3.36$, $p = 0.027$, $\eta_p^2 = 0.05$]. Independent *t* tests at each 1-s epoch revealed that OA were more variable than YA at the 11th epoch [$t(63) = -2.31$, $p = 0.024$]. The results for the NV condition demonstrated a main effects of group $(1, 63) = 11.07$, $p = 0.001$, $\eta_p^2 = 0.15$), such that YA (0.53% MVC SD 0.18% MVC) were more variable than OA (0.41% MVC SD 0.07%). The results also revealed a main effect of time [F(2.19,

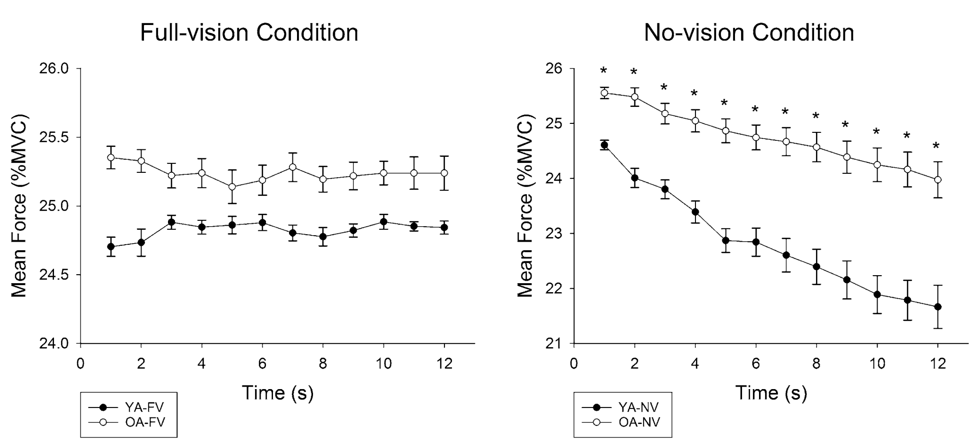


**Fig. 2** Mean force, in percent MVC, as a function of visual condition, group, and time. Data represent the last 12 s of trials in the full-vision (FV) and no-vision (NV) conditions. *Error bars* represent standard error of the mean

138.07) = 3.69, $p$ = 0.024, $\eta_p^2$ = 0.06]. Visual inspection demonstrated that the standard deviation of force was greatest at the first two epochs after visual feedback was removed. Thus, we conducted paired $t$ tests to examine differences between means at adjacent epochs. The results of this analysis demonstrated that a difference in variability occurred at between epoch 2 and 3 [$t$ (64) = 2.30, $p$ = 0.025], but that all other neighboring epochs were not different. The effect of group was such that YA (0.53% MVC SD 0.18% MVC) were more variable than OA (0.41% MVC SD 0.07%).

### Association with neuropsychological measures

Our previous work examining visuomotor memory demonstrated an association between the slope of the regression line for each participant and ratings of clinical symptomatology, and/or cognitive measures (Neely et al. 2016a, b). We used the same strategy in the present work and conducted five bivariate Pearson correlations between slope and performance measures for immediate and delayed recall, word recognition, and visuospatial working memory tasks. We also conducted three bivariate correlations between slope and RT for the word recognition, and visuospatial working memory tasks. The results of this analysis did not yield any significant correlations (all ps > 0.132).

## Discussion

Successful performance of the memory-guided force task requires participants to actively store and maintain an accurate representation of the motor goal in the absence of visual feedback. Further, participants must monitor force output to make adjustments in the absence of visual feedback. These are functions of short-term and working memory, and thus we hypothesized that the decay of force output observed in our previous work (Neely et al. 2016a, b) may be related to performance on memory tasks. To that end, we recruited healthy younger and older adults to examine how age-related deficits in short-term and working memory are related to motor memory. Since age-related deficits in working memory are well documented (Craik 2000; Grady and Craik 2000; Park et al. 2002), we anticipated that younger adults would outperform older adults in both neuropsychological tests of working memory and our memory guided force task. Further, we hypothesized that performance on the force task would be associated with verbal recall and visuospatial working memory. We report three novel findings. First, when real-time visual feedback was available, OA produced more force than YA. Second, when visual feedback was removed, OA were better than YA at maintaining force output, and thus the rate of force decay (i.e., the slope) was greater for YA. Third, bivariate correlations between the slope of force decay and accuracy and RT measures for verbal recall and visuospatial working memory demonstrated that task performance was not correlated. We discuss these findings below.

### Visually guided force control

Visually guided, isometric force production requires the performer to continuously update and integrate feedback to maintain force output. Such tasks rely on sensory feedback mechanisms to a greater degree than discrete motor tasks because performers must continuously adjust their motor output to stay on target (Deutsch and Newell 2001, 2003). In the current study, when visual feedback was available, OA produced 0.42% MVC more force than YA across all 12 epochs. The fact that the effect was not modulated by time suggests that OA did not have difficulty maintaining force output over the 20-s interval. It is important to note that the group means are approximately 0.20% MVC from the target: OA overshot by 0.24% MVC, whereas YA undershot by 0.18% MVC. Thus, although the difference between groups is statistically significant, the groups were similar in terms of accuracy, demonstrating the ability to appropriately scale force output to the target amplitude. Force output variability was greater for OA compared to YA, but only at the 11$^{th}$ epoch. For all other time points, variability was equivalent between groups. Therefore, OA produced more force across time and were more variable at one time point relative to YA. Although these are statistically significant findings, the modest differences between groups make it difficult to assert that OA and YA engaged in different strategies for the online integration of visual feedback in this task.

### Memory-guided force control

Previous studies of motor memory demonstrate that memory decay begins after 1.5 s for grip force production in healthy young (Vaillancourt and Russell 2002) and older adults (Vaillancourt et al. 2001). The memory-guided force task used here has been in studies of Parkinson's disease (Vaillancourt et al. 2001), ADHD (Neely et al. 2016a), ASD (Neely et al. 2016b), and healthy younger adults (Poon et al. 2012; Vaillancourt and Russell 2002). These investigations report a consistent decrease in force output as a function of time when visual feedback was removed. In the current study, consistent with previous work, younger and older adults decreased force output as a function of time; however, YA exhibited a faster rate of decay than OA. Such results suggest that OA may have developed a more stable representation of the motor goal, which is counter to our prediction.

One explanation for this finding is that older adults may have been more conscientious or motivated to participate in the research. A consequence of increased motivation could be enhanced attentional control, which in turn influences the ability to store and then recall an accurate representation of the force amplitude. Consistent with this interpretation, we observed that YA were more variable than OA when visual feedback was removed. This finding is likely a consequence of the sharp decrease in force output observed for YA in the first few seconds after visual feedback was removed. An alternate explanation is that OA and YA engage in different feedforward strategies for the maintenance of force output. In particular, OA may engage in a proactive strategy in which they produce more force to compensate for what they perceive to be a decrease in force when visual feedback is removed. Indeed, cutaneous sensory perception (Kalisch et al. 2009; Lin et al. 2005) and mechanotransduction (Wu et al. 2011) decrease with advancing age (for a review, see Decorps et al. 2014). A decrease in the resolution of sensory information could lead to the suggested compensation strategy; however, it may also contribute to sensory adaptation during the 20-s force interval. It is well known that prolonged stimulation leads to a reduction in responsivity of the peripheral and central nervous system (Bensmaia et al. 2005); however, little research has examined how cutaneous and tactile adaptation changes with age. Zhang and colleagues studied 120 individuals between the ages of 18 and 70 and found that although vibrotactile detection thresholds increased with age, vibrotactile amplitude discrimination and adaptation did not change as a function of increasing age (Zhang et al. 2011). Indeed, more work is needed to determine whether 20 s of isometric force with the fingertips is sufficient to elicit different patterns of adaptation or sensory reweighting in younger and older adults. Although the present study cannot disentangle these alternate explanations, the fact that force output changed as a function of time in the no-vision, but not the full-vision, condition suggests that participants engage in different control strategies in memory- and visually guided conditions.

## Relationship between memory-guided force and measures of cognition and working memory

A primary goal of this study was to determine if the rate of force decay was associated with working and/or visuospatial memory. To that end, we conducted word recall and recognition, and visuospatial working memory tasks to assess declarative and visuospatial working memory, respectively. Based on our recent work in clinical populations with executive function impairments (Neely et al. 2016a, b), we anticipated that behavioral performance on these tasks would be associated with performance on the memory-guided force task. Since age-related decline in working memory is well-established in the cognitive aging literature, we hypothesized that OA would demonstrate deficits in our memory tasks, and further, that performance in the memory tasks would be correlated with performance in the memory-guided force task. We found that OA had comparable accuracy to YA on the word recognition task; however, this was at the expense of age-related increases in reaction time. In contrast, although OA were less accurate that YA on the visuospatial working memory task, they were matched in response time. It is notable that although group differences in accuracy were not observed for the word recognition task, reaction times were longer for older compared to younger adults. This is consistent with the processing speed theory of adult aging, which hypothesizes a general decrease in processing speed that is associated with increasing age, and that affects all cognitive processes (Salthouse 1996).

In spite of group differences in the neuropsychological tasks, performance in these tasks was not associated with performance in the memory-guided force task. This finding suggests that motor memory may be independent of other memory systems, especially in healthy populations. In other words, cognitive or executive function impairments in clinical populations such as ADHD and ASD may have broad effects that negatively influence motor control. However, healthy individuals may not be as sensitive to individual differences in cognitive functions such as working memory, cognitive flexibility, and inhibitory control. Similarly, although we report group differences in our memory tasks, it is possible that there was not sufficient cognitive decline in our healthy OA to reveal a relationship between the neuropsychological and motor tasks.

## Limitations and conclusions

The lack of substantial group differences between younger and older adults in the neuropsychological tests may be due to the health of the older adults in the sample. That is, participants in this study were part of a larger study involving magnetic resonance imaging (MRI) and, therefore, met health- and safety-based inclusion criteria. In particular, this means that all participants were in good health without a history of neurological or psychological disorders (e.g., depression, stroke), major medical disorders (e.g., diabetes), or concussion involving loss of consciousness for longer than 5 min. Safety-based criteria excluded individuals with a pacemaker or other implanted devices. Further, as is common in a University community, older adults had achieved higher levels of education than the younger adults in our study had. Specifically, 32 of 33 older adults provided information about the number of years of education they had acquired, the average was 17.2 years (SD

2.49 years), and the range was 12–23 years. Therefore, our older adult sample represents a healthy and well-educated group of individuals. Age-related decline in physiological function and capacity is influenced by biological, behavioral, lifestyle, education, nutritional, and socioeconomic factors (Clark and Manini 2010; Clark and Fielding 2012; Clark et al. 2011). Further, intelligence and educational achievement are related to age-associated cognitive decline (Tucker and Stern 2011). The results of the current work demonstrate that younger adults decreased force at a faster rate compared to older adults. In other words, although both groups decreased force output with time, older adults did so at a slower rate. Further, the rate of force decay was not associated with behavioral performance on tests of working memory. These findings suggest that motor memory may be independent of cognition and working memory in healthy adults or that the OA studied here may not have sufficient cognitive decline to reveal a relationship between them.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare no competing financial interests.

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