



Published in final edited form as:

J Mot Behav. 2023 ; 55(1): 68–77. doi:10.1080/00222895.2022.2105793.

Mediation analysis of the effect of visuospatial memory on motor skill learning in older adults

Andrew Hooyman^{a,b}, Jennapher Lingo VanGilder^a, Sydney Y. Schaefer^{a,b,*}

^aSchool of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ, USA.

^bThe Arizona Alzheimer's Consortium, Phoenix, AZ, USA

Abstract

There is high inter-individual variability in motor skill learning among older adults. Identifying the nature of these individual differences remains challenging due to interactions between participant characteristics (e.g., age, cognition) and task-related factors (e.g., nature of task, level of skill pre-training), making it difficult to determine plausibly causal relationships. This study addresses these competing explanations by using mediation analysis to examine plausible causal inference between visuospatial memory and one-month retention of both gross and fine motor components of a functional upper-extremity task following training. Results suggest that better visuospatial memory results in more retention of fine but not gross motor skill, expanding on previous correlational studies in older adults and informing future interventions for maximizing motor learning in geriatric populations.

Keywords

motor learning; mediation analysis; older adult; visuospatial memory

Introduction

The ability to learn and generalize a motor skill is fundamental to motor development and motor rehabilitation. This is especially true among older adults where the preservation, (Smith et al., 2005) learning, (Seidler, 2007) and generalization (Hinder et al., 2011) of motor skill is essential for maintaining functional independence (Fauth et al., 2013). However, previous research has demonstrated that the extent of learning achieved following a given amount of practice on a given task can be highly variable across individuals (Anderson et al., 2021; Hooyman et al., 2021). This inter-individual variability has been attributed to a number of factors, such as the type or nature of task (Ranganathan et al., 2021), the difficulty of the task (Voelcker-Rehage, 2008), individual baseline motor skill (i.e., level of task performance prior to training) (Lee & Ranganathan, 2019), or cognitive status (Wang et al., 2020).

*Corresponding Author: Sydney Y. Schaefer, 501 E. Tyler Mall, MC 9709, Tempe, AZ 85287, sydney.schaefer@asu.edu.

Declaration of Interest. No author has any financial or business interests associated with the publishing of this paper.

In support of this, our previous work has shown that both visuospatial function (specifically, visuospatial memory) *and* initial task performance prior to training affect the extent of learning of a functional upper-extremity motor task (Lingo VanGilder et al., 2018, 2019; Lingo VanGilder et al., 2021; Lingo VanGilder et al., 2021), presenting competing explanations. This task is considered functional because it incorporates common household items (e.g., a spoon, plastic cups, and raw kidney beans) and because its performance has been associated with daily function (Schaefer et al., 2020; see also Fauth et al., 2017). As such, this task captures gross motor skill (i.e., targeted reaching when transporting beans with the spoon from one location to another) and fine motor skill (i.e., dexterity and tool-use when scooping of beans from a cup with a spoon) (Schaefer & Hengge, 2016). This is in contrast to other experimental motor paradigms that study only one or the other (Christova et al., 2018; Whitley, 1970). Considering how visuospatial function may affect both phases is important, as data show that these phases are differentially affected by the aging process (Hooyman, Wang, et al., 2021), such that poorer performance of the gross motor phase likely reflects general bradykinesia, whereas poorer performance of the fine motor phase likely reflects differences in movement quality (not speed) relative to younger adults (see also Raw et al., 2012). No study to date, however, has considered how the learning of the two phases (gross vs. fine) with extensive practice are differentially affected by visuospatial function, nor whether the observed effects of visuospatial function on learning are (plausibly) causal. A deeper understanding of how visuospatial (or other cognitive) deficits impair the learning of different aspects of movement (gross vs. fine) could be widely beneficial to areas of motor skill training and rehabilitation (Schaefer et al., 2021).

Ultimately, our goal is to understand whether visuospatial deficits lead to deficits in motor learning among older adults, which would in theory guide the development of new interventions and solutions that could enhance motor learning. To do so, however, we must use analyses that account for the strong associations between initial (pre-training) performance on the motor task and final (post-training) performance. Conceptually, initial performance is often predictive of learning (i.e., how much a task improves). Specifically, individuals with poor initial performance are far from the “ceiling” level of a task, and therefore (potentially) have more room for change compared to individuals whose initial performance is very close to a ceiling level (with little room for change). When using regression-based approaches, initial motor performance on a given task typically explains the most variance in final performance of that task, washing out effects from other variables that may otherwise be clinically/functionally meaningful and rendering these other explanatory variables insignificant. Thus, due to the strength of initial motor performance as a predictor of final motor performance on a given task or assessment, it is difficult to determine what other covariates are informative for potentially modifying or interfering with motor learning. This current study directly addresses this methodological issue by using mediation analysis (Hayes, 2009) to dissociate the effect of initial performance from the effect of visuospatial function to examine plausibly causal pathways through which visuospatial function might affect motor learning. The value of mediation analysis in modeling the interactions among multiple explanatory variables on a single outcome has been proposed in motor rehabilitation (Field-Fote, 2019), and is highly novel in the context of motor learning specifically. Mediation analysis is useful and appropriate here because it

first determines if initial task performance (modeled as a mediator variable) fully explains a direct effect of visuospatial function on motor learning. If so, this would suggest that initial task performance washes out any effect that visuospatial function had on motor learning and would also suggest that visuospatial function does not directly cause differences in motor skill retention. However, mediation analysis can also determine an indirect effect of visuospatial function on motor learning that is mediated through initial task performance. If so, this would suggest that the variance in motor learning that is explained by initial task performance is mediated by visuospatial function, whereby better visuospatial function results in better initial motor performance, ultimately leading to better motor learning.

Based on our previous work suggesting that initial performance of the fine (but not gross) motor phase of our task is sensitive to cognitive deficits (Hooyman, Wang, et al., 2021), we hypothesized that the learning of the fine motor phase (but not the gross motor phase) would be indirectly affected by visuospatial function, as defined by mediation analysis. While previous studies have *inferred* that visuospatial function influences motor learning in older adults based on empirical data, the mediation analysis provided here has potential to extend previous findings by directly testing a plausibly causal role of visuospatial function in the context of motor learning. This approach provides a clearer understanding of the interactions between task factors (e.g., task type and complexity), initial motor skill (i.e., level of performance on a given task prior to any practice), and cognition (in our case, visuospatial function specifically), which may 1) explain why such large inter-individual differences in motor skill learning exist, particularly among older adults (Voelcker-Rehage, 2008), and 2) guide interventions for maximizing motor learning in geriatric populations.

Materials and Methods

Participants

Fourteen non-demented, community-dwelling older adults (9 female) with a mean age of 71.14 ± 8.08 years participated in the study. All participants were right-handed, as measured through the Edinburgh Handedness Inventory (Oldfield, 1971). No participant reported any previous injury or musculoskeletal disability related to either hand. All participants were non-demented (Montreal Cognitive Assessment score > 21 , mean \pm SD: 27.18 ± 2.27) with no self-reported history of depression or psychiatric disorders. No participant reported any sensory loss/impairment as measured by Semmes-Winstein monofilament test; all within normal range. All participants reported full independence (score = 0) on the Index of Independence in Activities of Daily Living Scale (Katz et al., 1970). This is a retrospective analysis on previously published data (Lingo VanGilder, Lohse, et al., 2021). We acknowledge that the total number of participants within this study is relatively small; however, our sample size is in line with previous research in motor learning that has used mediation analyses in the past (Van Liew et al., 2021), and previous methodological research has demonstrated that mediation analysis is robust against a range of sample sizes due to the bootstrapping method utilized to generate confidence intervals (Pan et al., 2018). All participants provided written informed consent prior to enrollment according to the Declaration of Helsinki. This study was approved by the Arizona State University Institutional Review Board (IRB Study number 000004214).

Visuospatial memory assessment

Prior to motor task practice (described below in more detail), participants completed the Rey-Osterrieth Complex Figure Test (ROCFT). Based on our previous findings (Lingo VanGilder et al., 2019), we chose to only include the delayed recall portion of this test in our analysis because we have shown how this portion specifically is related to overall motor skill retention following training (Lingo VanGilder, Lohse, et al., 2021). Participant delayed recall scores were age-adjusted according to published methods (Caffarra et al., 2002), which accounted for participant age, education, and sex. Participants had a mean age-adjusted delayed recalled ROCFT score of 19.56 ± 7.4 . For reference, an abnormal score would be 9.46 (<5th percentile).

Motor task and motor training

This study used a functional upper-extremity motor task (Fig. 1), which has been published previously (Schaefer & Duff, 2015; Schaefer & Hengge, 2016; Schaefer et al., 2015, see also https://osf.io/phs57/wiki/Functional_reaching_task/ for more information). Importantly, this task has been related to objective and subjective measures of daily functioning in older adults, demonstrating its ecological validity (Schaefer et al., 2020) and is more related to cognition than gross motor assessments like grip strength (Hooyman et al., 2020). Participants completed the task with their nondominant hand to avoid a ceiling effect (Schaefer, 2015), and were instructed to move as quickly yet as accurately as possible. Task performance involved 15 repetitions of acquiring and transporting two objects (hard, kidney-shaped, $\sim 0.5 \text{ cm}^3$) at a time with a tool (spoon) from a central ‘home’ container (9.5 cm in diameter and 5.8 cm in height) to one of three distal ‘target’ containers that were the same size as the home container. Thirty objects were placed by the experimenter at the start. The target containers were secured radially around the home container at -40° , 0° , and 40° at distance of 16 cm. Participants started by moving to the target cup ipsilateral of the hand used, then returned to the central cup to acquire two more objects at a time to transport to the middle target cup, then the contralateral target cup, and then repeated this 3-cup sequence five times for a total of 15 out-and-back movements. Thus, this task involved both object manipulation (fine motor) and point-to-point reaching (gross motor). Overall task performance of a given trial was quantified as the amount of time taken to complete all 15 repetitions (i.e., trial time). Participants were timed by an experimenter using a stopwatch, where movement start occurred when the participant’s hand contacted with the spoon and movement end occurred when the last two beans were deposited into the last cup. Kinematic data (see description below) were collected throughout the 15 repetitions of each trial to analyze both the fine and gross motor stages. Errors such as transporting the wrong number of beans, dropping beans, or reaching in the wrong direction were recorded; however, less than 4% of all repetitions had any errors. There was no relationship between errors and trial time ($p = .69$).

Kinematic data were collected at sampling frequency of 100 Hz with a small 6 DOF electromagnetic sensor (Ascension Model 130, measured at 0.7 cm long and 0.15 cm diameter; Flock of Birds, via Motion Monitor integrated software) placed on the underside of (plastic) spoon handle at its base. Data were low-pass filtered offline at 8 Hz with a 4th order Butterworth filter. To parse each repetition into a fine and gross motor stage, we

identified three event markers for 1) start of object manipulation, 2) start of reach, and 3) end of reach. The start of object manipulation was registered when the spoon was within the container diameter and the vertical velocity (inferior-superior, movement toward superior – out of the container – is positive) changed direction from negative to positive for the first time. The start of reach was registered at the latest occurrence when resultant velocity exceeded 0.05 m/s while the spoon was within the container. The end of reach was registered when the spoon reached its largest y-position (anterior-posterior, movement towards anterior is positive).

The fine motor stage occurred during object acquisition and was defined from the start of object manipulation (event marker 1) to the start of reach (event marker 2). Kinematic variables of interest for the fine motor stage included: the 3-dimensional position of the spoon, time spent in the fine motor stage (dwell time), and cumulative distance traveled by the spoon. It is noted that this phase is of particular interest in studies of aging, as it is more susceptible to age-related changes in brain structure and function (Hirsiger et al., 2016; Seidler et al., 2015; Seidler et al., 2010). The gross motor stage occurred during the reaching movement towards the target and was defined from the start of reach (event marker 2) to the end of reach (event marker 3).

Once data collection was complete, we categorized the spoon position data into either fine or gross motor phases. The fine motor phase was defined as any time the spoon was within the home cup and the gross motor phase was defined as when the spoon left, dropped off the beans, and then returned to the home cup (see Supplemental Figure 1S for examples of kinematic data). Within the fine motor phase, average distance that the spoon traveled across all 15 reaches during the first trial on the practice and retention day was calculated. This measures how efficiently the participant was able to move the spoon to scoop the required number of kidney beans. The metric we used for the gross motor phase (shown visually in Supplemental Figure 1S) was the average time spent during transport for the first trial of the practice and retention day. Lower average transport times indicated better task proficiency. Participants completed three weekly sessions of training, which were each comprised of 50 trials (1 trial = 15 reaches). One month after the last training session, participants returned to complete one more trial to measure long-term retention. Kinematic data of the spoon were only recorded during the first trial of the first training session and the one-month retention trial.

Statistical Analysis

Rationale for using mediation analysis

Generally speaking, mediation analysis is appropriate only when the variables used (and the order in which they are placed in the model) are informed by an evidence- or theory-based conceptual model (MacKinnon & Fairchild, 2009). It is important that the relationships (i.e., the model conceptual paths) within the mediation model already have a previously established relationship, either based on existing literature and/or experimental data. In other words, the variables used (and relationships between them) must have some precedent; thus, mediation analysis should not be used in an exploratory fashion. This study adheres to this concern, as it is informed by a robust body of literature. In this study, visuospatial memory

(measured as the ROCFT delayed recall score) is the primary independent variable (IV), and initial motor performance is the mediator variable (MV). The initial performance for each phase of the motor task (fine and gross) was calculated. Initial performance for the fine motor phase was defined as the average distance moved and average movement time within the container per ‘scoop’ during the first trial of practice, for the gross motor phase, it was defined as the average transport time during the first trial of practice. Accordingly, the learning of each phase was the dependent variable (DV) and was defined as the change in performance from the first and one-month retention trials. This generates a conceptual model with paths between the independent variable (IV) and mediator variable (MV) that test for direct and indirect effects on the DV, respectively (Fig. 2). Figure 2 represents this conceptual model where paths *a* and *b* represent the indirect pathway that visuospatial function impacts motor skill learning through initial performance, whereas path *c*’ is the direct path of visuospatial function on motor skill learning. Again, the set up and direction of this conceptual model are based on previous data, as we expect visuospatial function to affect initial motor performance and skill learning (and not vice versa, i.e., an individual’s initial performance should not change their visuospatial function).

Mediation model

We used the mediation package (Tingley et al., 2014) to run our mediation analyses with the R statistical software version 4.0.0 (R Core Team, 2019). Direct and indirect effects for the mediation model were estimated. Confidence intervals (CIs) using the bias-corrected and percentile-based methods were constructed using bootstrapping (accounting for the related data) using 1000 replications. All indirect effects were computed as the product of paths *a* and *b* (*ab*). Path *a* connects the independent variable (visuospatial function) to the mediating variable (gross or fine motor phase). Path *b* connects the mediating variable to the dependent variable (motor learning). For example, a significant indirect effect would indicate that visuospatial memory indirectly causes motor skill retention through the mediator variable (in this case, initial motor task performance). The *c*’ path is the direct effect of the independent variable on the dependent variable, accounting for the mediating variable. For example, a significant direct effect would indicate that visuospatial memory directly causes motor skill retention while controlling for the mediator variable (i.e., initial motor task performance). We also included covariates of age and education to account for other control variables that may impact fine and gross motor skill learning. Separate analyses were performed for the fine and gross motor phase, and all assumptions of linear regression were checked and upheld prior to interpretation of results.

The linear model constructed for each path can be seen in Equations 1 and 2 below.

$$\text{Initial Performance (MV)} \sim a^* \text{Visuospatial (IV)} + \text{age} + \text{education} \quad (\text{Eq. 1})$$

$$\begin{aligned} \text{Motor Learning (DV)} &\sim b^* \text{Initial Performance (MV)} + c' * \text{Visuospatial (IV)} \\ &+ \text{age} + \\ &\text{education} \end{aligned} \quad (\text{Eq. 2})$$

The 95% confidence intervals computed for each effect determined whether the effect was significantly different from 0 given $\alpha=0.05$. If the direct effect (the c' path) is not statistically significant, this confirms that initial motor performance mediated the effect of visuospatial function on motor skill learning. If the indirect effect (the product of path a and b) is statistically significant, this supports that the effect of visuospatial function on motor learning works indirectly through initial motor performance. It is important to note that we are using mediation analysis to test for possible casual links between visuospatial memory, initial performance, and motor skill learning for each phase of the motor task. As a preliminary step, we aimed to confirm that the independent variable of visuospatial memory was significantly related to one-month change for each phase prior to mediation (since its relation to one-month change has only been explored previously for overall trial time, and not each individual motor phase). For results from this preliminary step and visualization of the relationship between each independent, dependent, and mediator variable for both analyses, see Supplemental Material (including Supplemental Figure 2S).

Results

Fine Motor Phase – Distance Travelled

First, through the calculation of Cook's distance (a measure of how much leverage a data point applies to a relationship) we confirmed that there were no outliers within any of the interpreted analyses. Initial analyses demonstrated that ROCFT delayed recall was related to one-month change in average distance traveled during the fine motor performance ($p = 0.03$, $\beta = 0.003$, 95% CI = [0.0003, 0.006]). Mediation analysis showed no significant direct effect (abbreviated as DE) ($p = 0.56$, DE = $9.24e-4$, 95% CI = [$-2.81e-3$, 0.00]), meaning that the mediator variable (in this case, initial performance on the fine motor phase) nullified the relationship between ROCFT delayed recall and retention of the average distance traveled during the fine motor phase. There was, however, a significant indirect effect (abbreviated as IE) ($p = 0.046$, IE = $2.27e-3$, 95% CI = [$1.45e-5$, 0.01]) indicating that differences in ROCFT delayed recall indirectly led to differences in retention of average distance traveled, as mediated through initial motor performance (Fig. 2). Specifically, the negative relationship of the a path (i.e., the correlation between delayed ROCFT and initial fine motor performance was negative) means that higher scores on the delayed ROCFT correlated with shorter distance traveled in the fine motor phase during initial exposure to the task. Then, the negative relationship of the b path (i.e., the correlation between initial fine motor performance and one-month change in fine motor performance was also negative), indicating that individuals who traveled more distance in the home cup at baseline had more one-month change in fine motor performance. These results together allow us to dissociate how initial motor proficiency on the task, which reflects motor output, and visuospatial function, which reflects cognitive processing, uniquely impact learning of the spatial component of the fine motor phase. This also demonstrates how low skill early on in practice should not be taken as an indication that an individual cannot learn or benefit from training. The relationship between each variable in the fine motor phase mediation model can be visualized in Fig. 2S. This strongly suggests that decline in delayed visuospatial memory results in worse initial fine motor performance in regards to average distance travelled, which then leads to worse retention of any learning of the fine motor phase

(as well as the task overall). Additionally, we determined that the achieved power of the indirect effect (ab) from this mediation analysis was 0.642 (Kenny, 2017), which suggests that although the sample used in this study was small, it is unlikely our results were due to a false positive. One would compare the result of this power analysis to that of a general linear model, for example, where $d = 0.5$ is considered a medium effect and $d = 0.8$ is a large effect. Finally, given the presence of an indirect effect in our mediation analysis, we performed additional analyses and visualizations examining if the relationship between initial performance and one-month change was due to mathematical coupling or measurement error (see Supplementary Material). These supplementary analyses indicate the validity of the indirect effect.

Fine Motor Phase – Movement Time

We could not confirm that ROCFT delayed recall was related to one-month change in average movement time during the fine motor phase ($p = 0.17$, $\beta = 0.06$, 95% CI = $[-0.03, 0.15]$). This demonstrates that although the mediation effect was in the same direction as that of average distance travelled, it was not large enough to yield significance. Mediation analysis showed no significant direct effect ($p = 0.49$, DE = 0.02, 95% CI = $[-0.05, 0.07]$). This effect is somewhat uninterpretable as the initial relationship between ROCFT delayed recall and average movement time was not initially significant so there is nothing to mediate. There was also no significant indirect effect ($p = 0.12$, IE = 0.045, 95% CI = $[-0.015, 0.13]$), indicating that differences in ROCFT delayed recall did not indirectly lead to differences in retention of average movement time during the fine motor phase, as mediated through initial motor performance. This suggests that overall, visuospatial memory does not directly or indirectly impact the average movement time spent during the fine motor phase.

Gross Motor Phase

We failed to show that ROCFT delayed recall was related to one-month change in gross motor performance average movement time ($p = 0.15$, $\beta = .007$, 95% CI = $[-0.003, 0.018]$). Mediation analysis showed no significant direct effect ($p = 0.1$, DE = 0.009, 95% CI = $[-0.003, 0.02]$), indicating that the mediator variable (in this case, initial performance on the gross motor phase) mediated the relationship between ROCFT delayed recall and retention of gross motor skill. However, in this case, there was also no significant indirect effect ($p = 0.72$, IE = -0.0008 , 95% CI = $[-0.014, 0.01]$), suggesting that ROCFT delayed recall did not indirectly lead to changes in retention of the gross motor phase. (Visualization of the relationships between variables in the gross motor phase can be seen in Supplemental Figure 2S). Together these findings from both the direct and indirect effects in the mediation analysis demonstrate that delayed visuospatial memory function does not play a role in the learning of the gross motor phase.

Discussion

Visuospatial function has been associated with motor learning in a number of studies (Lingo VanGilder et al., 2018; Lingo VanGilder, Lohse, et al., 2021). The purpose of this study was to use mediation analysis to understand the mechanism by which visuospatial function affects the learning of both fine and gross motor skill in older adults. Results showed that the

delayed recall portion of the Rey-Osterrieth Complex Figure test had an indirect effect on the learning of the spatial aspects of the fine motor phase (i.e., distance travelled), which was mediated through initial performance, but not the temporal aspects (i.e., movement time). This is not surprising, given that the ROCFT is an assessment of visuospatial ability, rather than processing or movement speed. In contrast, delayed recall scores had no direct nor indirect effect on the learning of the gross motor phase. We therefore interpret the indirect effect of visuospatial function on fine motor skill learning as evidence for a causal link between visuospatial function and motor learning, particularly in tasks involving fine motor control within an unconstrained space, whereby visuospatial deficits lead to deficits in motor learning.

It is plausible that the indirect effect observed here is due to a ceiling effect in the relationship between initial performance and learning of the motor task. In other words, could initial performance on the task only be linked to learning due to a ceiling effect, where participants with lower (worse) motor performance at baseline experience greater change with practice than participants with better motor performance who are already close their peak performance? While this is an alternative interpretation of our results, we have several explanations that suggest that this is not likely the case. First, the motor task used here does not have a hard ceiling effect like tasks/tests measured on an interval scale, such as many clinical assessments (e.g., the Fugl-Meyer Assessment or the Action Research Arm Test). Our motor task is measured on a continuous scale, and therefore has a “softer” ceiling that is participant-specific. Second, the fact that participants with worse motor performance initially tend to improve is well documented in motor learning research (see Anderson et al., 2021). Thus, this pattern of low performers making the greatest gains is more the rule rather than the exception. Finally, with that being said, one should not assume that those with worse initial performance *always* make the largest gains. In this study we enrolled cognitively-intact older adults, but in other work that focuses on clinical populations with significant cognitive impairment (i.e., Mild Cognitive Impairment, dementia) has shown that there are individuals who have poor initial performance and do not improve (Duff et al., 2011). This lack of a practice effect has been used to inform how the possible effects of disease related neurodegeneration impact the ability to improve with task exposure and may inform long-term prognosis (Schaefer et al., 2020). Thus, we interpret that within this cognitively-intact group of older adults, the indirect link between visuospatial function and learning was mediated by initial performance. However, the nature and psychometrics of a given task should be considered if it is being used in mediation analyses in general.

Previous discussions of potential mechanisms of motor learning have typically implicated the primary motor and visual cortices as primary contributors of the learning of specific physical properties or features of a task (Censor et al., 2012). However, results from this study suggest that the extent to which these mechanisms can predict learning may be task-specific, meaning some task types may better follow one specific mechanistic pathway than others (Ranganathan et al., 2021). For example, the cerebellum has been more linked to error-based learning (Kawato & Gomi, 1992) while the motor cortex is linked to learning of more ballistic type movements (Muellbacher et al., 2001). As we have demonstrated here in older adults, visuospatial memory influences the learning of fine but not gross motor skill, suggesting that these types of movements are learned through different neural pathways.

Given the confirmed role of visuospatial memory in fine motor skill learning, it is plausible that the integrity of white matter tracts connecting parietal and motor cortices, such as the superficial longitudinal fasciculus and anterior corona radiata, may be critical for both initial levels of fine motor skill as well as improvements with practice (Koshiyama et al., 2020; Theilmann et al., 2013). In the context of our study, participants with lower ROCFT delayed recall (and therefore poor initial performance) may have had less structural integrity of these associative tracts (and/or focal degeneration within parietal and motor cortices in parallel), which could be explored with future neuroimaging studies.

Advancing age clearly affects motor learning (Seidler et al., 2010), such that older adults tend to learn motor tasks slower and to a lesser extent than younger adults. However, different types of motor tasks appear to be differentially affected by age. This study now identifies visuospatial memory as an explanation for why older age has been associated with declines in motor learning on certain tasks, as well as fine motor deficits (Fauth et al., 2017). Furthermore, this study supports recent work that links post-training performance on this task with one-year functional decline in patients with amnesic Mild Cognitive Impairment, indicating more advanced progression towards dementia. Since accelerated visuospatial decline may be an early symptom of Alzheimer's disease progression (Caselli et al., 2020), motor tasks that involve fine motor skill could help give insights into diagnosis or prognosis of dementia. It is important to note that although our previous research has shown that memory of a visually constructed item (i.e., the recall of a previously drawn figure) is critical for learning the task used in this study, other visuospatial processes such as mental rotation (Jeunet et al., 2015, 2016) or visuospatial working memory (Bo et al., 2009, 2011; Seidler et al., 2012) may be more sensitive to learning other forms of motor learning (e.g., motor sequencing, visuomotor adaptation). Findings from this study are also clinically relevant, as they suggest that improving visuospatial function through cognitive therapy and/or neuromodulation could in fact improve motor rehabilitation for older patients (Kraemer, 2016).

Limitations

As noted above, there have been statistical concerns within motor learning (and motor recovery) about using initial motor performance to predict a change in motor performance due to potential mathematical coupling (i.e., an initial score is essentially predicting itself within the change score) (Hawe et al., 2019). Data simulations from post-stroke cohorts have shown that a spurious relationship between an initial level of performance and a change score for a given motor assessment (e.g., Fugl-Meyer) are due to differences in the magnitude of sample variance between pre- and post-recovery measurements (Hope et al., 2019), which can be extended to pre- and post-training in the context of motor learning. Analyses within Supplemental Material confirm, however, that this was not the case here. Additionally, the lack of indirect or direct effects for learning of the gross motor phase may be due to the overall sample size, although previous research has demonstrated that gross motor performance does not have as strong relationship with cognition compared to fine motor skill (Voelcker-Rehage, 2008).

In conclusion, this study provides further evidence for the causal role of cognition in motor skill learning among older adults. This cognitive associations with motor learning have been observed previously, but with a focus primarily on cognition as a global or somewhat abstract construct [e.g., Magill & Hall, 1990]. Considering which cognitive deficits are most disruptive to motor learning are not only important for a theoretical understanding of motor skill learning but also for translation to cognitive aging research and neurorehabilitation (Lingo VanGilder et al., 2020).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements.

We would like to thank Jessica Trevino for her assistance in recruitment and data collection, and Dr. Peiyuan 'Boki' Wang for her assistance in preparing the kinematic data for analysis.

Funding Details.

This work was supported in part by the National Institute on Aging at the National Institutes of Health (K01AG047926 to SYS, and F31AG062057 to JLV). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Data Availability Statement.

The metadata used in this study will be made available upon reasonable request.

REFERENCES

- Anderson DI, Lohse KR, Lopes TCV, & Williams AM (2021). Individual differences in motor skill learning: Past, present and future. *Human Movement Science*, 78, 102818. 10.1016/j.humov.2021.102818 [PubMed: 34049152]
- Bo J, Borza V, & Seidler RD (2009). Age-related declines in visuospatial working memory correlate with deficits in explicit motor sequence learning. *Journal of Neurophysiology*, 102(5), 2744–2754. 10.1152/jn.00393.2009 [PubMed: 19726728]
- Bo J, Jennett S, & Seidler RD (2011). Working memory capacity correlates with implicit serial reaction time task performance. *Experimental Brain Research*, 214(1), 73–81. 10.1007/s00221-011-2807-8 [PubMed: 21809082]
- Caffarra P, Vezzadini G, Dieci F, Zonato F, & Venneri A (2002). Rey-Osterrieth complex figure: normative values in an Italian population sample. *Neurological Sciences*, 22(6), 443–447. 10.1007/s100720200003 [PubMed: 11976975]
- Caselli RJ, Langlais BT, Dueck AC, Chen Y, Su Y, Locke DEC, Woodruff BK, & Reiman EM (2020). Neuropsychological decline up to 20 years before incident mild cognitive impairment. *Alzheimer's & Dementia*, 16(3), 512–523. 10.1016/j.jalz.2019.09.085
- Censor N, Sagi D, & Cohen LG (2012). Common mechanisms of human perceptual and motor learning. *Nature Reviews Neuroscience*, 13(9), 658–664. 10.1038/nrn3315 [PubMed: 22903222]
- Christova M, Aftenberger H, Nardone R, & Gallasch E (2018). Adult Gross Motor Learning and Sleep: Is There a Mutual Benefit? *Neural Plasticity*, 2018, 1–12. 10.1155/2018/3076986
- Duff K, Lyketsos CG, Beglinger LJ, Chelune G, Moser DJ, Arndt S, Schultz SK, Paulsen JS, Petersen RC, & McCaffrey RJ (2011). Practice Effects Predict Cognitive Outcome in Amnesic Mild Cognitive Impairment. *The American Journal of Geriatric Psychiatry*, 19(11), 932–939. 10.1097/JGP.0b013e318209dd3a [PubMed: 22024617]

- Fauth EB, Schaefer SY, Zarit SH, Ernsth-Bravell M, & Johansson B (2017). Associations Between Fine Motor Performance in Activities of Daily Living and Cognitive Ability in a Nondemented Sample of Older Adults: Implications for Geriatric Physical Rehabilitation. *Journal of Aging and Health*, 29(7), 1144–1159. 10.1177/0898264316654674 [PubMed: 27339106]
- Fauth EB, Schwartz S, Tschanz JT, Østbye T, Corcoran C, & Norton MC (2013). Baseline disability in activities of daily living predicts dementia risk even after controlling for baseline global cognitive ability and depressive symptoms. *International Journal of Geriatric Psychiatry*, 28(6), 597–606. 10.1002/gps.3865 [PubMed: 22968965]
- Field-Fote E (2019). Mediators and Moderators, Confounders and Covariates: Exploring the Variables That Illuminate or Obscure the “Active Ingredients” in Neurorehabilitation. *Journal of Neurologic Physical Therapy*, 43(2), 83–84. 10.1097/NPT.0000000000000275 [PubMed: 30883494]
- Hawe RL, Scott SH, & Dukelow SP (2019). Taking Proportional Out of Stroke Recovery. *Stroke*, 50(1), 204–211. 10.1161/STROKEAHA.118.023006
- Hayes AF (2009). Beyond Baron and Kenny: Statistical Mediation Analysis in the New Millennium. 10.1080/03637750903310360, 76(4), 408–420. 10.1080/03637750903310360
- Hinder MR, Schmidt MW, Garry MI, Carroll TJ, & Summers JJ (2011). Absence of cross-limb transfer of performance gains following ballistic motor practice in older adults. *Journal of Applied Physiology*, 110(1), 166–175. 10.1152/JAPPLPHYSIOL.00958.2010/ASSET/IMAGES/LARGE/ZDG0011194130006.JPEG [PubMed: 21088207]
- Hirsiger S, Koppelmans V, Mérillat S, Liem F, Erdeniz B, Seidler RD, & Jäncke L (2016). Structural and functional connectivity in healthy aging: Associations for cognition and motor behavior. *Human Brain Mapping*, 37(3), 855–867. 10.1002/hbm.23067 [PubMed: 26663386]
- Hooyman A, Gordon J, & Winstein C (2021). Unique behavioral strategies in visuomotor learning: Hope for the non-learner. *Human Movement Science*, 79, 102858. 10.1016/j.humov.2021.102858 [PubMed: 34392189]
- Hooyman A, Malek-Ahmadi M, Fauth EB, & Schaefer SY (2020). Challenging the relationship of grip strength with cognitive status in older adults. *International Journal of Geriatric Psychiatry*, 35(4), 5441. 10.1002/gps.5441
- Hooyman A, Wang P, & Schaefer SY (2021). Age-related differences in functional tool-use are due to changes in movement quality and not simply motor slowing. *Experimental Brain Research*, 239(5), 1617–1626. 10.1007/S00221-021-06084-X [PubMed: 33760958]
- Hope TMH, Friston K, Price CJ, Leff AP, Rotshtein P, & Bowman H (2019). Recovery after stroke: not so proportional after all? *Brain*, 142(1), 15–22. 10.1093/BRAIN/AWY302 [PubMed: 30535098]
- Jeunet C, Jahanpour E, & Lotte F (2016). Why standard brain-computer interface (BCI) training protocols should be changed: an experimental study. *Journal of Neural Engineering*, 13(3), 036024. 10.1088/1741-2560/13/3/036024 [PubMed: 27172246]
- Jeunet C, N’Kaoua B, Subramanian S, Hachet M, & Lotte F (2015). Predicting Mental Imagery-Based BCI Performance from Personality, Cognitive Profile and Neurophysiological Patterns. *PloS One*, 10(12), e0143962. 10.1371/journal.pone.0143962 [PubMed: 26625261]
- Katz S, Downs TD, Cash HR, & Grotz RC (1970). Progress in Development of the Index of ADL. *The Gerontologist*, 10(1 Part 1), 20–30. 10.1093/geront/10.1_Part_1.20 [PubMed: 5420677]
- Kawato M, & Gomi H (1992). A computational model of four regions of the cerebellum based on feedback-error learning. *Biological Cybernetics*, 68(2), 95–103. 10.1007/BF00201431 [PubMed: 1486143]
- Koshiyama D, Fukunaga M, Okada N, Morita K, Nemoto K, Yamashita F, Yamamori H, Yasuda Y, Matsumoto J, Fujimoto M, Kudo N, Azechi H, Watanabe Y, Kasai K, & Hashimoto R (2020). Association between the superior longitudinal fasciculus and perceptual organization and working memory: A diffusion tensor imaging study. *Neuroscience Letters*, 738, 135349. 10.1016/j.neulet.2020.135349 [PubMed: 32889005]
- Kraemer HC (2016). Messages for Clinicians: Moderators and Mediators of Treatment Outcome in Randomized Clinical Trials. *American Journal of Psychiatry*, 173(7), 672–679. 10.1176/appi.ajp.2016.15101333 [PubMed: 26988629]

- Lee M-H, & Ranganathan R (2019). Age-related deficits in motor learning are associated with altered motor exploration strategies. *Neuroscience*, 412, 40–47. 10.1016/j.neuroscience.2019.05.047 [PubMed: 31158435]
- Lingo VanGilder J, Hengge CR, Duff K, & Schaefer SY (2018). Visuospatial function predicts one-week motor skill retention in cognitively intact older adults. *Neuroscience Letters*, 664, 139–143. 10.1016/j.neulet.2017.11.032 [PubMed: 29154858]
- Lingo VanGilder J, Hooyman A, Bosch PR, & Schaefer SY (2021). Generalizing the predictive relationship between 1-month motor skill retention and Rey–Osterrieth Delayed Recall scores from nondemented older adults to individuals with chronic stroke: a short report. *Journal of NeuroEngineering and Rehabilitation*, 18(1), 94. 10.1186/s12984-021-00886-4 [PubMed: 34082761]
- Lingo VanGilder J, Hooyman A, Peterson DS, & Schaefer SY (2020). Post-Stroke Cognitive Impairments and Responsiveness to Motor Rehabilitation: A Review. *Current Physical Medicine and Rehabilitation Reports*. 10.1007/s40141-020-00283-3
- Lingo VanGilder J, Lohse KR, Duff K, Wang P, & Schaefer SY (2021). Evidence for associations between Rey-Osterrieth Complex Figure test and motor skill learning in older adults. *Acta Psychologica*, 214, 103261. 10.1016/j.actpsy.2021.103261 [PubMed: 33524606]
- Lingo VanGilder J, Walter CS, Hengge CR, & Schaefer SY (2019). Exploring the relationship between visuospatial function and age-related deficits in motor skill transfer. *Aging Clinical and Experimental Research*, 1–8. 10.1007/s40520-019-01345-w
- MacKinnon DP, & Fairchild AJ (2009). Current Directions in Mediation Analysis. *Current Directions in Psychological Science*, 18(1), 16–20. 10.1111/j.1467-8721.2009.01598.x [PubMed: 20157637]
- Magill RA, & Hall KG (1990). A review of the contextual interference effect in motor skill acquisition. *Human Movement Science*, 9(3–5), 241–289. 10.1016/0167-9457(90)90005-X
- Muellbacher W, Ziemann U, Boroojerdi B, Cohen L, & Hallett M (2001). Role of the human motor cortex in rapid motor learning. *Experimental Brain Research*, 136(4), 431–438. 10.1007/s002210000614 [PubMed: 11291723]
- Oldfield RC (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9(1), 97–113. 10.1016/0028-3932(71)90067-4 [PubMed: 5146491]
- Pan H, Liu S, Miao D, & Yuan Y (2018). Sample size determination for mediation analysis of longitudinal data. *BMC Medical Research Methodology*, 18(1), 32. 10.1186/s12874-018-0473-2 [PubMed: 29580203]
- R Core Team. (2019). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. <https://www.r-project.org>
- Ranganathan R, Tomlinson AD, Lokesh R, Lin T-H, & Patel P (2021). A tale of too many tasks: task fragmentation in motor learning and a call for model task paradigms. *Experimental Brain Research*, 239(1), 1–19. 10.1007/s00221-020-05908-6 [PubMed: 33170341]
- Raw RK, Kountouriotis GK, Mon-Williams M, & Wilkie RM (2012). Movement control in older adults: Does old age mean middle of the road? *Journal of Experimental Psychology: Human Perception and Performance*, 38(3), 735–745. 10.1037/a0026568 [PubMed: 22141585]
- Schaefer SY (2015). Preserved motor asymmetry in late adulthood: Is measuring chronological age enough? *Neuroscience*, 294, 51–59. 10.1016/j.neuroscience.2015.03.013 [PubMed: 25772792]
- Schaefer SY, & Duff K (2015). Rapid Responsiveness to Practice Predicts Longer-Term Retention of Upper Extremity Motor Skill in Non-Demented Older Adults. *Frontiers in Aging Neuroscience*, 7, 214. 10.3389/fnagi.2015.00214 [PubMed: 26635601]
- Schaefer SY, & Hengge CR (2016). Testing the concurrent validity of a naturalistic upper extremity reaching task. *Experimental Brain Research*, 234(1), 229–240. 10.1007/s00221-015-4454-y [PubMed: 26438508]
- Schaefer SY, Dibble LE, & Duff K (2015). Efficacy and Feasibility of Functional Upper Extremity Task-Specific Training for Older Adults With and Without Cognitive Impairment. *Neurorehabilitation and Neural Repair*, 29(7), 636–644. 10.1177/1545968314558604 [PubMed: 25416739]

- Schaefer Sydney Y., Hooyman A, & Duff K (2020). Using a Timed Motor Task to Predict One-Year Functional Decline in Amnesic Mild Cognitive Impairment. *Journal of Alzheimer's Disease* : JAD, 77(1), 53–58. 10.3233/JAD-200518
- Schaefer Sydney Y., McCulloch KL, & Lang CE (2021). Pondering the Cognitive-Motor Interface in Neurologic Physical Therapy. *Journal of Neurologic Physical Therapy*, Publish Ah. 10.1097/NPT.0000000000000381
- Seidler RD (2007). Older adults can learn to learn new motor skills. *Behavioural Brain Research*, 183(1), 118–122. 10.1016/j.bbr.2007.05.024 [PubMed: 17602760]
- Seidler RD, Bernard JA, Burutolu TB, Fling BW, Gordon MT, Gwin JT, Kwak Y, & Lipps DB (2010). Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. *Neuroscience & Biobehavioral Reviews*, 34(5), 721–733. 10.1016/J.NEUBIOREV.2009.10.005 [PubMed: 19850077]
- Seidler RD, Bo J, & Anguera JA (2012). Neurocognitive contributions to motor skill learning: the role of working memory. *Journal of Motor Behavior*, 44(6), 445–453. 10.1080/00222895.2012.672348 [PubMed: 23237467]
- Seidler R, Erdeniz B, Koppelmans V, Hirsiger S, Méritat S, & Jäncke L (2015). Associations between age, motor function, and resting state sensorimotor network connectivity in healthy older adults. *NeuroImage*, 108, 47–59. 10.1016/j.neuroimage.2014.12.023 [PubMed: 25514517]
- Smith CD, Walton A, Loveland AD, Umberger GH, Kryscio RJ, & Gash DM (2005). Memories that last in old age: motor skill learning and memory preservation. *Neurobiology of Aging*, 26(6), 883–890. 10.1016/J.NEUROBIOLAGING.2004.08.014 [PubMed: 15718047]
- Theilmann RJ, Reed JD, Song DD, Huang MX, Lee RR, Litvan I, & Harrington DL (2013). White-Matter Changes Correlate with Cognitive Functioning in Parkinson's Disease. *Frontiers in Neurology*, 4. 10.3389/fneur.2013.00037
- Tingley D, Yamamoto T, Hirose K, Keele L, & Imai K (2014). mediation : R Package for Causal Mediation Analysis. *Journal of Statistical Software*, 59(5). 10.18637/jss.v059.i05
- Van Liew C, Monaghan AS, Dibble LE, Foreman KB, MacKinnon DP, & Peterson DS (2021). Perturbation practice in multiple sclerosis: Assessing generalization from support surface translations to tether-release tasks. *Multiple Sclerosis and Related Disorders*, 56, 103218. 10.1016/j.msard.2021.103218 [PubMed: 34454306]
- Voelcker-Rehage C (2008). Motor-skill learning in older adults—a review of studies on age-related differences. *European Review of Aging and Physical Activity*, 5(1), 5–16. 10.1007/s11556-008-0030-9
- Wang P, Infurna FJ, & Schaefer SY (2020). Predicting Motor Skill Learning in Older Adults Using Visuospatial Performance. *Journal of Motor Learning and Development*, 8(1), 38–51. 10.1123/jmld.2018-0017 [PubMed: 34109252]
- Whitley JD (1970). Effects of Practice Distribution on Learning a Fine Motor Task. *Research Quarterly*. American Association for Health, Physical Education and Recreation, 41(4), 576–583. 10.1080/10671188.1970.10615018

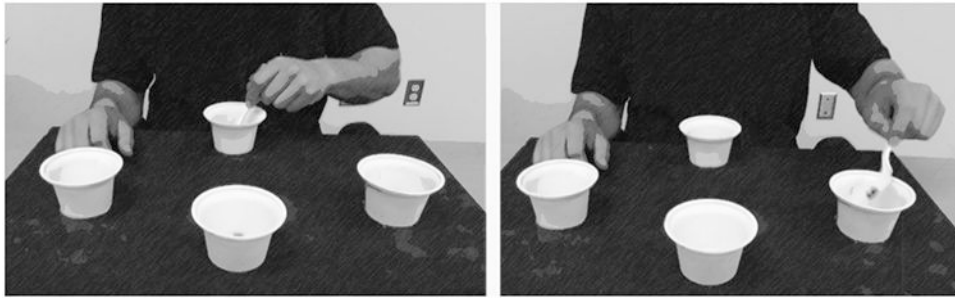


Figure 1.

Functional upper-extremity motor task. Participants are timed at how quickly they can scoop and acquire (i.e., the fine motor phase) and transport (i.e., the gross motor phase) two raw beans at a time from the home cup (left panel) to one of three target cups (right panel). A single task trial consists of 15 reaches. This figure was adapted from “Dexterity and Reaching Motor Tasks” by MRL Laboratory is licensed under CC BY 2.0.

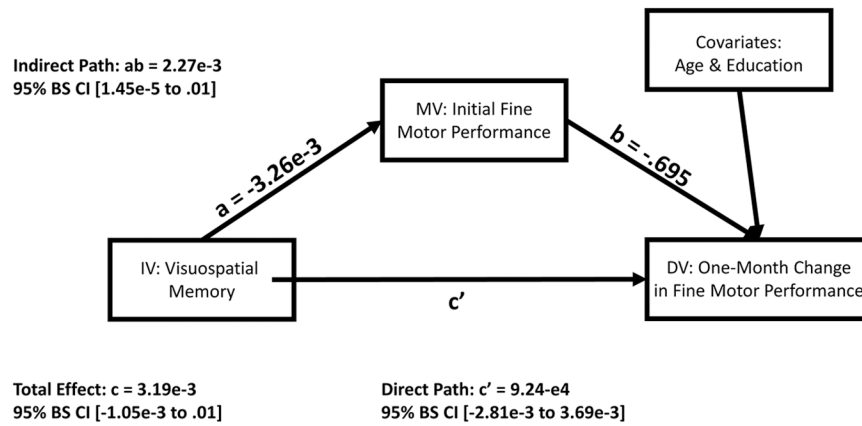


Figure 2. Conceptual model and results of Mediation Analysis of Fine Motor Phase. The model consists of two primary paths: the direct path (c') which represents the direct effect of visuospatial memory (independent variable, IV), measured prior to practice, on one-month change in fine motor performance (dependent variable, DV), and the indirect path (ab) which represents the effect of visuospatial memory on one-month change in fine motor performance (DV) *through* initial fine motor performance (mediator variable, MV). The effect of each path is controlled for including covariates of age and education. Results demonstrated that the indirect path (i.e., the effect of visuospatial memory on one-month change in fine motor performance through initial fine motor performance) was significant. Numbers along each arrow represent the coefficient for each path. 95% BS CI = 95% Bootstrapped Confidence Interval.