EYE MOVEMENTS AND ATTENTION ARE RELATED TO IMPAIRED HAND MOTOR CONTROL IN OLDER ADULTS

by

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A Dissertation Submitted in
Partial Fulfillment of the
Requirements for the Degree of

Doctor of Philosophy
in Kinesiology

at

The University of Wisconsin-Milwaukee
August 2020

ABSTRACT

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The University of Wisconsin-Milwaukee, 2020
Under the Supervision of Professor Kevin G. Keenan

Visual information is critical for many goal-directed movements and changes in visual information influence hand motor performance in older adults. Knowledge of eye movements during hand motor tasks would provide greater insight into impaired hand function in older adults. This dissertation examined age-related changes in eye movements and the association with hand motor impairments in older adults. Given that attention plays a role in motor performance and declines with age, the relationship between attentional processes and hand motor control was also assessed. A total of 23 young (age 20 – 38) and 28 older (age 65 – 90) adults were recruited. Eye movements were recorded during common hand tasks including pegboard tests of manual dexterity, Archimedes spiral tracing, and a pinch force-matching task. Measures of the subsystems of attention and a dual task were performed. Results provide evidence for decreased ability to control gaze location and altered visual strategies during hand tasks in older adults, and hand motor performance decrements may be associated with these age-related changes in eye movements. Findings also illustrate a relationship between attentional processes and pegboard performance impairments in older adults. This dissertation contributes novel findings regarding age-associated impairments in hand motor control as they relate to eye movements, offering more insight into decreased function and loss of independence in older adults.

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ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Kevin Keenan, for the tremendous support over the years and for fostering a desire for life-long learning in the field of motor control. Thank you for sharing wisdom while simultaneously allowing for self-discovery and demonstrating what it means to be an inspiring teacher, dedicated researcher, and outstanding mentor. Thank you to Dr. Wendy Huddleston for allowing me to be a guest in her lab, without which this work would not have been possible, and for generously offering her time, positive encouragement, and mentorship. Thank you to rest of my dissertation committee, including Dr. Jinsung Wang, Dr. Kristian O'Connor, and Dr. Marie Hoeger Bement. Their guidance with this project and throughout my studies has been exceptional. Thank you to the fellow members of the Neural Control of Movement Laboratory, Jeffrey Peterson and Mukta Joshi, and other kinesiology graduate students including Christopher Fueger, Alex Morgan, and Erin Lally. I am grateful for their support throughout my graduate studies and the friendships we have developed. Thank you to my family for their endless love and encouragement, especially Braxton, Ben, Hanna, Mom, Jim, and Moose. I would like to specifically acknowledge my dad, Dan, whose response to recent events exemplifies what it means to keep fighting, no matter how difficult the battle, and to never, ever give up. To my husband, Tygh. Thank you for standing by my side, always, for celebrating victories and helping me push past failures, and for encouraging me to find joy in all I do. Finally, I would like to acknowledge the Center for Aging and Translational Research and my funding sources, the University of Wisconsin-Milwaukee College of Health Sciences and the Helen Bader Age & Community Scholarship.

Chapter 1: Introduction

The number of older adults (65+ years) living in the United States is expected to double from years 2016 to 2060 (Vespa et al., 2018) and impairments in hand function are well-documented in this population (Desrosiers et al., 1999; Seidel et al., 2009). Hand motor control progressively declines after age 65 and is associated with difficulties performing activities of daily living and common hand tasks (e.g., tying a knot, opening a jar, handling coins) (Carmeli et al., 2003; Seidel et al., 2009; Shiffman, 1992). Moreover, impairments in hand function contribute to loss of independence and need for assisted living which are associated with increased health care expenditure (Falconer et al., 1991; Lubitz et al., 2003; Ostwald et al., 1989; Williams et al., 1982).

Numerous measures are commonly used to examine impairments in hand motor control such as 1) pegboard tests of manual dexterity, 2) Archimedes spiral tracing, and 3) visually guided force-matching tasks. Pegboard tests are common, standardized measures of manual dexterity recommended by the National Institute of Health (NIH) (Reuben et al., 2013; Wang et al., 2011). These tests assess manual dexterity by asking participants to pick up pegs from a tray and place them into holes on a pegboard as quickly as possible. Archimedes spiral tracing is a common, clinical assessment used in patient populations including essential tremor (Deuschl et al., 2015), Parkinson’s disease (Westin et al., 2010), and multiple sclerosis (Heenan et al., 2014), and is sensitive to age-associated changes in hand function (Heintz & Keenan, 2018; Hoogendam et al., 2014; Marmon et al., 2011). To complete the task, individuals are asked to trace an Archimedes spiral template as accurately as possible using a pen/pencil on paper (Deuschl et al., 2015) or, more recently, on digitizing tablets (Hoogendam et al., 2014; Marmon et al., 2011). Visually guided force-matching tasks ask participants to maintain a target force as accurately as possible. Visual feedback of force is typically provided via a line that fluctuates in magnitude with force output relative to a target force line. Age-related declines on finger force-matching tasks reflect a decreased ability to control finger forces and are associated with impaired hand function in older adults (Kornatz et al., 2005; Marmon et al., 2011).

Visual information plays an important role in many goal-directed movements. Evidence suggests that age-related visuomotor changes play a role in hand motor impairments in older adults (Coats and Wann, 2011; Critchley et al., 2014; Seidler-Dobrin & Stelmach, 1998; Sosnoff & Newell, 2006a; Tracy et al., 2007). Specifically, greater amounts of visual feedback have been shown to preferentially impair performance on force-matching tasks in older compared to young adults (Critchley et al., 2014; Sosnoff & Newell, 2006a; Tracy et al., 2007). Other studies have demonstrated that decreased amounts of visual information impair performance to a greater degree in older versus young adults during manual dexterity and reaching tasks (Coats & Wann, 2011; Seidler-Dobrin & Stelmach, 1998). Similarly, results from a study conducted in our laboratory suggest that older adults rely more on visual information for Archimedes spiral tracing (Heintz & Keenan, 2018). This study examined performance on a touchscreen spiral tracing task when tracing with the index finger versus a stylus. There were no differences in performance between age groups when tracing with a stylus. However, performance was impaired in older compared to young adults when tracing with the finger. Tracing with the relatively larger diameter finger occludes more vision of the touchscreen than tracing with a stylus (Vogel & Baudisch, 2007). Thus, age-related impairments when tracing with the finger may be due to a greater reliance on visual feedback in older adults (Heintz & Keenan, 2018).

Visual information is obtained through stereotypical eye movements. Specifically, saccades involve the rapid relocation of gaze and are used to orient the area of highest visual acuity (i.e. fovea) with elements of interest in the visual field (Henderson 2003; Land et al., 1999). Fixations are periods of relatively stable gaze used to maintain a still image on the fovea with the purpose of obtaining visual information (Hayhoe & Ballard, 2005). Eye movements reflect moment-to-moment input into the visual system, play a significant role in the control of everyday movements, and provide valuable information regarding the interaction between the visual and motor systems (Johansson et al., 2001; Land et al., 1999; Pelz & Canosa, 2001).

Though evidence suggesting that age-related visuomotor changes play a role in hand motor impairments (Coats and Wann, 2011; Critchley et al., 2014; Seidler-Dobrin & Stelmach, 1998; Tracy et al., 2007), a limited number of studies have examined eye movements during hand tasks in young and older adults (Coats et al., 2016; Keenan et al., 2017; Rand & Stelmach, 2011, 2012). These studies provide evidence for altered visual strategy and impaired ability to control gaze location in older adults during manual reaching (Rand & Stelmach, 2011, 2012) and object manipulation tasks (Coats et al., 2016). Additionally, one study found a relationship between age-related changes in visual strategy and decreased performance on a pinch force-matching task with pursuit feedback in older adults (Keenan et al., 2017). Pursuit feedback is a type of visual feedback. Force feedback is displayed as a trace that moves up and down with force magnitude while moving left to right with time relative to a target force line. Young and older adults gazed near the target line and made saccades that moved left to right across the screen. However, older adults made fewer saccades than young adults and decreased saccade number was related to decreased force steadiness in older adults (Keenan et al., 2017). Thus, age-related changes in eye movements may play a role in hand motor impairments and decreased hand function in older adults.

Despite these findings, more work is needed to understand how age-associated changes in eye movements contribute to hand motor impairments in older adults. First, the number of studies examining eye movements during hand tasks in older adults is relatively limited; therefore, eye tracking during measures of hand function, such as the commonly used pegboard test of manual dexterity (Wang et al., 2011), would provide greater insight into eye movements and hand motor control in older adults. Second, despite the potential association between decreased visual feedback and spiral tracing impairments in older adults (Heintz & Keenan, 2018), eye movements during the Archimedes spiral tracing task and their association spiral tracing performance have not been assessed. Third, it is not known whether decreased saccade number in older versus young adults during a pinch force-matching task (Keenan et al., 2017) was due to differences in visual feedback or age-related changes in the control of eye movements. The force trace fluctuated in magnitude with force output. Because force fluctuations were greater in older adults, force feedback was different (i.e. more variable) between age groups. This could have led to decreased saccade number in older adults independent of age-related changes in the control of eye movements. Further, increased amount of visual feedback, commonly manipulated by increasing the gain of the ordinate scale (Keenan et al., 2017), is associated with decreased force-steadiness in older adults (Critchley et al., 2014; Tracy et al., 2007). However, it is not known how the amount of visual feedback influences eye movements during force-matching tasks with pursuit feedback.

Attention also plays an important role in the performance of voluntary motor tasks (Posner, 1980) and may contribute to hand motor impairments in older adults. Age-related declines in attentional processes are well-documented (Huddleston et al., 2014) and have been associated with manual dexterity impairments in older adults (Keenan et al., 2017). Though the word “attention” is commonly used to refer to a singular mechanism or resource, authors suggest that attention includes multiple independent, but interrelated subsystems, including selective attention, sustained attention, attentional switching, and divided attention (Pashler, 1994; Posner & Petersen, 1990). Additionally, dual-task paradigms are commonly used to examine age-related changes in the ability to allocate attentional resources across multiple tasks by asking participants to perform two tasks concurrently (Woollacott & Shumway-Cook, 2002). A majority of studies utilizing dual-task paradigms have targeted falls risk in older adults by examining tasks of balance, posture, and locomotion (Hausdorff et al., 2008; Peterson & Keenan, 2018; Schrodt et al., 2004; Silsupadol et al., 2006; Springer et al., 2006). Fewer studies have examined the effect of dual tasks on upper extremity motor tasks and have found preferential performance impairments in older versus young adults (Pereira et al., 2015; Voelcker-Rehage et al., 2006). Thus, more work is needed to understand the effect of dual tasks on hand motor performance in older adults. Further, subsystems of attention may uniquely contribute to different tasks of hand function. Determining their relationship with performance common hand tasks would provide a more comprehensive understanding of motor impairments in older adults.

Statement of Purpose

The above evidence collectively supports the need to explore age-related changes in eye movements during hand motor tasks and to determine how eye movements and attention are associated with impaired hand motor control in older adults. Thus, the *primary purpose* of this dissertation was to examine age-related changes in eye movements during hand motor tasks and the association with hand motor performance in older adults. The relationship between attentional processes and performance on hand motor tasks was also assessed. Eye movements were recorded in young and older adults during common hand tasks of 1) static pinch force-matching, 2) pegboard tests of manual dexterity, and 3) Archimedes spiral tracing. Measures of the subsystems of attention and a dual task were performed. The *central hypothesis* was that there would be age-related changes in eye movements, and these would be associated with impaired hand motor performance in older adults. Further, age-related declines in attentional processes would be associated with impaired performance on hand tasks in older adults.

Specific Aims and Hypotheses

The central hypothesis was tested, and the objectives of this dissertation were accomplished by pursuing the following three specific aims:

Aim 1: To assess how pegboard test impairments in older adults are related to changes in eye movements and attention with advancing age. Eye and hand movements were recorded during pegboard tests of manual dexterity. The relationship between pegboard test performance and attentional processes, assessed using measures of the subsystems of attention and a dual task, was also determined. Though no studies to date have recorded eye movements during pegboard tests in young and older adults, age-related changes in eye movements have been found during manual reaching and object manipulation tasks (Coats et al., 2016; Rand & Stelmach, 2011), both component parts of pegboard tests. These studies found that older adults made more corrective saccades (Rand & Stelmach, 2011) and used a different visual strategy (Coats et al., 2016) than young adults. During the object manipulation task, specifically, participants picked up and placed objects onto designated targets (Coats et al., 2016). Older adults spent less time fixating on the object when picking it up and more time fixating on the target when placing the object compared to young adults. Authors suggest this altered visual strategy was used to obtain greater amounts visual information during the more complex part of the task (Coats et al., 2016). Placing the pegs into the pegboard is more complex than picking up the pegs from the tray. Therefore, the hypothesis was that older adults would make more corrective saccades (Rand & Stelmach, 2011) and would spend more time gazing at the pegboard (Coats et al., 2016) than young adults. Additionally, it was hypothesized that decreased performance on the measure of attentional switching would be related to decreased pegboard performance in older adults. Attentional switching is the ability to change focus of attention from one item to another (Posner & Petersen, 1990), which may be important for shifting the focus of attention from picking up a peg to placing a peg during the pegboard test. It was expected that the addition of a visuospatial task during the pegboard test would impair pegboard performance, especially in older adults (Pereira et al., 2015; Voelcker-Rehage et al., 2006).

Aim 2: To determine how spiral tracing impairments in older adults are related to age-associated changes in eye movements and attention. Eye movements were recorded during a touchscreen Archimedes spiral tracing task while tracing with the finger and a stylus. A dual task was performed during the spiral tracing task to determine the relationship between spiral tracing performance and attentional processes in older adults. Older adults used fewer saccades than young adults while viewing visual feedback of force during a pinch force-matching task and this was related to decreased force steadiness (Keenan et al., 2017). Therefore, it was hypothesized that older adults would use fewer saccades than young adults during the spiral tracing task and decreased saccade number would be related to spiral tracing impairments when tracing with the finger in older adults. It was also hypothesized that the dual task would impair spiral tracing performance, especially in older adults (Pereira et al., 2015; Voelcker-Rehage et al., 2006).

Aim 3. To investigate how decreased finger force control in older adults is related to age-associated changes in eye movements and attention. Eye movements were recorded during a pinch force-matching task with higher and lower gain pursuit feedback. Participants also performed a visual-tracking task by following the leading edge of a preprogrammed force trace with their gaze. The trace was presented with higher and lower variability to reflect that produced by older and young adults during the force-matching task, respectively. Measures of the subsystems of attention and a dual task were performed. It was hypothesized that older adults would use fewer saccades than young adults during the force-matching task (Keenan et al., 2017), especially with increased visual feedback, and this would be related to increased force fluctuations. It was also hypothesized that, during the visual-tracking task, older adults would make fewer saccades than young adults; however, there would but no difference in saccade number while visually tracking the force trace with higher versus lower variability. This would suggest that decreased saccade number in older versus young adults during the force-matching task (Keenan et al., 2017) were due to age-associated changes in the control of eye movements and not differences in visual feedback between age groups.

Delimitations of the Study

1. Data was collected on healthy young and older adults. Therefore, generalizations to other populations are limited.

2. Accurate eye tracking data requires that specific experimental setups be used. Specifically, head placement and location/orientation of the equipment must be controlled. Thus, findings from this study may not be representative of those found in less controlled settings.
3. Factors not directly assessed in this study may influence eye movements, attention, and motor performance including, but not limited to, motivation and anxiety. Therefore, age-related differences found in this study may not be generalizable to all healthy older adults.

Assumptions of the Study

1. Participants performed all tests and measures to the best of their ability.
2. Calibration of the eye-tracking device was completed within acceptable limits for all participants.
3. Sample of participants included in this study reflects population of interest.

Significance

The current dissertation is innovative because it uniquely examines eye movements and attention using common assessments of hand motor control, which are relatively understudied in regard to their potential contribution to hand movement impairments in older adults. Expected results are *significant* because they would provide a more comprehensive understanding of age-related impairments in hand function and would be an important step towards future work targeting hand function and independence in the rapidly increasing older adult population. Moreover, results would inform future studies assessing the role of eye movements in hand motor control in older adults and other patient populations.

Chapter 2: Age-related differences in visual strategy during pegboard tests and the associations between performance, hand movement variability, and attention in older adults

Introduction

The number of older adults (65+ years) living in the United States is expected to double from years 2016 to 2060 (Vespa et al., 2018) and hand function progressively declines with advancing age (Desrosiers et al., 1999). Impaired manual dexterity in older adults is associated with difficulties performing common hand tasks (e.g., opening a jar, handling coins, tying a knot) (Seidel et al., 2009; Shiffman, 1992) and negatively impacts functional independence (Falconer et al., 1991; Ostwald et al., 1989; Williams et al., 1982). Specifically, manual ability was found to be one of the main determinants of admittance to nursing homes (Ostwald et al., 1989) and the best marker of dependency compared to a plethora of other factors (e.g., socioeconomic status, education level, number of medications, etc.) (Falconer et al., 1991; Williams et al., 1982).

Pegboard tests are common, standardized measures of manual dexterity included in the NIH Toolbox (Reuben et al., 2013; Wang et al., 2011). Pegboard tests ask participants to pick up small pegs from a tray and place them into holes on a pegboard one at a time and as quickly as possible. Declines in pegboard performance are well-documented with age (Reuben et al., 2013; Wang et al., 2011). Studies have examined age-related changes associated with these performance decrements, such as handgrip strength (Hamilton et al., 2017; Marmon et al., 2011), fingertip sensation (Hamilton et al., 2017), and movement variability (Kornatz et al., 2005). For example, greater movement variability during a finger force-matching task in older versus young adults was associated with increased pegboard completion time (Kornatz et al., 2005). A generalized movement slowing also occurs with advancing age (Desrosiers et al., 1999) and could contribute to pegboard performance impairments in older adults.

Visual information plays an important role in many dexterous tasks (Johansson et al., 2001). Changes in the amount of visual information have been shown to preferentially impair hand motor performance in older versus young adults (Coats & Wann, 2011; Haaland et al., 1993; Seidler-Dobrin & Stelmach, 1998). For example, older adults were just as good as young adults when performing a pegboard test under normal vision conditions but performance preferentially declined in older versus young adults when vision of the hand was obstructed, suggesting a greater reliance on visual information in older adults (Coats & Wann, 2011). Research examining the use of visual information during reaching tasks report consistent findings; specifically, greater impairments in older versus young adults when visual feedback was incorporated into movement control (Seidler-Dobrin & Stelmach, 1998).

Despite a greater reliance on visual information for dexterous manipulation (Coats & Wann, 2011), it is not known where older adults look during the pegboard tests of manual dexterity. Eye movements are used to obtain task-relevant information and provide insight into ongoing visual and cognitive processes (Henderson, 2003). Specifically, saccades are the rapid relocation of eye position used to align gaze with areas of interest in the visual field. Fixations are periods of relatively stable gaze used to obtain task-relevant information (Johansson et al., 2001; Land et al., 1999). Studies have examined age-related differences in eye movements during manual reaching and object manipulation tasks (Coats et al., 2016; Rand & Stelmach, 2011, 2012), both component parts of the pegboard tests. During a manual reaching task, both young and older adults fixated on the target locations when reaching to them; however, older adults made more corrective saccades than young adults (Rand & Stelmach, 2011). Another study asked participants to pick up objects and place them onto designated targets (Coats et al., 2016). Both young and older adults fixated on the object when picking it up and on the target when placing the object. However, older adults spent less time fixating on the object and more time fixating on the target than young adults. Authors suggest this altered visual strategy was used by older adults to obtain more visual information during complex part of the task (Coats et al., 2016). Despite these findings, no study to date has recorded eye movements during the pegboard tests in young and older adults.

Declines in attention occur with advancing age (Huddleston et al., 2014) and have been associated with manual dexterity impairments in older adults (Keenan et al., 2017). Though the word "attention" is commonly used to refer to a singular mechanism or resource, authors suggest that attention includes multiple subsystems (Pashler, 1994; Posner & Petersen, 1990) including visual selective attention, sustained attention, attentional switching and divided attention. Additionally, dual-task paradigms are commonly used to examine age-related changes in the ability to allocate attentional resources across multiple tasks (Woollacott & Shumway-Cook, 2002). Dual tasks have been shown to preferentially impair motor performance in older adults (Hausdorff et al., 2008; Pereira et al., 2015; Peterson & Keenan, 2018; Schrodt et al., 2004; Voelcker-Rehage et al., 2006). However, a majority of these studies have targeted falls risk by asking participants to complete tasks of balance, posture, and locomotion (Hausdorff et al., 2008; Peterson & Keenan, 2018; Schrodt et al., 2004). Fewer studies have examined the effect of dual tasks on upper extremity motor performance in older adults (Pereira et al., 2015; Voelcker-Rehage et al., 2006). Determining the relationships between subsystems of attention and pegboard performance and implementation of a dual task would further the current understanding of age-related manual dexterity impairments.

The primary purpose of this study was to examine age-related changes in eye and hand movements during the commonly used pegboard tests of manual dexterity and to determine if these changes were associated with impairments in pegboard performance. In addition, we examined how the different subsystems of attention where related to performance on the pegboard tests in older adults. A visuospatial task was also performed during the pegboard test to examine whether there were age-related changes in manual dexterity when attention was allocated across multiple tasks. Our hypothesis was that older adults would make more corrective saccades (Rand & Stelmach, 2011) and spend more time gazing at the pegboard (Coats et al., 2016) than young adults. We hypothesized that decreased performance on measures of subsystems of attention, specifically attentional switching, would be related to decreased performance on the pegboard tests in older adults. Attentional switching is the ability to change the focus of attention from one item to the other and may be important for shifting focus of attention from picking up a peg to placing a peg during the pegboard test. In addition, we expected that the addition of a visuospatial task during the pegboard test would impair pegboard performance, especially in older adults (Pereira et al., 2015; Voelcker-Rehage et al., 2006).

Methods

Participants. A total of 51 participants, 23 young (age, 25.3 ± 4.4 years; range, 20 – 38 years; 12 females) and 28 older (age, 72.6 ± 6.6 years; range, 65 – 90 years; 13 female) adults, were recruited from the surrounding community. Written informed consent was obtained from all participants as approved by the Institutional Review Board at the University of Wisconsin-Milwaukee. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971) and had normal or corrected to normal vision as assessed by the

Snellen Eye Chart test for visual acuity (Hallowell, 2008). Exclusion criteria included presence of functional deficiencies or neuromuscular disorders, pain currently in the upper extremities that may limit normal movement, hand pathologies (e.g., arthritis), currently taking medications that influence neuromuscular function or vision, and inability to sit comfortably for extended periods. Participants were asked to abstain from caffeine 12 hours prior to testing (Lorist et al., 1995). The Montreal Cognitive Assessment (MoCA) was used to assess cognitive impairments (Nasreddine et al., 2005).

Pegboard Tests. Participants sat facing a pegboard stand rigidly fixed to a table (Fig. 2.1). A head support was positioned in front of the stand to minimize extraneous head movement and control visual angle. This setup was selected among others tested during piloting based on its ability to best 1) decrease eye data artifact, 2) promote participant comfort and natural movement, 3) minimize upper extremity fatigue, and 3) encourage visibility of the hand and pegboard.

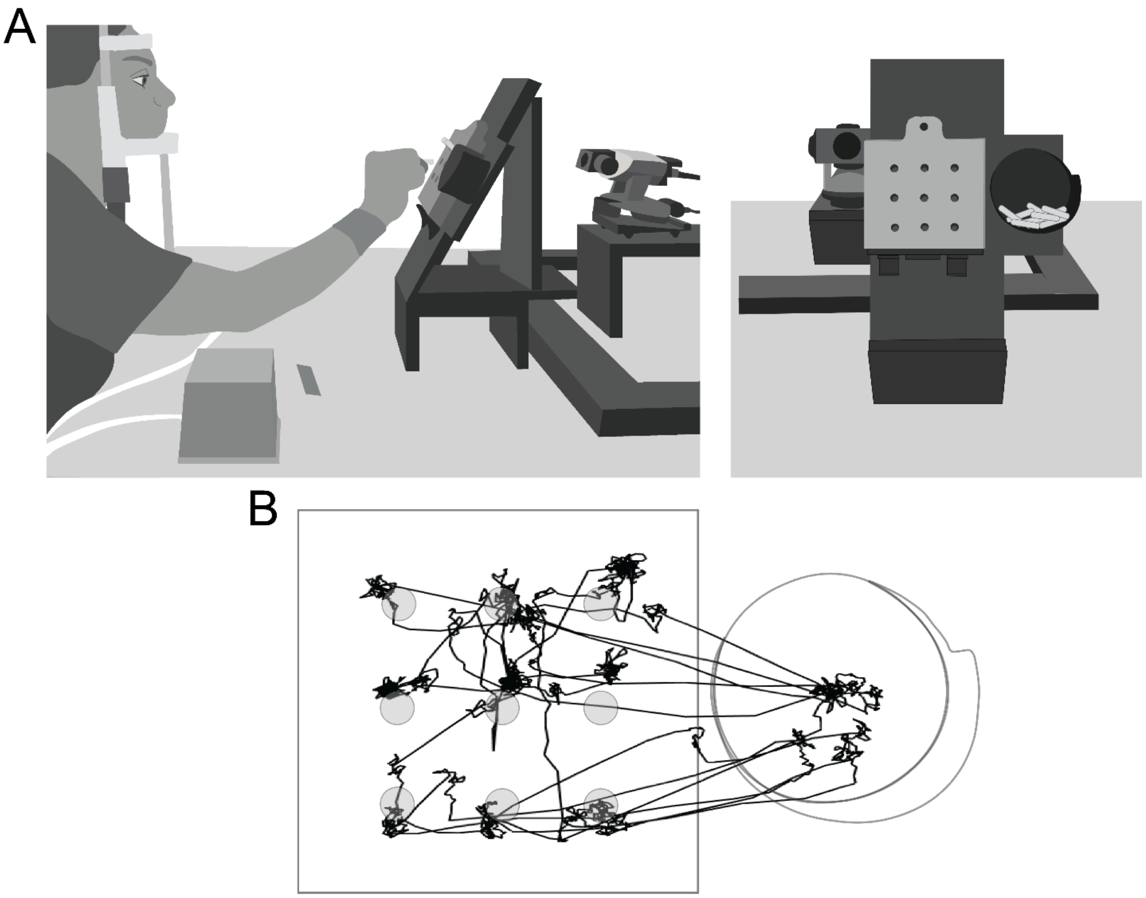


Figure 2.1. Experimental setup for the pegboard test and representative eye movement data. (A) Participants sat with their eyes positioned 40.5 cm in front of the pegboard on a custom-built stand. The bottom edge of the pegboard was 21.0 cm above the table surface with the tray located directly to the right of the pegboard. A kinematic sensor was secured to the right wrist. Participants began with their fingers on a tape marker on the table. The horizontal and vertical visual angles were 28.5 ° and 16.0 °, respectively. A similar setup was used for the Grooved Pegboard test. Left = side view, Right = participant's point of view. (B) Eye movements were recorded in the horizontal and vertical directions. Representative eye movement data demonstrate fixations at the tray and pegboard holes while picking up and placing the pegs.

Participants completed the pegboard test under three conditions: 1) 9-Hole Pegboard, 2) Grooved Pegboard, and 3) Grooved Pegboard + Visuospatial (VS) task. The Jamar 9-Hole Pegboard test (4MD Medical Solutions, Lakewood, NJ) and Grooved Pegboard test (Lafayette Instrument Company, Lafayette, IN) are two of the more commonly used pegboard tests and vary in task demands and difficulty (Reuben et al., 2013; Wang et al., 2011). The 9-Hole Pegboard consists of 9 round pegs (0.6 cm diameter) and a pegboard (31 cm x 26 cm x 4 cm) with 9 round holes in a 3 x 3 grid. Instructions were to place all nine pegs in the holes, one at a time and as quickly as possible. The Grooved Pegboard consists of 25 grooved pegs (0.3 cm diameter) and a pegboard (20.3 cm x 12.7 cm x 17.8 cm) with 25 grooved holes oriented in different directions in a 5 x 5 grid. Each peg must be manipulated so the groove matches the orientation of the hole, presenting greater motor coordination and visual perceptual demands compared to 9-Hole Pegboard (Ashendorf et al., 2009; Reuben et al., 2013; Wang et al., 2011). Instructions were to place the pegs into the holes one at a time and as quickly as possible. Pilot testing revealed potential for upper extremity fatigue when completing all 25 holes, especially in older adults. To minimize age-related differences due to fatigue, participants completed the top 2 rows of the Grooved Pegboard resulting in a total of 10 holes in a 2 x 5 grid.

For the Groove Pegboard + VS condition, participants completed the Grooved Pegboard test while simultaneously performing a visuospatial task based on Brooks' spatial memory task (Brooks, 1967) and that used previously (Peterson & Keenan, 2018). Participants visualized a star moving around four boxes in a 2 x 2 grid, labeled 1 through 4. The star always started in Box 1. Participants were told a series of four randomized directions that signified the direction of the star's movement (i.e. right, left, up, down, or diagonal). Each series began when the experimenter said, "Start" followed by four directions, and ended when the experimenter asked, "Location?" upon which the participant stated the final star location. Prior to testing, participants completed five trials while viewing an image of the grid followed by a series of practice trials without the image. Three consecutive correct practice trials without the image were required before proceeding.

For all pegboard conditions, participants began with their hand resting on the table and fingers placed on a tape marker (Fig. 2.1A). The trial started when the experimenter said, “Go” and ended when the last peg was in the final hole. One practice trial and two test trials were performed for each condition using the right hand. At least 30 s of rest were provided between trials. Additional trials were performed if the participant 1) dropped one or more pegs, 2) picked up two pegs at once, or 3) began before the “Go” signal. Completion time was calculated as the time from the start to end of each trial, averaged across two trials for each condition.

Eye movements were recorded in the horizontal (X) and vertical (Y) directions with an infrared R6 Remote Optics Eye Tracking System (Applied Science Laboratories, Bedford, MA) at 120 Hz (Huddleston et al., 2013; Keenan et al., 2017) (Fig. 2.1B). Participants completed a full-field 9-point eye tracking calibration prior to testing and a 5-point calibration to establish the pegboard location within the eye tracking coordinate system. Kinematics were recorded using an electromagnetic miniBIRD tracking system (Ascension Technology, Burlington, VT) at 120 Hz, similar to sampling rates used during previous studies of kinematics during object manipulation tasks (Coats et al., 2016; Cole et al., 2010). The miniBIRD sensor (1.80 cm x 0.81 cm x 0.81 cm) was secured to the right wrist at the radial styloid process using medical tape and pre-wrap. Sensor placement was selected to minimize obstruction of dexterous movement and vision of the fingers, peg, and pegboard, and is consistent with previous work assessing hand movements in older adults while picking up and placing objects (Coats et al., 2016). MiniBIRD sensor position was recorded in the direction relative to a transmitter coordinate reference frame. A 5-point calibration was completed to establish the location of the pegboard within the transmitter coordinate reference frame. Eye movement and kinematic data were collected on a laptop computer (Dell Optiplex GX620, Austin, TX) using Eye-Trac 6 User Interface program (Applied

Science Laboratories, Bedford, MA). The sequence of trials was block randomized across pegboard conditions.

Measures of Attention.

Test of Everyday Attention. The Test of Everyday Attention is a common, reliable measure of the subsystems of attention designed to reflect everyday tasks (Robertson et al., 1994). Three subtests from the Test of Everyday Attention were performed to assess different subsystems of attention, including 1) Visual Elevator, 2) Telephone Search, and 3) Telephone Search While Counting. Tests were administered and scored based on methods set forth by the manual (Robertson et al., 1994).

Visual Elevator (attentional switching). Participants were shown a series of elevator door images with smaller arrows signifying the direction of counting. Larger arrows were dispersed between elevator images pointing in the upward and downward directions. Each elevator door image represented one floor. Participants were instructed to count each elevator door image beginning at one and counting upward. When a downward arrow appeared, the participant said "down" and counted backwards. When an upward arrow appeared, the participant said "up" and counted upwards. Participants were instructed to complete the subtest as quickly and accurately as possible. Two practice trials were completed prior to 10 test trials. Timing score was calculated as the completion time for each trial summed across all correct trials, divided by the number of switches (i.e. number of larger upward and downward arrows) summed across all correct trials. Timing score is reported in seconds.

Telephone Search (visual selective attention). Participants were presented with a telephone directory page. Two symbols (i.e. star, square, circle, or cross) were placed next to each directory entry. Participants were instructed to search the directory from top to bottom and left to right to locate and circle instances when two identical symbols appeared together. Instructions were to complete the subtest as quickly and accurately as possible. Time per target score was calculated as the completion time divided by the number of correctly circled symbols and is reported in seconds.

Telephone Search While Counting (divided attention and sustained attention). Participants completed the Telephone Search subtest while simultaneously counting strings of tones played on an audiotape. Each string began when the audiotape said, “Ready” and ended when the audiotape asked, “How many?”, upon which the participant stated the number of tones in the string. Dual task decrement score was calculated by subtracting the time per target score from the Telephone Search from time per target score from this subtest and is reported in seconds.

Trail Making Test (TMT). The TMT is a common neuropsychological assessment of cognitive processes and executive function (Tombaugh, 2004) and consists of two parts, Part A and Part B. Both parts measure sustained attention and visual selective attention. Part B also measures attentional switching (Sanchez-Cubillo et al., 2009).

Participants performed Part A and Part B of the TMT using standardized procedures (Bowie & Harvey, 2006). For both tests, participants used a pencil to connect 25 circles displayed on a piece of paper as quickly as possible using the right hand. For Part A, participants connected the 25 circles numbered 1 through 25 in ascending order. For Part B, participants connected a series of 25 circles numbered 1 through 13 and lettered A through L in numerical and alphabetical order, alternating between number and letter (e.g., 1-A-2-B-3-C…13-L). One practice trial and one test trial were performed for each part. Completion time was recorded in seconds. The sequence of trials was block randomized across attention tests.

Data Analysis. Eye tracking data was exported using EyeNal software (Applied Science Laboratories, Bedford, MA). Eye tracking data and kinematic data were analyzed offline using MATLAB (The MathWorks, Inc., Natick, MA). Eye data associated with blinks and artifact were removed, defined as X, Y, or pupil size of zero. Additional data associated with blinks and artifact were removed manually, including transient spikes. Transient spikes were defined as instances when eye position exceeded the field of view. Eye data artifact was replaced with a line of best fit extending from one data point before and after the first and last point of artifact, respectively, to allow for accurate calculations of pegboard hole gaze time (see below). Participants with > 20% eye data artifact were excluded based on previous standards for eye movement recordings during functional measures in older adults (Zietz & Hollands, 2009). Eye position data was not filtered, consistent with previous methods (Huddleston et al., 2013; Keenan et al., 2017; Rand & Stelmach, 2011). Kinematic data was filtered using a low pass, 4th order, zero lag Butterworth filter with a 12 Hz cutoff frequency. Cutoff frequency was within the range used previously (Coats et al., 2016; Cole et al., 2010) and was confirmed using a residual analysis.

All participants moved their hand through four phases to fill one pegboard hole: 1) pick up one peg from the tray, 2) move hand to the pegboard, 3) place peg into the pegboard hole, and 4) move hand from the pegboard to the tray. Hand velocity was calculated as the first derivative of hand position. The times the hand arrived at and left the pegboard and tray were defined as the first data point after horizontal hand velocity fell below and first data point before horizontal hand velocity exceeded 3.6 cm/s, respectively. Horizontal hand velocity was used to determine these landmarks based on previous methods (Coats et al., 2016) and because the hand moved primarily in the horizontal direction when reaching to and from the pegboard and tray. The velocity cutoff was determined based on review of hand velocity profiles and was similar to values used previously (Coats et al., 2016; Rand & Stelmach, 2011). Landmarks were used to segment the movement into the four phases (Fig. 2.2A):

1. Peg Pickup: Time hand arrived at the tray to time hand left the tray.
2. Tray → Pegboard Transition: Time hand left the tray to time hand arrived at the pegboard.
3. Peg Placement: Time hand arrived at the pegboard to time hand left the pegboard.
4. Pegboard → Tray Transition: Time hand left the pegboard to time hand arrived at the tray.

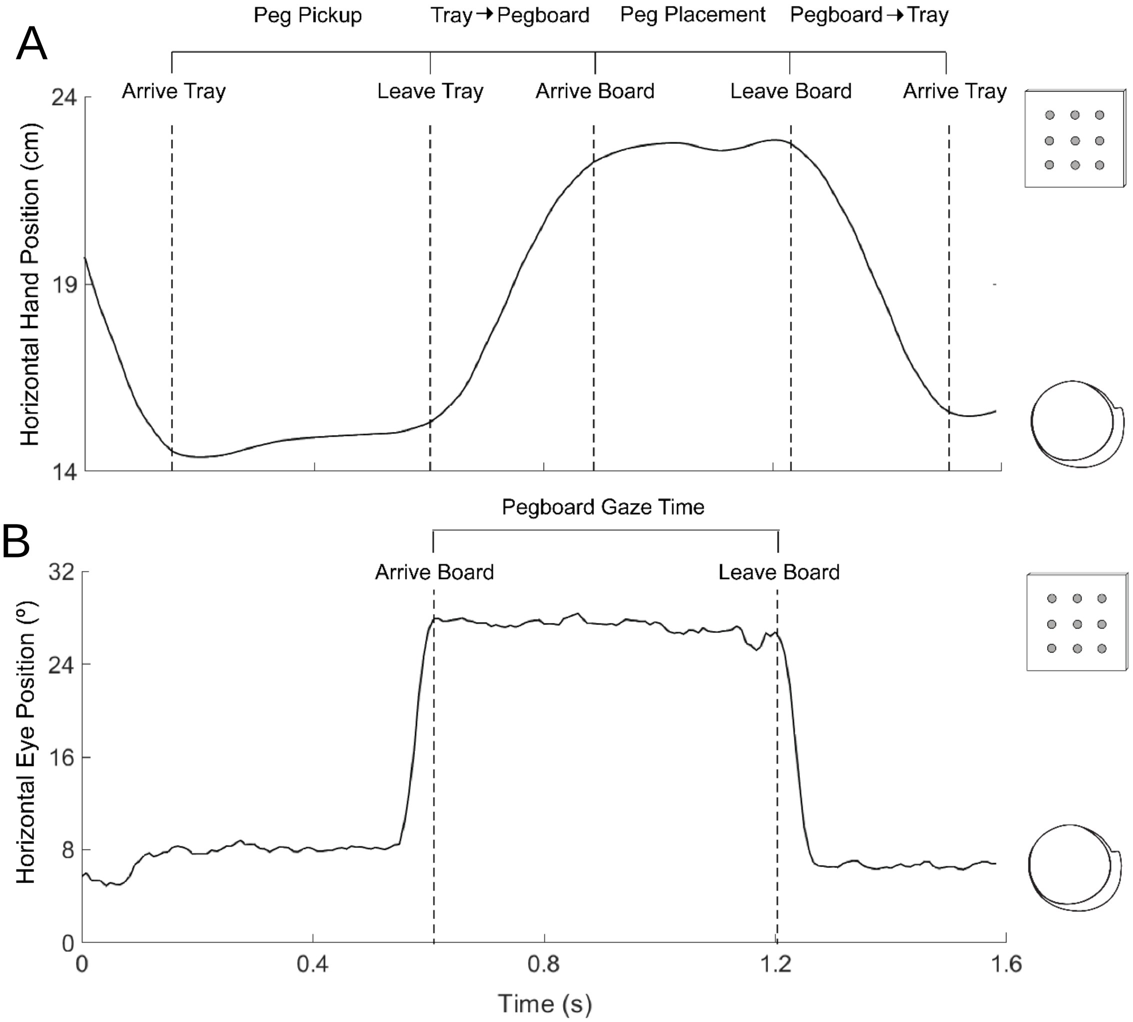


Figure 2.2. Segmentation of hand and eye movements during one hole of the 9-Hole Pegboard. The pegboard tray was positioned to the right of the pegboard. Increased position corresponded to movements toward the pegboard. Decreased position corresponded to movements toward the tray. (A) Hand velocity cutoffs were used to determine when the hand arrived at and left the tray (Arrive Tray and Leave Tray, respectively) and pegboard (Arrive Board and Leave Board, respectively). These landmarks were used to segment the hand movement into four phases, including 1) Peg Pickup, 2) Tray → Pegboard Transition, 3) Peg Placement, and 4) Pegboard → Tray Transition. (B) Participants fixated on the pegboard hole for peg placement. Eye velocity cutoffs were used to determine the end of the saccade to the pegboard (Arrive Board) to the start of the saccade away from the pegboard (Leave Board). These landmarks were used to calculate gaze time at the pegboard hole (Pegboard Gaze Time).

Data for the first and last pegboard holes were removed prior to analysis due to behavioral differences at the start and end of the pegboard test, including differences in eye position prior to fixating on the first hole and hand position after placing the peg in the last hole. Thus, succeeding kinematic and eye tracking analysis included data from hand leaving the pegboard for Hole 1 to hand leaving the pegboard for Hole 8 (9-Hole) or Hole 9 (Grooved and Grooved + VS). Time analyzed was calculated as the total time between these cutoffs.

Eye velocity was calculated as the first derivative of horizontal eye position using the first central difference method. All participants fixated on the pegboard holes for peg placement (Fig. 2.1B). Therefore, eye velocity was used to calculate two landmarks including, 1) end of saccade to the pegboard hole and 1) start of saccade away from the pegboard hole, defined as the data point after eye velocity fell below and exceeded a cutoff velocity of 30.5 °/s, respectively (Fig. 2.2B). Horizontal eye velocity was used to determine these landmarks based on methods used previously to segment eye movements into phases while picking up and placing objects (Coats et al., 2016) and because eye movements travelled primarily in the horizontal direction when gazing to and from the pegboard and tray. Cutoff velocity was determined based on examination of eye velocity profiles (Rand & Stelmach, 2011).

Some participants made corrective saccades after the primary saccade to the pegboard and before fixating on the pegboard hole. The number of holes with corrective saccades were counted manually, summed across all holes, and divided by the total number of holes for each trial. Gaze time at the pegboard holes was calculated as the percent of total trial time participants fixated on the pegboard holes during peg placement (Fig. 2.2B). Specifically, time from the end of the saccade to the pegboard to the start of the saccade away from the pegboard was calculated for each hole, summed across all holes, and divided by the time analyzed for each trial. If a corrective saccade was made, pegboard gaze time was calculated from the end of the corrective saccade to the start of the saccade away from the pegboard (Rand & Stelmach, 2011). Pegboard gaze time and percentage of holes with corrective saccades are reported as the average across the two trials for each condition.

To examine whether age-related movement slowing (Desrosiers et al., 1999) played a role in pegboard performance impairments, peak hand velocity was calculated to examine age-related differences in hand velocity when reading to and from the pegboard and tray. Peak hand velocity was calculated during Tray → Pegboard Transition and Pegboard → Tray Transition for each hole, averaged across all holes for each trial. Peak hand velocity was averaged across the two trials for each condition and is reported in centimeters/second. Because movement variability has been associated with impaired pegboard performance in older adults (Kornatz et al., 2005), hand position variability during peg placement was calculated (Fig. 2.3). Specifically, the line of best fit between the horizontal hand position when the hand arrived at and left the pegboard was determined. The Root Mean Square Error (RMSE) between the line of best fit and participant's horizontal hand position was calculated during peg placement to quantify the amount of hand position variability. RMSE was used to account for differences in peg placement time across pegboard tests and age groups. RMSE was calculated as the average across all pegboard holes, reported in millimeters, and is reported as the average across two trials for each condition.

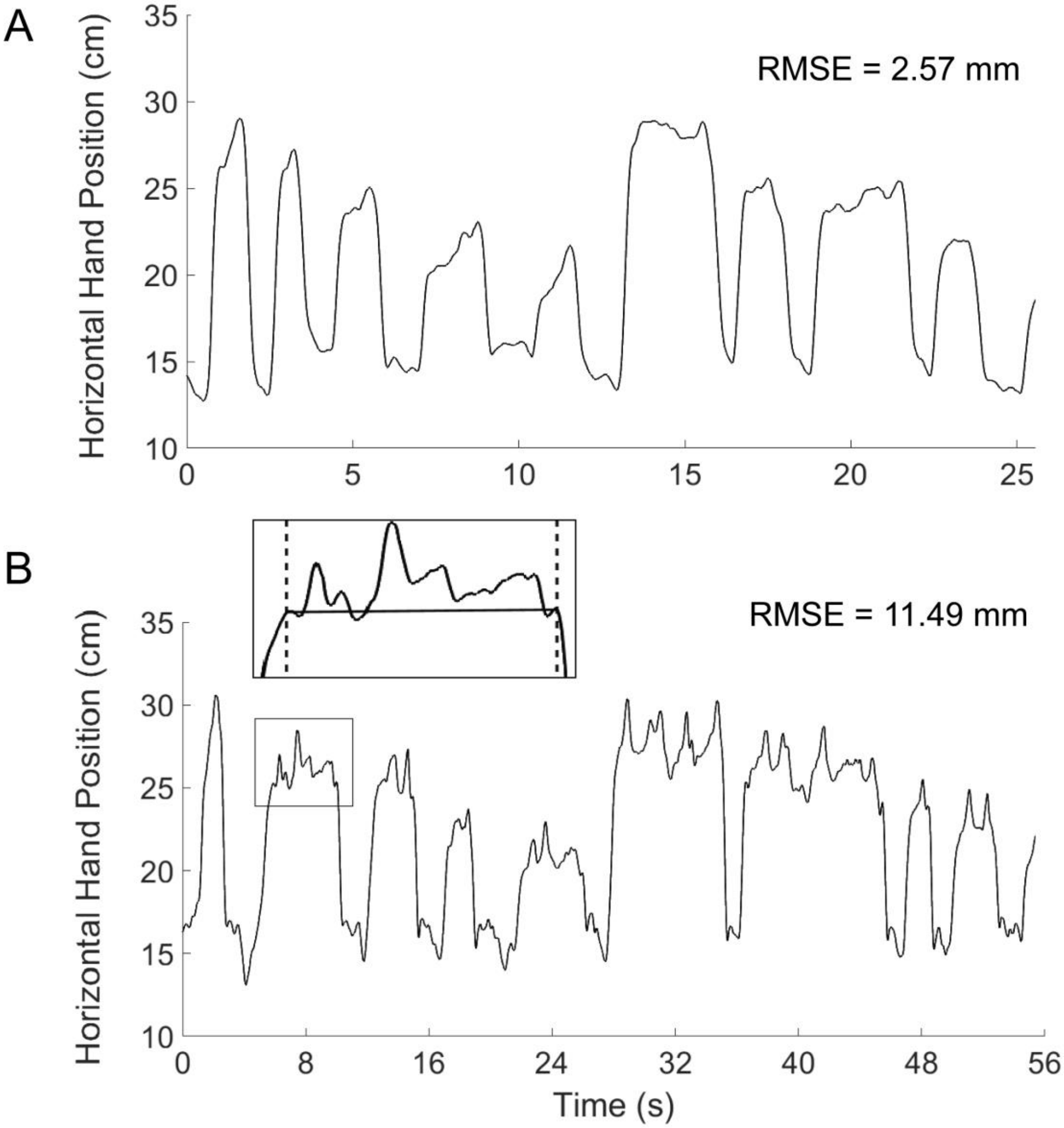


Figure 2.3. Representative hand position data and calculation of hand position variability. Data is from one (A) young and (B) older adult during Grooved Pegboard with lower and higher Root Mean Square Error (RMSE), respectively. (B inset image) The line of best fit (horizontal solid line) was calculated from the time the hand arrived at the pegboard to the time the hand left the pegboard (vertical dashed lines). RMSE was calculated between the line of best fit and participant's hand position to quantify movement variability while placing the peg. Greater RMSE corresponds to greater hand position variability. Greater and lesser horizontal hand position is associated with pegboard location and tray location, respectively (Fig. 2.1A).

Statistical Analysis. Statistical analysis was performed using SPSS 25 (SPSS, Chicago, IL). Statistical significance for all tests was set at $p < 0.05$. Data are reported as mean ± SD in text and mean + SE in figures unless otherwise noted. Normality was confirmed using a Shapiro Wilk's test and visual inspection of Q-Q plots.

A two-sample, independent t-test was used to examine differences in MoCA scores between young and older adults. Pegboard completion time did not conform to a normal distribution and was transformed using an inverse transformation (Osborne, 2002). A mixed between-within subjects ANOVA was performed to examine differences in pegboard completion time, pegboard gaze time, percent holes with corrective saccades, and hand position variability between young and older adults and across the 9-Hole Pegboard, Grooved Pegboard, and Grooved Pegboard + VS, with a between-subjects factor of age group and within-subjects factor of pegboard condition. Significant results were followed with post-hoc tests with Bonferroni corrections. Pearson's correlations were performed to determine the relationship between pegboard gaze time and pegboard completion time and between percent holes with corrective saccades and pegboard completion time. A Pearson's correlation was also used to determine the relationship between hand position variability and pegboard completion time.

A mixed between-within subjects ANOVA was performed to investigate differences in peak hand velocity between age groups (young and older adults), and across transitions (Tray → Pegboard Transition and Pegboard → Tray Transition) and pegboard conditions (9-Hole, Grooved, and Grooved + VS), with a between-subjects factor of age group and within-subjects factors of transition and pegboard condition. Significant results were followed with post-hoc tests with Bonferroni corrections. Attention scores did not follow a normal distribution. A normal distribution was not achieved with transformations. Therefore, a Kruskal-Wallis test was performed to examine differences in attention scores between young and older adults.

Spearman's correlations were used to examine the relationship between attention scores and pegboard completion time.

Results

Participants. Data from 40 participants, 20 young (age, 25.2 ± 4.7 years; range, 20 - 38 years; 10 female) and 20 older (age, 71.9 years; range, 65 – 85 years, 11 female) adults, were included, consistent with an a priori power analysis using G*Power (Faul et al., 2007). Data from 3 young (age, 26 ± 2.6 years; range, 23 - 28 years; 2 female) and 8 older (age, 74.5 ± 8.3 years; range, 67 – 90 years, 2 female) adults were discarded due to > 20 % eye data loss. There was no significant difference in MoCA scores ($t(38) = 1.082$, $p = 0.143$) between young (28.5 ± 1.2) and older (28.0 ± 1.2) adults. No participants scored below the cutoff for cognitive impairment (i.e., < 26) (Nasreddine et al., 2005).

Pegboard Performance. Pegboard completion time was significantly greater ($F(2) = 46.077$, $p < .001$, $\eta_p^2 = .979$) for older vs. young adults (mean = 31.45 s, 95% CI = [28.89, 35.59] and mean = 22.68 s, 95% CI = [20.88, 24.81], respectively) (Fig. 2.4). There was a main effect of pegboard condition on completion time ($F(2) = 753.44$, $p < .001$, $\eta_p^2 = .952$). Completion time was greater for Grooved vs. 9-Hole ($p < .001$), Grooved + VS vs. 9-Hole ($p < .001$), and Grooved + VS vs. Grooved ($p < .001$) (9-Hole, mean = 17.73 s, 95% CI = [16.78, 18.83]; Grooved, mean = 32.89 s, 95% CI = [30.21, 36.23]; Grooved + VS, mean = 36.76 s, 95% CI = [33.67, 40.49]). There was no significant interaction effect on completion time ($p = .845$).

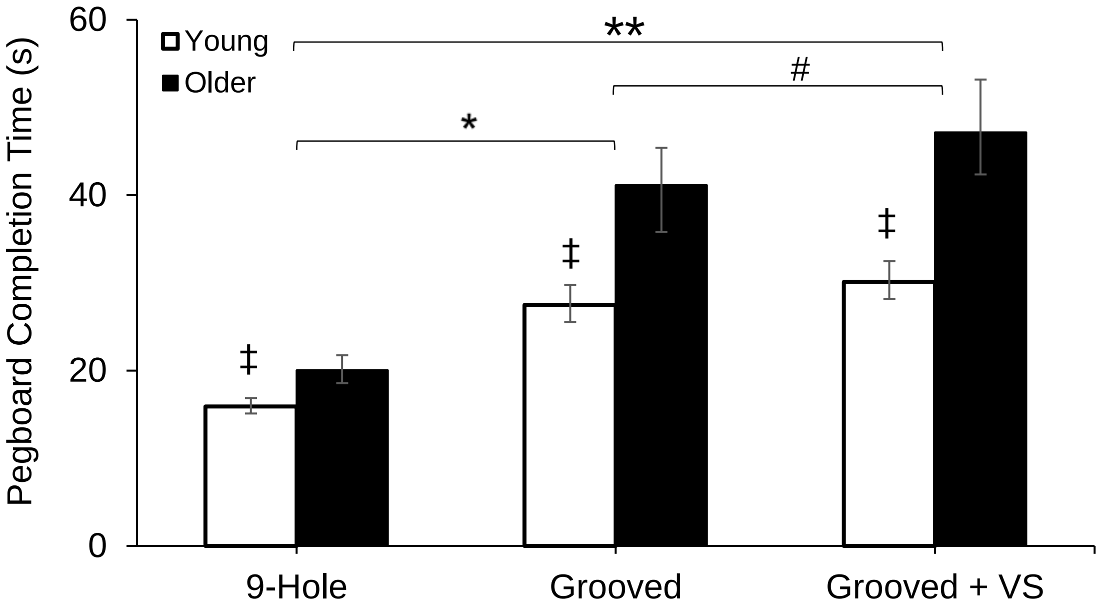


Figure 2.4. Pegboard completion time between age groups and across conditions. Completion time was significantly greater (‡p = < .001) for older vs. young adults. There was a main effect of pegboard condition on completion time ($p < .001$). Completion time was greater for 9-Hole vs. Grooved (*$p < .001$), Grooved vs. Grooved + VS ($^{\#}p < .001$), and 9-Hole vs. Grooved + VS (**$p < .001$). Data are back-transformed mean and 95% CI.

Eye Movements. All participants fixated on the pegboard hole during peg placement. All older adults and most young adults also fixated on the pegboard tray for peg pickup (Fig. 2.1C). A select number of young adults (N = 4) did not fixate on the pegboard tray during the pegboard tests and instead, made saccades directly from one hole to the next. Statistical comparisons were difficult given the small sample size (VanVoorhis & Morgan, 2007); however, completion time was relatively similar between young adults who did and did not use the altered visual strategy for 9-Hole (Mdn = 15.21 s, IQR = 14.24 – 15.46 and Mdn = 16.33 s, IQR = 15.40 – 17.15, respectively), Grooved (Mdn = 26.51 s, IQR = 24.79 – 28.66 and Mdn = 26.80 s, IQR = 24.13 – 34.26, respectively), and Grooved + VS (Mdn = 28.35 s, IQR = 24.89 – 29.54 and Mdn = 30.04 s, IQR = 28.17 – 34.49, respectively).

Corrective saccades were significantly greater ($F(1) = 17.285, p < .001, \eta_p^2 = .313$) for older (49.05 ± 27.22 % holes) vs. young adults (23.75 ± 19.25 % holes) adults (Fig. 2.5A). There was a main effect of pegboard condition on corrective saccades ($F(2) = 11.242, p < .001$), $\eta_p^2 = .228$). Participants made more corrective saccades during 9-Hole vs. Grooved ($p = .002$) and 9-Hole vs. Grooved + VS ($p = .001$) (9-Hole, 46.69 ± 25.41 % holes; Grooved, 31.34 ± 30.14 % holes; Grooved + VS, 31.26 ± 24.05 % holes). There was no difference in corrective saccades for Grooved vs. Grooved + VS ($p = .940$). The age by condition interaction was not significant ($p = .311$).

Young adults spent a significantly greater percentage of time gazing at the pegboard holes ($F(1) = 12.120, p = .001, \eta_p^2 = .242$) compared to older adults (70.37 ± 14.89 % total time and 58.23 ± 14.34 % total time, respectively) (Fig. 2.5B). There was a significant main effect of condition on pegboard hole gaze time ($F(2) = 53.429, p < .001, \eta_p^2 = .584$). Participants spent a greater percentage of timing gazing at the pegboard holes for Grooved (68.50 ± 14.26 % total time) vs. 9-Hole (53.74 ± 15.48 % total time) (p < .001) and 9-Hole vs. Grooved + VS (70.66 ± 12.51 % total time) (p <.001), with no difference in pegboard gaze time between Grooved and Grooved + VS ($p = .631$). The age by condition interaction was not significant ($F(2) = 2.162, p = .122, \eta_p^2 = .054$).

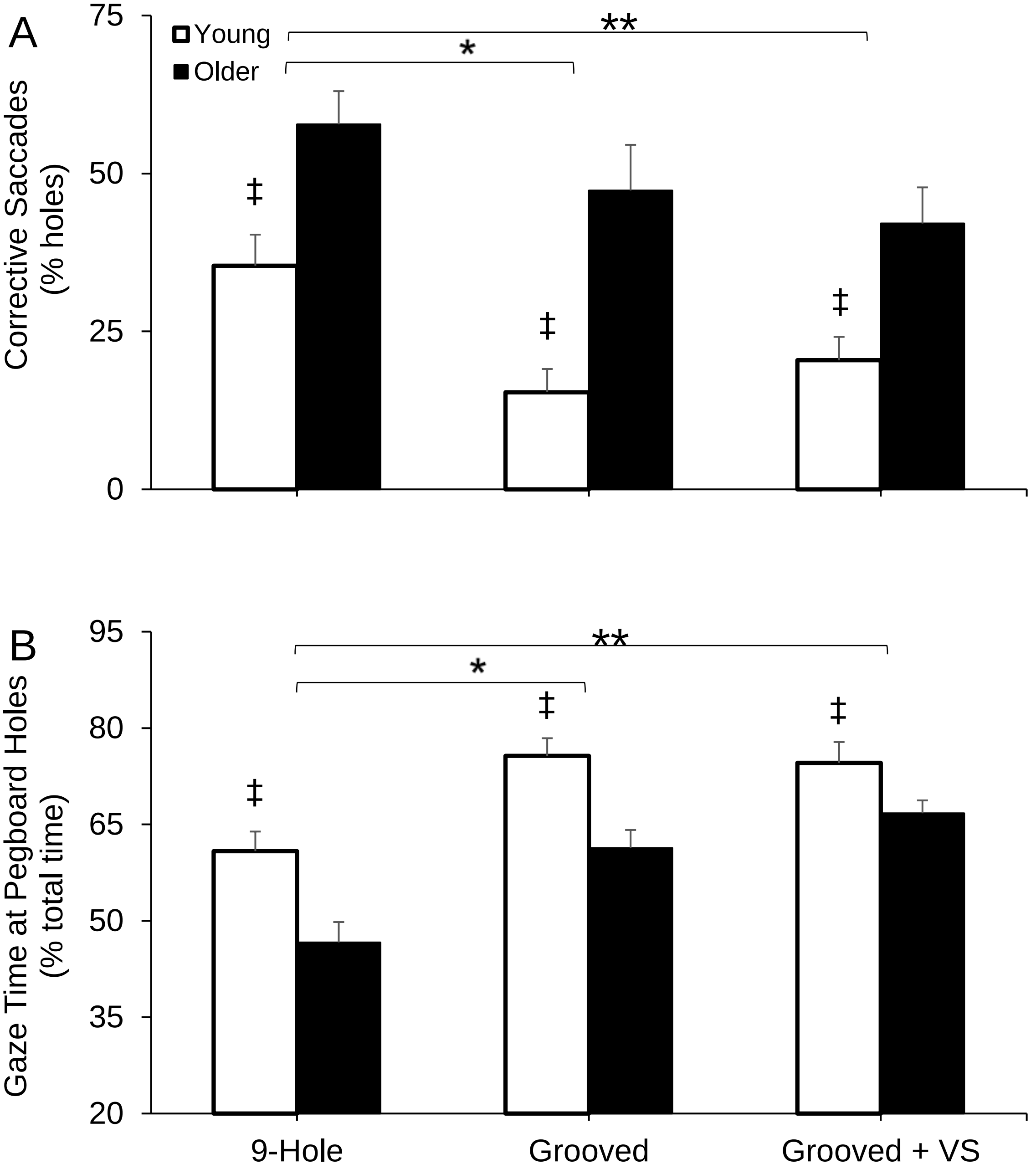


Figure 2.5. Corrective saccades and pegboard gaze time in young and older adults. (A) Percent holes with corrective saccades were significantly greater (‡*p* < .001) in older vs. young adults for all conditions. There was a main effect of pegboard condition on corrective saccades (*p* < .001). Corrective saccades were greater for 9-Hole vs. Grooved (**p* = .002) and 9-Hole vs. Grooved + VS (***p* = .001). (B) Young adults spent a significantly (‡*p* = .001) greater percentage of total time gazing at the pegboard holes than older adults. There was a main effect of pegboard condition on gaze time (p < .001). Gaze time at the pegboard holes was greater for 9-Hole vs. Grooved (**p* < .001) and Grooved + VS (***p* < .001).

Because corrective saccades and pegboard gaze time were different between age groups, their relationships with pegboard completion time were examined. There was a significant, inverse relationship between pegboard gaze time and completion time for Grooved Pegboard in older adults ($r = -.466$, $p = .038$) (Table 2.1). There were no other significant correlations.

	Young			**Older**		
	9-Hole	**Grooved**	**Grooved + VS**	**9-Hole**	**Grooved**	**Grooved + VS**
Corrective Saccades	$r = -.363$ $p = .115$	$r = .016$ $p = .946$	$r = .036$ $p = .880$	$r = .144$ $p = .545$	$r = .392$ $p = .087$	$r = .277$ $p = .238$
Pegboard Hole Gaze Time	$r = .180$ $p = .447$	$r = .148$ $p = .535$	$r = -.098$ $p = .681$	$r = -.238$ $p = .312$	**$r = -.466$** ****$p = .038$**	$r = .106$ $p = .666$

Table 2.1. Relationships between eye movements and pegboard completion time. There was a significant, inverse relationship between pegboard gaze time and Grooved Pegboard completion time in older adults. There were no other significant correlations. (**, bold text = significant).

Hand Movements. Mauchly's Test of Sphericity revealed that the assumption of sphericity was violated for peak velocity. Therefore, Greenhouse-Geisser corrections were used. There was a significant pegboard condition by transition (i.e. Tray → Pegboard Transition and Pegboard → Tray Transition) interaction effect on peak velocity ($F(2) = 119.800$, $p < .001$, $\eta_p^2 = .759$). Peak velocity was greater when moving from the pegboard to tray vs. tray to pegboard for all pegboard conditions, including 9-Hole ($p < .001$) (38.68 ± 6.35 cm/s and 32.30 ± 4.76 cm/s, respectively), Grooved ($p < .001$) (41.49 ± 8.01 cm/s and 24.42 ± 5.58 cm/s, respectively), and Grooved + VS ($p < .001$) (39.93 ± 7.86 cm/s and 22.89 ± 4.38 cm/s, respectively). Peak velocity when moving from the tray to pegboard was greater for 9-Hole vs. Grooved ($p < .001$), 9-Hole vs. Grooved + VS ($p < .001$) and for Grooved vs. Grooved + VS ($p = .007$). Peak velocity when moving from the pegboard to tray was greater for Grooved vs. 9-Hole ($p = .003$) and Grooved vs. Grooved + VS ($p = .034$), however there was no difference for 9-Hole vs. Grooved + VS ($p = .397$). There was a significant main effect of transition on peak velocity ($F(1) = 195.760$, $p < .001$, $\eta_p^2 = .837$) and a significant main effect of pegboard condition on peak velocity ($F(2) = 23.343$, $p < .001$, $\eta_p^2 = .381$). There was no significant effect of age on peak velocity ($p > .258$).

There was a significant age by condition interaction effect on hand position variability during peg placement ($F(2) = 5.302$, $p = .007$, $\eta_p^2 = .122$) (Fig. 2.6). Hand position variability was greater in older vs. young adults for all pegboard conditions, including 9-Hole ($p = .002$), Grooved ($p = .045$), and Grooved + VS ($p = .001$). In young adults, hand position variability was greater for Grooved vs. 9-Hole ($p < .001$) and Grooved + VS vs. 9-Hole ($p = .008$) (9-Hole, 1.36 ± .63 mm; Grooved, 5.88 ± 3.62 mm; Grooved + VS, 5.74 ± 1.97 mm). In older adults, hand position variability was greater for Grooved vs. 9-Hole ($p < .001$) and Grooved + VS vs. 9-Hole ($p < .001$) (9-Hole, 1.94 ± 0.76 mm; Grooved, 8.42 ± 3.31 mm; Grooved + VS, 9.29 ± 3.71 mm). There was no difference in hand position variability between Grooved and Grooved + VS in young ($p = .956$) and older ($p = .357$) adults. There was a significant main effect of pegboard condition ($F(2) = 100.655$, $p < .001$, $\eta_p^2 = .726$) and a significant main effect of age ($F(2) = 11.617$, $p = .002$, $\eta_p^2 = .234$) on hand position variability.

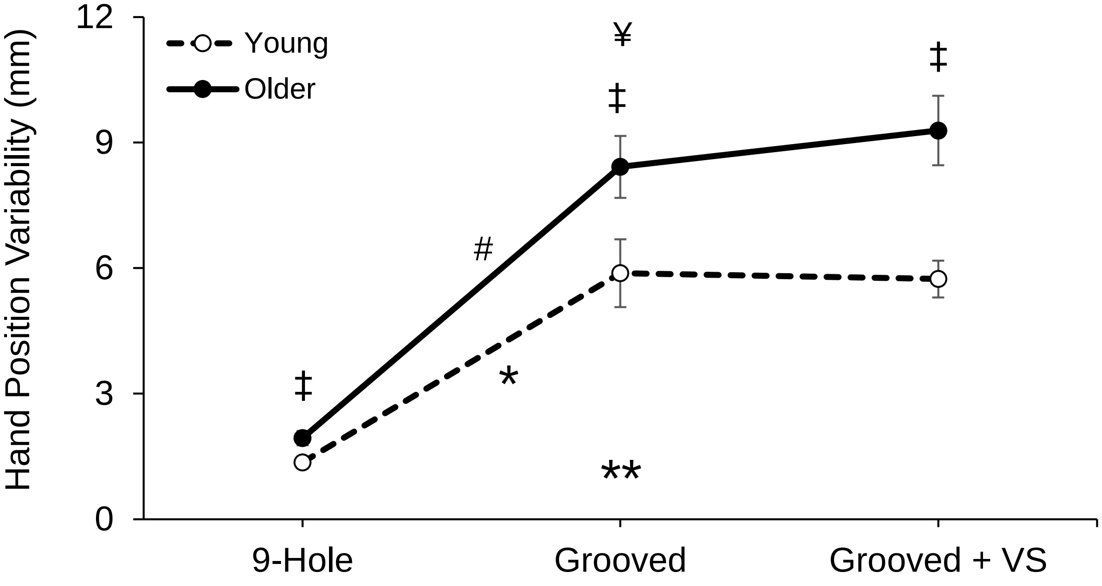
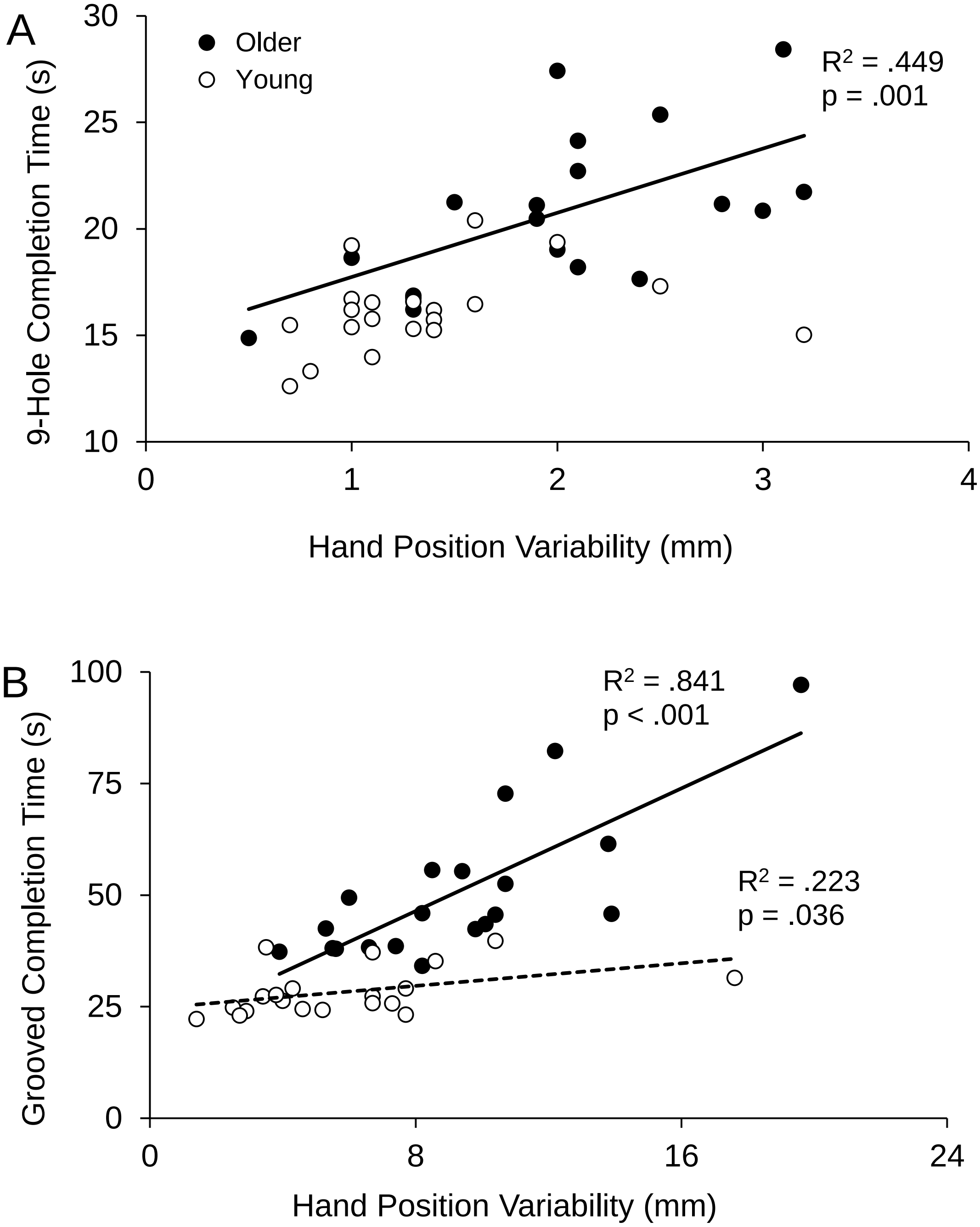


Figure 2.6. Hand position variability during peg placement between age groups and across conditions. Hand position variability, calculated by RMSE, was greater for older vs. young adults for all conditions ($^{‡}p$ = .007). Hand position variability was greater for Grooved vs. 9-Hole in young (**p* < .001) and older ($^{\#}p$ < .001) adults and for Grooved + VS vs. 9-Hole in young (***p* = .008) and older ($^{¥}$p < .001) adults.

Because hand position variability differed between age groups, the relationships between hand position variability and pegboard completion time were examined (Fig. 2.7). In older adults, there was a significant, positive correlation between hand position variability and completion time for 9-Hole (*r* = .670, *p* = .001), Grooved (*r* = .917, *p* < .001), and Grooved + VS (*r* = .743, *p* < .001). In young adults, there was a significant, positive correlation between hand position variability and completion time for Grooved (*r* = .472, *p* = .036) and Grooved + VS (*r* = .525, *p* = .018), but not for 9-Hole (*r* = .299, *p* = .201).


A
30
25
20
15
10
9-Hole Completion Time (s)
● Older
○ Young
R2 = .449
p = .001
0
1
2
3
4
Hand Position Variability (mm)
B
100
75
50
25
0
Grooved Completion Time (s)
R2 = .841
p < .001
R2 = .223
p = .036
0
8
16
24
Hand Position Variability (mm)

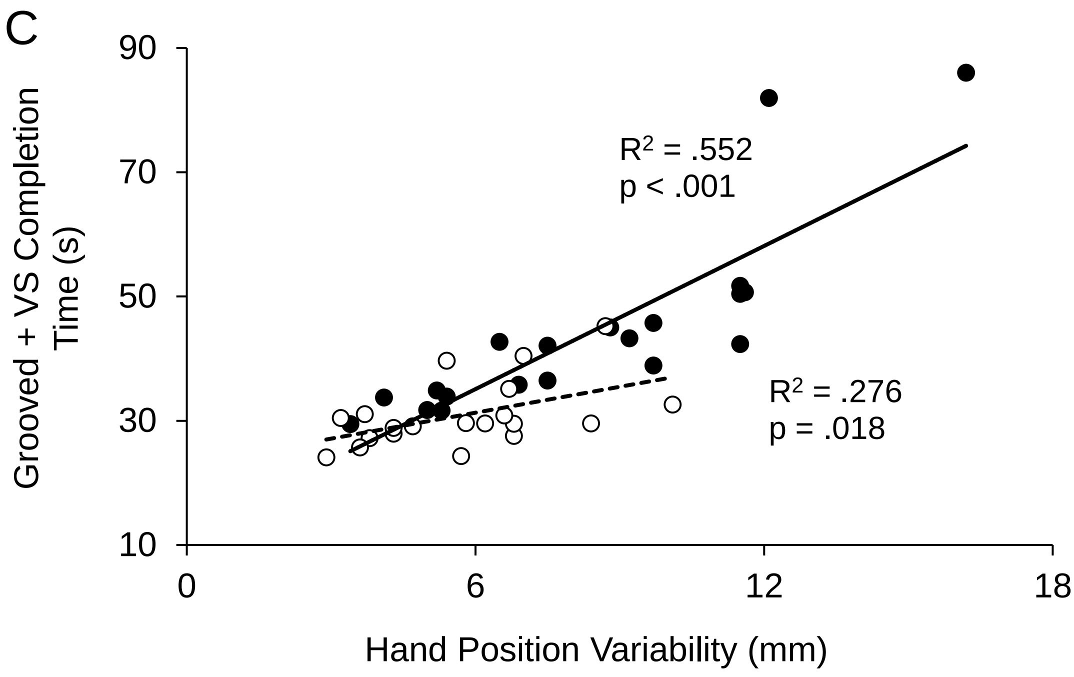
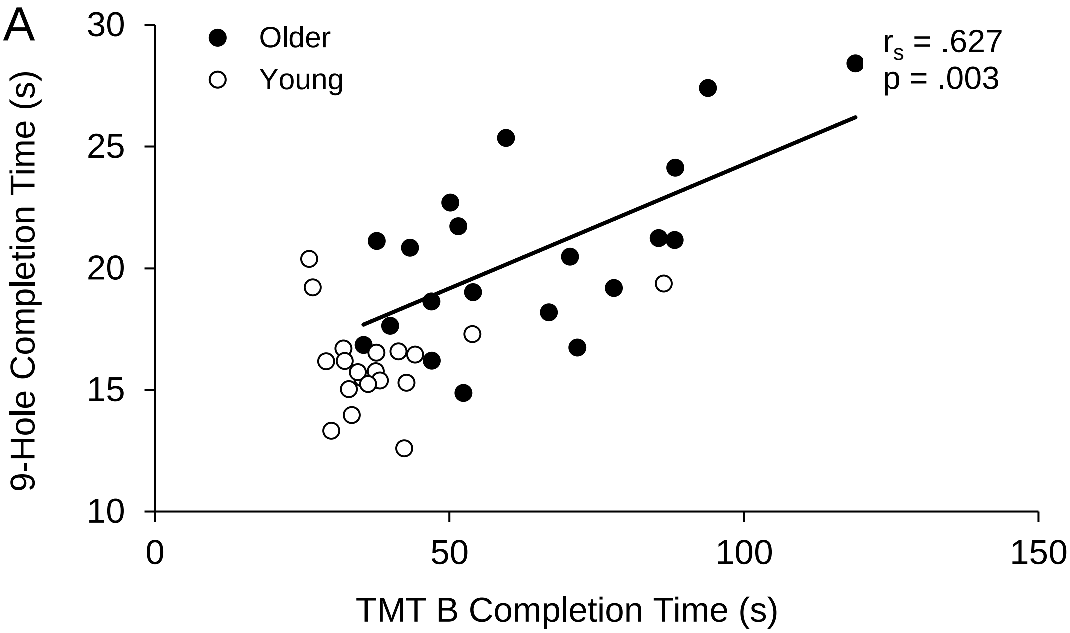


Figure 2.7. Relationship between hand position variability and pegboard completion time. (A) There was a significant, positive relationship in older (*p* = .001) but not young (*p* = .201) adults for 9-Hole pegboard, (B) a significant, positive relationship in older (*p* < .001) and young (*p* = .036) adults for Grooved pegboard, and (C) a significant, positive relationship in older (*p* < .001) and young (*p* = .018) adults for Grooved + VS. Data are presented as back-transformed values.

Attention. TMT A completion time was greater ($H(1) = 21.396$, $p < .001$, $\varepsilon^2 = .549$) for older (Mdn = 29.13 s, IQR = 23.87 – 46.94) vs. young (Mdn = 17.56 s, IQR = 14.51 - 22.45) adults. TMT B completion time was greater ($H(1) = 18.036$, $p < .001$, $\varepsilon^2 = .462$) for older (Mdn = 56.80 s, IQR = 46.94 – 83.60) vs. young (Mdn = 35.70 s, IQR = 32.06 – 42.08) adults. Time Per Target Score was greater ($H(1) = 26.421$, $p < .001$, $\varepsilon^2 = .677$) for older (Mdn = 3.88, IQR = 3.44 – 4.32) vs. young (Mdn = 2.49, IQR = 2.15 – 2.72) adults. Dual Task Decrement Score was greater ($H(1) = 8.067$, $p = .005$, $\varepsilon^2 = .207$) for older (Mdn = .74, IRQ = .26 – 2.43) vs. young (Mdn = .09, IQR = -.14 - .48) adults. Timing Score was greater ($H(1) = 27.539$, $p < .001$, $\varepsilon^2 = .706$) for older (Mdn = 4.28, IQR = 3.93 – 4.84) vs. young (Mdn = 2.61, IQR = 2.37 – 3.01) adults.

Due to age-related differences on all measures of attention, Spearman's correlations were performed to assess the relationship between pegboard performance and attention test scores. In older adults, there was a significant, positive relationship between TMT B completion time and pegboard completion time for all conditions, including 9-Hole ($r_s = .627$; $p = .003$), Grooved ($r_s = .645$, $p = .002$), and Grooved + VS ($r_s = .731$, $p < .001$) (Fig. 2.8). In young adults, there was a significant, positive relationship between TMT B completion time and pegboard completion time for Grooved ($r_s = .488$, $p = .048$) and Grooved + VS ($r_s = .506$, $p = .023$) but not for 9-Hole ($r_s = .241$; $p = .306$).



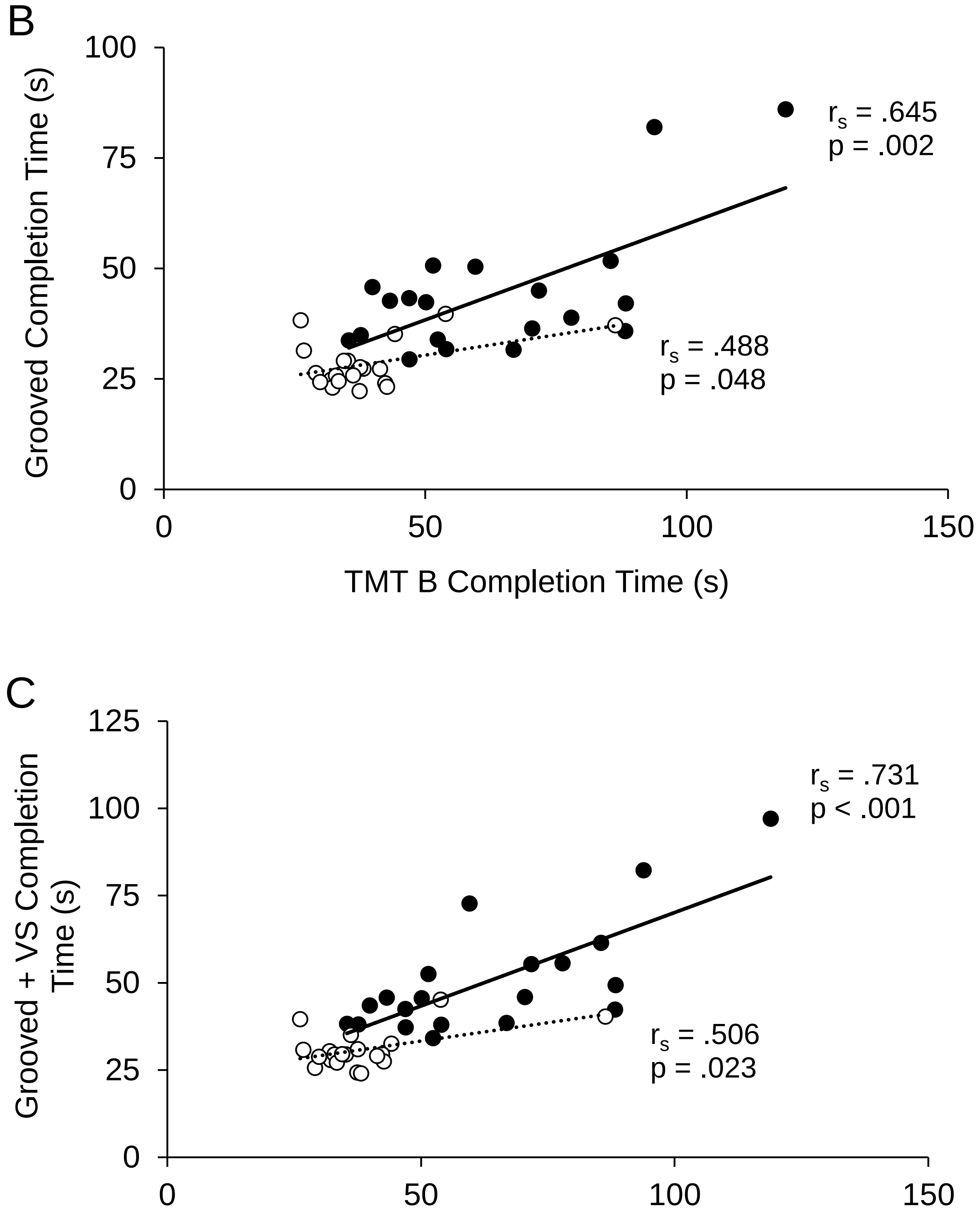


Figure 2.8. Relationship between TMT B completion time and pegboard completion time. Spearman's correlations revealed significant, positive relationships between TMT B completion time and pegboard completion time for all conditions in older adults including (A) 9-Hole, (B) Grooved, and (C) Grooved + VS. In young adults, there was a significant, positive relationship TMT B and pegboard completion time for Grooved and Grooved + VS but not for 9-Hole.

There was a significant, positive relationship between Dual Task Decrement and pegboard completion time for 9-Hole ($r_s = .558$, $p = .011$), Grooved ($r_s = .645$, $p = .002$), and Grooved + VS ($r_s = .694$, $p = .001$) in young adults. There were no other significant relationships between attention test scores and pegboard completion time in young and older adults ($p > .096$) (Table 2.2).

Young Adults	9-Hole	Grooved	Grooved + VS
TMT A	$r_s = .021$, $p = .929$	$r_s = -.369$, $p = .109$	$r_s = -.243$, $p = .302$
Time per Target	$r_s = -.173$, $p = .466$	$r_s = -.382$; $p = .096$	$r_s = -.364$, $p = .114$
Dual Task Decrement	**$r_s = .558$, **$p = .011$**	**$r_s = .645$, **$p = .002$**	**$r_s = .694$, **$p = .001$**
Timing Score	$r_s = .307$, $p = .187$	$r_s = .127$, $p = .594$	$r_s = .028$, $p = .906$

Older Adults	9-Hole	Grooved	Grooved + VS
TMT A	$r_s = .275$, $p = .240$	$r_s = .269$, $p = .251$	$r_s = .360$, $p = .119$
Time per Target	$r_s = .342$, $p = .140$	$r_s = .344$, $p = .138$	$r_s = .372$, $p = .106$
Dual Task Decrement	$r_s = .123$, $p = .605$	$r_s = .314$, $p = .178$	$r_s = .303$, $p = .194$
Timing Score	$r_s = -.122$, $p = .609$	$r_s = .262$, $p = .265$	$r_s = .184$, $p = .432$

Table 2.2. Relationships between attention test scores and pegboard completion time. There was a significant, positive relationship between Dual Task Decrement and pegboard completion time for all pegboard conditions in young (top) but not older (bottom) adults. There were no other significant relationships between attention test scores and pegboard completion time. (**, bold text = significant relationship).

Discussion

The main findings of the current study were 1) age-related differences in eye movements during the pegboard tests, 2) an association between increased hand movement variability and decreased pegboard performance in older adults, and 3) a relationship between attentional processes and pegboard performance in older adults. This novel implementation of eye tracking allowed us to examine eye movement behavior during a commonly used, standardized measure of manual dexterity (Reuben et al., 2013; Wang et al., 2011). Results revealed that older adults made more corrective saccades and spent less time gazing at the pegboard than young adults. Simultaneous assessment of hand movements provides further evidence that increased movement variability plays a role in dexterity impairments in older adults (Kornatz et al., 2005). A relationship between pegboard completion time and TMT B demonstrates that a decline in cognitive processes and executive function is associated with pegboard performance impairments in older adults (Tombaugh, 2004). Taken together, this study provides further insight into manual dexterity impairments in older adults and supports future use of eye tracking in older adults and patient populations.

Eye Movements. Most participants made saccades to and then fixated on the tray and pegboard during peg pickup and placement, respectively (Fig. 2.1C). Consistent with previous work (Rand & Stelmach, 2011), older adults made more corrective saccades after the primary saccade to the pegboard than young adults (Fig. 2.5A). Corrective saccades were likely used to more closely align gaze location with the pegboard hole and are thought to be due to landing errors of the primary saccade (Wu et al., 2010). Thus, results support the idea that aging leads to declines in controlling gaze location (Rand & Stelmach, 2011). Previous work has also reported a greater number of corrective saccades when making saccades to smaller versus larger targets (Rand & Stelmach, 2011; Wu et al., 2010).

Young adults spent a greater percentage of time gazing at the pegboard holes compared to older adults (Fig. 2.5B). This is contradictory to a previous study of eye movements during an object manipulation task where participants picked up and placed objects onto targets (Coats et al., 2016). Specifically, older adults used a visual strategy to obtain greater amounts of visual information during the more complex part of the task (i.e. placing the ball onto the target) compared to young adults (Coats et al., 2016). In the current study, older adults spent less time gazing at the pegboard holes during peg placement (i.e. the more complex part of the task) than young adults. Results could be due to 1) more corrective saccades and/or 2) an altered visual strategy. First, a greater number of corrective saccades in older versus young adults could have led to decreased gaze time at the pegboard holes. Second, results could reflect an altered visual strategy used by older adults to allow for more visual information when picking up the pegs compared to young adults. If so, peg pickup was likely more challenging for older adults than anticipated. Comparatively, a greater percentage of time gazing at the pegboard holes in young adults could reflect an optimal visual strategy given the visual-perceptual demands of peg placement (Reuben et al., 2013; Wang et al., 2011). Additionally, young and older adults spent more time gazing at the pegboard holes during the Grooved compared to 9-Hole Pegboard (Fig. 2.5B). The Grooved Pegboard test has an added manipulation component to align the groove of the peg with the orientation of the hole that the 9-Hole Pegboard test does not (Reuben et al., 2013; Wang et al., 2011). Increased gaze time at the pegboard holes, and therefore greater amounts of visual information when placing the peg, may be important for successful peg placement during the Grooved Pegboard test.

Hand Movements. Peak hand velocity was greater when reaching from the pegboard to tray versus from the tray to pegboard. The pegboard hole presents as a smaller reaching target than the tray. Therefore, results are consistent with the well-established speed-accuracy tradeoff where movement speed decreases when reaching towards smaller targets (Meyer et al., 1982). Peak hand velocity when reaching to and from the pegboard and tray was no different between young and older adults. Results from previous work examining age-related differences in hand velocity during reaching tasks are conflicting (Cooke et al., 1989; Darling et al., 1989; Goggin & Stelmach, 1990; Pratt et al., 1994; Seidler-Dobrin & Stelmach, 1994). While some studies report age-related differences (Goggin & Stelmach, 1990), the current findings concur with numerous studies reporting no difference in hand velocity between young and older adults (Cooke et al., 1989; Darling et al., 1989). According to Pratt et al. (1994), conflicting results are likely due to inherent differences across reaching tasks (e.g., muscles used, task instructions, target location). Applying this justification to the current findings, characteristics of the reaching movements during pegboard tests are such that do not result in age-related differences in hand velocity. Results indicate that decreased hand velocity when reaching to and from the pegboard and tray is likely not the main source of pegboard performance impairments in older adults.

Hand position variability was greater during peg placement for the Grooved versus 9-Hole Pegboard (Fig. 2.6). This seems reasonable given the added peg manipulation component during the Grooved compared to 9-Hole Pegboard test. Additionally, hand position variability during peg placement was approximately 34% higher for older compared to young adults (Fig. 2.6) and increased movement variability was related to decreased pegboard performance in older adults (Fig. 2.7). Consistent with current findings, increased motor variability in older adults has been associated with declines in pegboard performance (Almuklass et al., 2016; Hamilton et al., 2017; Keenan et al., 2017; Kornatz et al., 2005; Marmon et al., 2011). Greater variability in older adults when placing the pegs may have been due to decreased amounts of visual information during peg placement. There was little relationship between eye movements and pegboard completion time (Table 2.1). However, older adults depend more on visual information than young adults for manual dexterity tasks (Coats & Wann, 2011). Decreased gaze time at the pegboard holes while placing the pegs could exacerbate age-related differences in movement variability and impair pegboard performance in older adults.

Based on these findings, we suggest that age-related changes in eye movements may indirectly contribute to pegboard performance impairments in older adults. Further, results indicate that pegboard tests of manual dexterity may be more sensitive to age-related changes in fine manual dexterity than slowing of gross reaching movements. Future work should continue to explore these relationships in older adults and patient populations where increased movement variability is suggested to influence motor performance (e.g., those with Parkinson's disease (Vaillancourt et al., 2002) and stroke survivors (Lodha et al., 2013)).

Attention. TMT B completion time was related to decreased pegboard performance in older adults (Fig. 2.8). No other measures of attention were related to pegboard performance in older adults (Table 2.2). Reasoning for this is twofold. First, TMT B may be more sensitive to age-related declines in attentional processes than the other measures of attention. Agreeably, TMT B has been shown to be more sensitive to age-related changes in attentional processes than TMT A (Tombaugh, 2004). Second, TMT B is a more generalized measure of cognitive processes and executive function (Tombaugh, 2004). Performance on the pegboard tests may be related to a more generalized decline in cognitive processes and executive function in older adults compared to the other subsystems of attention, which is consistent with relationships between Grooved Pegboard completion time and performance on tests of decision-making (Hamilton et al., 2019) and cognitive functioning (Ashendorf et al., 2009) reported previously. Findings support the use of TMT B as sensitive assessment of attentional processes in the aging population and highlight the role of age-related declines in attentional processes in manual dexterity impairments in older adults.

Curiously, decreased performance on the Telephone Search while Counting subtest was related to increased pegboard completion time in young but not older adults (Table 2.2). Telephone Search while Counting is a measure of divided attention, which is the ability to attend to multiple stimuli at once (Robertson et al., 1994). Young adults spent more time fixating on the pegboard holes than older adults. Therefore, young adults may have visually attended to the pegboard hole while simultaneously attending to hand movements required to pick up the peg, which would have required divided attention. We suspect that older adults attended to one part of the task (i.e. peg placement and pickup) before moving on to the next, which could explain why divided attention was not related to pegboard performance in this age group.

Decreased performance on the Grooved Pegboard test with the addition of a visuospatial task in both young and older adults (Fig. 2.4) provides evidence for pegboard impairments when allocating attentional resources across multiple tasks (Woollacott & Shumway-Cook, 2002). However, contrary to our expected findings, older adults were not preferentially impaired by the addition of the visuospatial task compared to young adults. The effect of dual tasks on motor performance depends on the type of motor task being performed (Peterson & Keenan, 2018); therefore, it seems reasonable that a dual task would influence performance on the Grooved Pegboard test differently than it would performance on the force-matching tasks used in previous work (Pereira et al., 2015; Voelcker-Rehage et al., 2006). Additionally, dual tasks employed in other studies of upper extremity motor tasks (e.g., backwards counting) may have been more difficult than the visuospatial task used here, which could have led to greater motor impairments in older adults. Nonetheless, the current findings highlight the role of attentional processes in Grooved Pegboard performance and supports the idea that decreased attentional resources may play a role in manual dexterity impairments (Pereira et al., 2015; Voelcker-Rehage et al., 2006).

Limitations. The following limitations should be considered. The kinematic sensor was secured to the right wrist to examine hand movements during the pegboard tests of manual dexterity, as done previously (Coats et al., 2016). Because assessment of hand movements using this methodology revealed increased hand position variability in older adults and an association with impaired manual dexterity in older adults, it may be useful to further examine age-related changes in dexterous manipulation by recording movements of the index finger and thumb in future studies. The pegboard tests were included in this study because they are common, standardized measures of manual dexterity recommended by the NIH (Reuben et al., 2013; Wang et al., 2011). However, other commonly used measures of manual dexterity exist, such as the Box and Block test (Desrosiers et al., 1994) or tapping tasks (Bowden & McNulty, 2013). Future studies could extend these findings to other measures of manual dexterity to further understand how age-related changes in eye and hand movements contribute to impaired hand function. The current study was limited to one type of dual task during the Grooved Pegboard test. It may be useful to implement a more difficult dual task, such as the backwards counting task (Pereira et al., 2015) and compare the effect on pegboard performance with those found here. Lastly, the goal of this study was to examine age-related changes associated with impaired manual dexterity in healthy older adults. Only relatively higher functioning young and older adults were included in this study. Future studies could determine how well these results generalize to other populations where changes in eye and hand movements could influence performance, such those with Parkinson’s disease (Vaillancourt et al., 2002) or stroke survivors (Lodha et al., 2013).

Conclusion. This study revealed age-related changes in eye and hand movements during the commonly used pegboard tests of manual dexterity. Older adults made more corrective saccades and spent less time gazing at the pegboard during peg placement compared to young adults, which may indirectly influence older adult’s ability to place pegs into the pegboard holes. Greater hand movement variability when placing the pegs in older adults was associated with impaired pegboard performance; however, there were no differences in hand velocity when reaching to and from the pegboard and tray. We propose that pegboard tests are more sensitive to age-related changes in fine manual dexterity than a slowing of gross reaching movements. Findings also highlight the role of attentional processes in manual dexterity impairments in older adults and supports the use of TMT B as a sensitive measure of age-related changes in attentional processes. Taken together, results provide more insight into manual dexterity impairments and decreased hand function in older adults.

Chapter 3: Saccade amplitude, among other age-related differences in eye movements, is related to Archimedes spiral tracing performance in older adults

Introduction

The United States population is aging rapidly and impairments in hand function are well-documented in older adults (Desrosiers et al., 1999; Seidel et al., 2009). According to the 2017 National Populations Projections, one in five people in the United States will fit the description of an “older adult” (65+ years) by 2030 (Vespa et al., 2018). Hand function progressively declines after age 65 and is associated with difficulties performing activities of daily living and common tasks of hand function (e.g., writing, pouring water, opening a jar) (Carmeli et al., 2003; Seidel et al., 2009; Shiffman, 1992). Moreover, impairments in hand function contribute to loss of independence and the need for assisted living, which are associated with increased health care expenditure (Falconer et al., 1991; Lubitz et al., 2003; Ostwald et al., 1989; Williams et al., 1982).

Archimedes spiral tracing is a common, clinical assessment of tremor used in patient populations, including those living with essential tremor (Deuschl et al., 2015), Parkinson’s disease (Westin et al., 2010), and multiple sclerosis (Heenan et al., 2014), and is sensitive to age-associated impairments in hand function (Heintz & Keenan, 2018; Hoogendam et al., 2014; Marmon et al., 2011). To complete the task, individuals are asked to trace an Archimedes spiral template as accurately as possible. The traditional, clinical assessment is performed using a pen/pencil on paper and subjectively scored by a rater based on visual inspection. However, this scoring method may not quantify small changes in performance and has low to moderate reliability (Bain et al., 1993; Miralles et al., 2006). More recently, studies have implemented the spiral tracing task on digitizing tablets and other technologies, which can provide a more objective, sensitive measure of hand function (Heintz & Keenan, 2018; Hoogendam et al., 2014; Marmon et al., 2011; Westin et al., 2010).

Visual information plays a critical role in many goal-directed motor tasks and age-related changes in the use of visual feedback could contribute to impaired hand function in older adults. Older adults rely more on visual feedback than young adults for some hand tasks (Coats & Wann, 2011; Heintz & Keenan, 2018; Seidler-Dobrin & Stelmach, 1998) and evidence suggests that decreased visual feedback may contribute to age-related spiral tracing impairments (Heintz & Keenan, 2018). Specifically, participants performed a touchscreen Archimedes spiral tracing task by tracing with the finger and a stylus. While there were no differences in performance between age groups when tracing with a stylus, spiral tracing error was greater in older compared to young adults when tracing with the finger. Tracing with the relatively larger diameter finger occludes more vision of the touchscreen than tracing with a stylus (Vogel & Baudisch, 2007). Thus, increased error when tracing with the finger in older adults may be due to decreased visual feedback of spiral tracing performance or decreased visual information of the upcoming spiral template used for future movement planning (Heintz & Keenan, 2018).

Despite the potential association between decreased visual feedback and spiral tracing impairments in older adults (Heintz & Keenan, 2018), eye movements used during the Archimedes spiral tracing task are not known. Eye movements reflect moment-to-moment input into the visual system and provide valuable information regarding cognitive and visuomotor processes (Johansson et al., 2001; Land et al., 1999; Pelz & Canosa, 2001). Specifically, saccades involve the rapid relocation of gaze. Between saccades, stable fixations are used to create a relatively still image on the fovea (Land, 1999) with the purpose of obtaining visual information (Hayhoe & Ballard, 2005). The few studies that have examined eye movements during hand motor tasks in young and older adults demonstrate age-related changes in eye movements (Coats et al., 2016; Keenan et al., 2017; Rand & Stelmach, 2011), including decreased number of saccades (Keenan et al., 2017) and ability to control gaze location (Rand & Stelmach, 2011, 2012) in older compared to young adults. Given that saccades are used to orient gaze with elements of interest in the visual field (Henderson, 2003; Land, 1999), decreased number of saccades in older adults may reflect a maladaptive visual strategy that would provide less up to date visual feedback (Keenan et al., 2017), which could be detrimental to spiral tracing performance in older adults. Examining eye movements during the touchscreen Archimedes spiral tracing task would shed light on the interaction between the visual and motor systems and would provide a more complete understanding of impaired hand motor control in older adults.

Age-related declines in attentional processes may also contribute spiral tracing impairments in older adults. Attentional processes are thought to play a critical role in motor performance (Posner & Petersen, 1990) and declines in attention are well-documented with advancing age ((Huddleston et al., 2014; Keenan et al., 2017). Dual-task paradigms are commonly used to examine age-related changes in the ability to allocate attentional resources across multiple tasks (Woollacott & Shumway-Cook, 2002) and are similar to everyday task demands (Pashler, 1994) (e.g., having a conversation while texting on a touchscreen, writing while listening to music). Dual tasks have been shown to preferentially impair motor performance in older adults; however, a majority of these studies have targeted falls risk by asking participants to complete tasks of balance, posture, and locomotion (Hausdorff et al., 2008; Peterson & Keenan, 2018; Schrodt et al., 2004). Fewer studies have examined the effect of dual tasks on upper extremity motor performance in older adults (Pereira et al., 2018; Voelcker-

Rehage et al., 2006). Implementation of a dual task during Archimedes spiral tracing would further our understanding of age-related impairments in hand function using a common, clinical assessment.

The primary purpose of this study was to examine age-related changes in eye movements during a touchscreen Archimedes spiral tracing task and to determine if these changes were associated with spiral tracing impairments in older adults. In addition, we examined whether age-related declines in attentional processes (Huddleston et al., 2014), using a dual task, contributed to spiral tracing impairments in older adults. We also wanted to determine the relationship between performance on the Grooved Pegboard test and spiral tracing performance. Pegboard tests are some of the more commonly used measures of manual dexterity and are included in the NIH Toolbox (Reuben et al., 2013; Wang et al., 2011). Further, age-related impairments on the Grooved Pegboard test have been shown to relate to saccadic eye movements (Keenan et al., 2017). We hypothesized that older adults would use fewer saccades than young adults, and decreased saccade number would be related to spiral tracing impairments in older adults when tracing with the finger. Additionally, we expected that the dual task would impair spiral tracing performance, especially in older adults, and declines in grooved pegboard performance in older compared to young adults would be related to decreased spiral tracing performance. Results have been previously reported in abstract form (Heintz et al., 2019)

Methods

Participants. A total of 51 participants, 23 young (age, 25.3 ± 4.4 years; range, 20 – 38; 12 females) and 28 older (age, 72.6 ± 6.6 years; range, 65 – 90; 13 female) adults, were recruited from the surrounding community. Written informed consent was obtained from all participants as approved by the Institutional Review Board at the University of Wisconsin – Milwaukee. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971) and had normal or corrected to normal vision as assessed by the Snellen Eye Chart test for visual acuity (Hallowell, 2008). Exclusion criteria included presence of functional deficiencies or neuromuscular disorders, pain currently in the upper extremities that may limit normal movement, presence of hand pathologies (e.g., arthritis), currently taking medications that influence neuromuscular function or vision, and inability to sit comfortably for extended periods. Participants were asked to abstain from caffeine 12 hours prior to testing (Lorist et al., 1994; Lorist et al., 1995).

Baseline Measures. The Montreal Cognitive Assessment (MoCA) was used to assess cognitive impairments (Nasreddine et al., 2005). A questionnaire was used to assess current touchscreen ownership and comfort using a touchscreen (0 = not at all comfortable, 10 = extremely comfortable) (Heintz & Keenan, 2018).

Spiral Tracing. Participants sat with their eyes 36.0 cm in front of an iPad mini (13.4 cm x 20.0 cm x 0.7 cm, Apple Inc., Cupertino, CA) with an LED-backlit Multi-Touch display (1024 x 768 resolution, 64.2 pixels per cm, 20.1 cm diagonal) mounted to a custom-built stand (Fig. 3.1). A headrest was used to facilitate eye movement recordings, decrease extraneous head movement, and control visual angle. The setup was selected among others tested during piloting based on its ability to allow for accurate eye movement recordings and facilitate clear vision of the upper extremity, hand, drawing implement, and touchscreen.

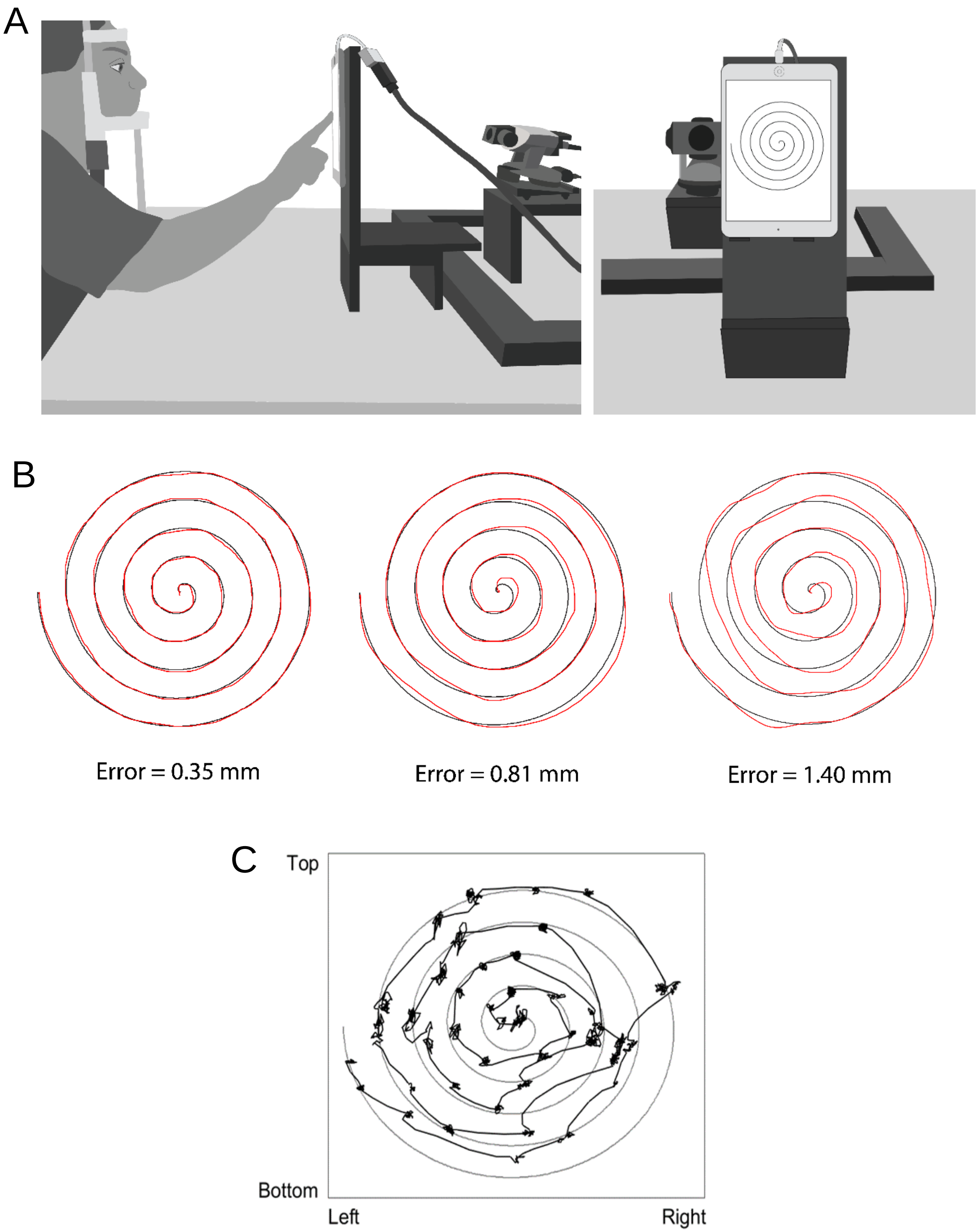


Figure 3.1. Experimental setup for the spiral tracing task and representative data. (A) Participants sat with their head in a headrest facing a touchscreen mounted vertically to a custom-built stand. The bottom edge of the touchscreen was 19.5 cm above the table surface.

The horizontal and vertical visual angles of the touchscreen display were 19.0 ° and 25.0 °, respectively. Left = side view, right = participant's point of view. (B) Participants traced over a black spiral template and feedback was provided via a red line. Root Mean Square Error (RMSE) between the participant's trace and template was calculated to quantify performance. Representative data demonstrates (left) low, (middle) medium, and (right) high RMSE. (C) Eye movements were recorded during the spiral tracing task. All participants used a series of saccades and fixations while tracing the spiral. Top, Bottom, Left, and Right correspond to the top, bottom, left, and right of the touchscreen.

Participants performed a touchscreen spiral tracing task based on previous methods (Heintz & Keenan, 2018). Specifically, participants traced over an Archimedes spiral displayed as a black line on the iPad touchscreen. Live feedback of the participant's trace was provided via a red line superimposed onto the spiral template (Fig. 3.1B). Instructions were to begin in the center of the spiral working outwards, remain as close to the spiral template as possible (Heintz & Keenan, 2018; Marmon et al., 2011; Miralles et al., 2006), and avoid lifting the drawing implement once the trial began (Heintz & Keenan, 2018). The task was performed at a self-selected pace to replicate the clinical task as closely as possible (Bain et al., 1993) and based on previous studies (Heintz & Keenan, 2018; Marmon et al., 2011; Miralles et al., 2006a). Participants began when the experimenter said, "Go" and completed the task when they reached the end of the spiral template. The participant was free to move their upper extremity as long as the drawing implement did not leave the touchscreen and a second point of contact was not made with the touchscreen.

The spiral tracing task was performed under three conditions, including 1) Stylus, 2) Finger, and 3) Finger + Visuospatial Task (VS). Participants traced the spiral using a stylus (i.e. Stylus condition) (11.99 cm x 0.89 cm x 0.89 cm, Bamboo Solo CS100K, Wacom, Portland, OR) and their index finger (i.e. Finger condition) to determine how changes in drawing implement influenced eye movements during the spiral tracing task. For the Finger + VS condition, participants traced the spiral with their finger while simultaneously performing a visuospatial task based on Brooks' spatial memory task (Brooks, 1967) and that used previously (Peterson & Keenan, 2018). Specifically, participants visualized a star moving around four boxes in a 2 x 2 grid, labeled 1 through 4. The star always started in box 1. Participants were told a series of four directions that signified the direction of the star's movement (i.e. right, left, up, down, diagonal). Each series began when the experimenter said, "Start" followed by four randomized locations, and ended when the experimenter asked, "Location?" upon which the participant was instructed to report the final star location by stating the number of the box the star was in. Prior to testing, participants completed five trials while viewing the grid followed by a series of practice trials without the visual. Three consecutive correct practice trials were required before proceeding.

One practice trial and three test trials were performed for each condition with the right hand, with at least 30 seconds of rest between each trial. Trials were excluded and additional trials were performed if the participant lifted the drawing implement off the touchscreen before ending the trace or a second point of touchscreen contact was made. Eye movements were recorded in the horizontal (X) and vertical (Y) directions with an infrared R6 Remote Optics Eye Tracking System (Applied Science Laboratories, Bedford, MA; 0.25 º resolution) at 120 Hz (Huddleston et al., 2013; Keenan et al., 2017). Participants completed a full-field 9-point eye tracking calibration prior to testing. Eye movement data were collected on a laptop computer (Dell Latitude E6510, Austin, TX) using Eye-Trac 6 User Interface program (Applied Science Laboratories, Bedford, MA). The sequence of trials was block randomized across spiral tracing conditions.

Grooved Pegboard. Participants completed the Grooved Pegboard test of manual dexterity based on standardized methods (Reuben et al., 2013; Wang et al., 2011). Specifically, the Grooved Pegboard consists of 25 grooved pegs (0.3 cm diameter) and a pegboard (20.3 cm x 12.7 cm x 17.8 cm) with 25 grooved holes oriented in different directions in a 5 x 5 grid. Each peg must be manipulated so the groove matches the orientation of the hole. Instructions were to place the pegs into the holes, one at a time and as quickly as possible. One practice trial and two test trials were performed with the right hand. Completion time was recorded for each trial and is reported as the average across the two trials, in seconds.

Data Analysis. The participant's spiral trace was exported from the iPad as a PDF file using PDF-Notes (AMuseTec Co., Ltd., Seoul, South Korea). Spiral traces were analyzed using custom-written scripts in MATLAB (The MathWorks, Inc., Natick, MA). Eye tracking data was analyzed using EyeNal software (Applied Science Laboratories, Bedford, MA). Eye position data associated with blinks and artifact were removed, defined as X, Y, or pupil size of zero. Additional data associated with artifact were removed, including instances when eye position exceeded the field of view. Similar to previous studies, eye position data was not filtered (Huddleston et al., 2013; Keenan et al., 2017; Rand & Stelmach, 2011). Participants were excluded if eye data loss was > 20% based on previous standards for eye movement data in young and older adults (Zietz & Hollands, 2009)

To quantify spiral tracing performance, Root Mean Square Error (RMSE) was calculated to assess the proximity of the subject's spiral trace to the original template, as done previously (Heintz & Keenan, 2018) (Fig. 3.1B). The line representing the original spiral template was composed of 916 pixels. The radial distance between each pixel on the spiral template and the corresponding participant's trace was calculated. RMSE for one trial was calculated as the average radial distance derived from the 916 values, reported in millimeters. RMSE was averaged across all three trials for each condition. Completion time was calculated as the time from the beginning to end of each trial, or when the experimenter said, “Go” to when the participant reached the end of the spiral template, respectively. Completion time was averaged across all trials for each condition and is reported in seconds.

Number of saccades was calculated based on number of fixations. Fixations were defined as times when the standard deviation of eye position did not exceed 0.5 degrees in the X and Y directions for a duration ≥ 100 ms (Huddleston et al., 2013; Keenan et al., 2017). Total saccade number was calculated as the number of saccades for each trial, averaged across all three trials for each condition. Saccade amplitude was calculated as the distance of each saccade in degrees, averaged across all saccades within each trial. Saccade amplitude variability was calculated as the coefficient of variation (CV) of saccade amplitude across all saccades within each trial. Saccade amplitude and saccade amplitude variability are reported as the average across all three trials for each condition.

Due to the nature of the task, the hand and/or drawing implement may have obstructed relatively more or less visual information of the upcoming spiral template depending on the part of the template being traced (Fig. 3.2A). To examine whether this influenced eye movements and spiral tracing performance, the spiral template was split into four equally-size quadrants (Fig. 3.2B). The number of saccades within each quadrant were calculated, expressed as a percent of total number of saccades, and averaged across all three trials for each condition. Spiral tracing performance within each quadrant, calculated as RMSE, was also determined. RMSE within each quadrant was averaged across all three trials for each condition.

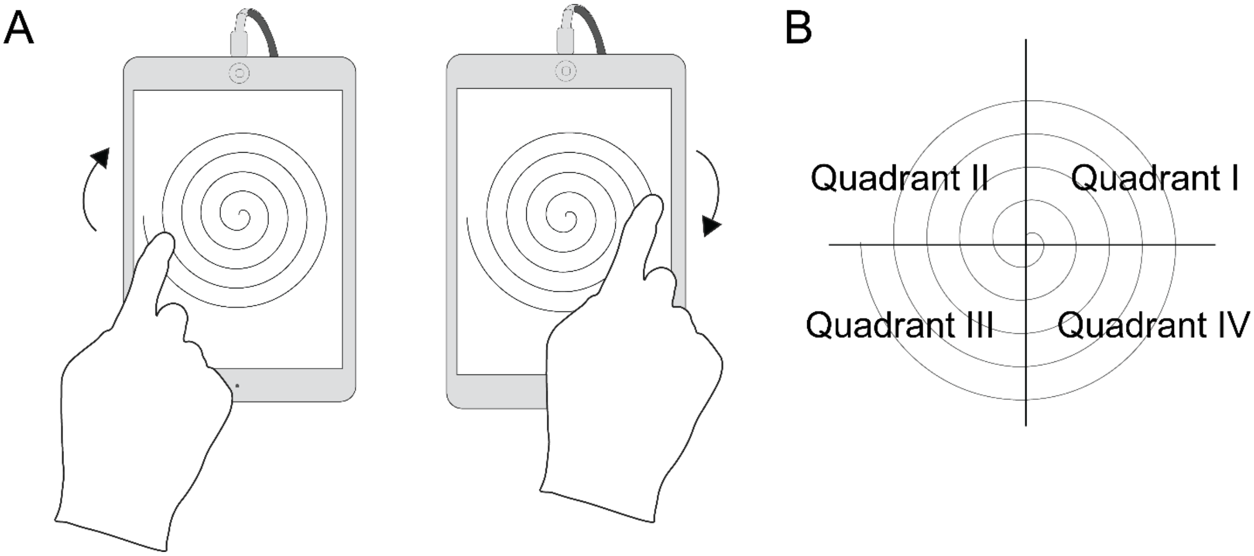


Figure 3.2. Hand position and visual obstruction of the spiral template and the four quadrants. (A) Due to the nature of the task and experimental setup, the hand may have blocked relatively less (Quadrants II and III) or more (Quadrants I and IV) visual information of the upcoming spiral template when tracing different parts of the spiral. (B) To examine the effect on eye movements and spiral tracing performance, the spiral template was split into four quadrants, labeled I – IV in the counterclockwise direction.

Statistical Analysis. Statistical analysis was performed using SPSS 25 (SPSS, Chicago, IL). Statistical significance for all tests was set at $p < 0.05$. Data are reported as mean ± SD in the text and mean + SE unless otherwise noted. Normality of the transformed data were confirmed using Shapiro Wilk's test and visual inspection of Q-Q plots. Spiral tracing completion time, total saccade number, and saccade amplitude did not conform to a normal distribution and were transformed using a log transformation (Osborne, 2002).

A two-sample, independent t-test was used to examine differences in MoCA scores between young and older adults. Differences in RMSE between older adults who did and did not own a touchscreen device were examined using a Kruskal-Wallis test. A two-sample, independent t-test was used to examine differences in level of comfort using a touchscreen between young and older adults. A Pearson's correlation was used to determine the relationship between RMSE and level of comfort using a touchscreen in older adults.

Differences in RMSE and completion time between age groups and across conditions were examined using a mixed between-within subjects ANOVA with between subjects factor of age (young and older adults) and within subjects factor of condition (Stylus, Finger, and Finger + VS). Mixed between-within subjects ANOVAs were also used to determine differences in saccade number, saccade amplitude, and saccade amplitude variability between age groups and across spiral tracing conditions, with between-subjects factor of age (young and older adults) and within-subjects factor of condition (Stylus, Finger, Finger + VS). Significant results were followed with post-hoc tests with Bonferroni corrections. Pearson's correlations were used to determine the relationship between completion time and RMSE, total saccade number and RMSE, saccade amplitude and RMSE, and saccade amplitude variability and RMSE.

Differences in the number of saccades and spiral tracing RMSE within each quadrant were examined using a mixed-between subjects ANOVA, with between-subjects factor of age (young and older adults) and within-subjects factors of spiral tracing condition (Stylus, Finger, Finger + VS) and quadrant (Quadrants I-IV). Significant results were followed with post-hoc tests with Bonferroni corrections. A two-sample, independent t-test was used to examine differences in Grooved Pegboard completion time between young and older adults. Pearson's correlations used to examine the relationship between Grooved Pegboard completion time and spiral tracing RMSE in young and older adults.

Results

Participants. Data from 41 participants, 21 young (age, 25.6 ± 4.5 years; range, 20 - 38; 12 female) and 20 older (age, 73.0 ± 6.0 years; range, 65 – 85, 10 female) adults, were included, consistent with an a priori power analysis using G*Power (Faul et al., 2007) and sample sizes used in similar work (Heintz & Keenan, 2018; Keenan et al., 2017). Data from 10 participants, 2 young (age, 22 ± 1.4 years; range, 21 - 23; 0 female) and 8 older (age, 71.8 ± 8.4 years; range, 66 – 90, 3 female) adults, were discarded due to > 20% eye data loss. There was no significant difference ($t(39) = 1.046$, $p = .874$, $d = .272$) in MoCA scores between young (28.4 ± 1.2; range, 26 – 30) and older (28.0 ± 1.7; range, 26 – 30) adults. No participants scored below the cutoff for cognitive impairment (i.e., < 26) (Nasreddine et al., 2005).

Spiral Tracing Performance. There was a significant condition by age interaction effect on RMSE ($F(2) = 11.318$, $p < .001$, $\eta_p^2 = .373$) (Fig. 3.3). There was no difference in RMSE between older and young adults ($p = .130$) when tracing with the stylus (.79 ± .15 mm and .69 ± .23 mm, respectively). However, RMSE was greater for older vs. young adults ($p < .001$) when tracing with the finger (1.06 ± .27 mm and .73 ± .25 mm, respectively) and when tracing with the finger while performing the visuospatial task ($p < .001$, 1.08 ± .27 mm and .74 ± .27 mm, respectively). There were differences in RMSE across conditions in older ($F(2) = 21.536$, $p < .001$, $\eta_p^2 = .545$) but not young adults ($F(2) = .598$, $p = .555$, $\eta_p^2 = .029$). In older adults, RMSE was greater when tracing with the finger vs. stylus ($p < .001$) and when tracing with the finger while performing the VS task vs. tracing with the stylus ($p < .001$), but no difference in RMSE when tracing with the finger vs. tracing with the finger while performing the visuospatial task ($p = .927$). There was a significant main effect of condition on RMSE ($F(2) = 19.195$, $p < .001$, $\eta_p^2 = .503$) and a significant main effect of age on RMSE ($F(1) = 14.544$, $p < .001$, $\eta_p^2 = .272$).

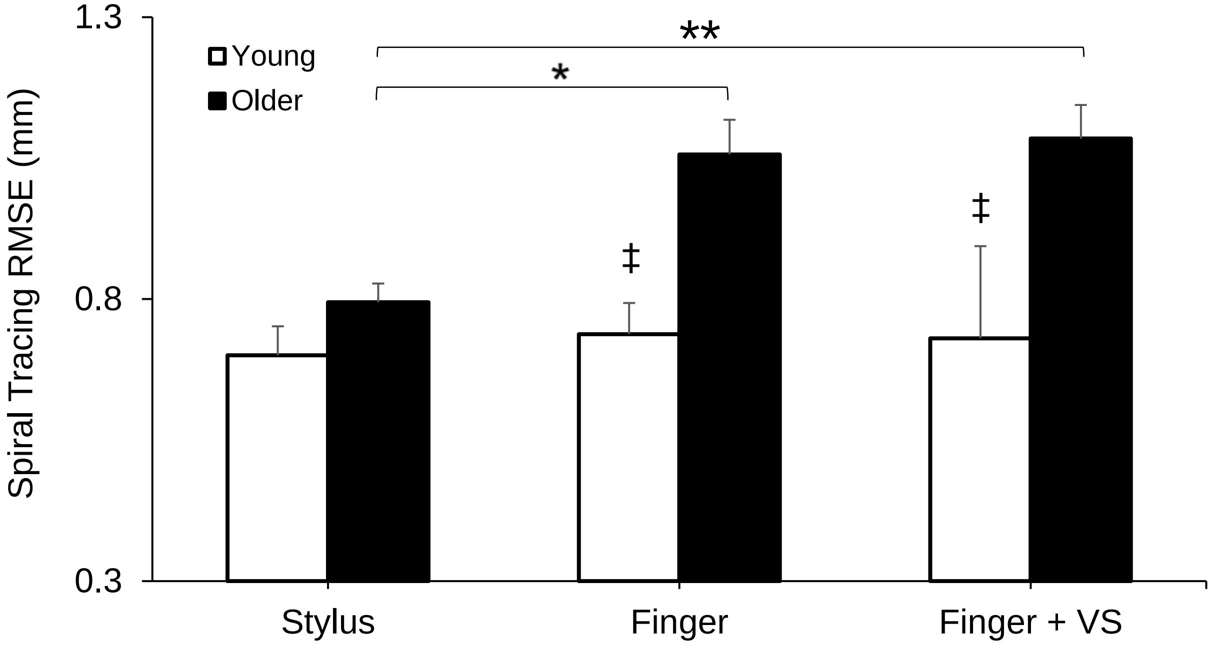


Figure 3.3. Effect of age and spiral tracing condition on spiral tracing performance. Increased RMSE corresponds to decreased spiral tracing performance. There was no difference in RMSE between young and older adults when tracing with the stylus (*p* = .130) however, RMSE was greater in older vs. young adults when tracing with the finger and when tracing with the finger while performing the visuospatial task ($^{‡}p$ < .001). There were no differences in RMSE across conditions in young adults, however RMSE was greater for Finger vs. Stylus (**p* < .001) and Finger + VS vs. Stylus (***p* < .001) in older adults.

All young adults and 16 older adults owned a touchscreen device while 4 older adults did not. There was no significant difference in RMSE between older adults who did and did not own a touchscreen device across all conditions, including Stylus (*p* = .345) (Mdn = .78 mm, IRQ = .58 - .98 and Mdn = .87 mm, IQR = .48 – 1.26, respectively), Finger (*p* = .070) (Mdn = 1.00 mm, IQR = .62 – 1.38 and Mdn = 1.30 mm, IQR = .75 – 1.85, respectively), and Finger + VS (*p* = .413) (Mdn = 1.03 mm, IQR = .75 – 1.35 and Mdn = 1.20 mm, IQR = .60 – 1.80, respectively). Level of comfort using a touchscreen device was significantly greater (*t*(39) = 4.103, *p* = .005, *d* = 1.269) in young (9.42 ± .83) compared to older (7.29 ± 2.24) adults. There was no relationship between level of comfort using a touchscreen and RMSE in older adults for all conditions, including Stylus ($r = -.425$, $p = .062$), Finger ($r = -.359$, $p = .120$), and Finger + VS ($r = -.112$, $p = .639$).

There was no difference in completion time between age groups ($F(1) = 2.413$, $p = .128$, $\eta_p^2 = .058$) (young, mean = 32.26 s, 95% CI = [26.95, 38.65]; older, mean = 24.27 s, 95% CI = [21.21, 27.77]) or across condition ($F(2) = .442$, $p = .645$, $\eta_p^2 = .011$) (Stylus, mean = 27.83 s, 95% CI = [23.78, 32.56]; Finger, mean = 27.10 s, 95% CI = [22.45, 32.70]; Finger + VS, mean = 28.15 s, 95% CI = [22.92, 34.58]). There was no age by condition interaction effect on completion time ($F(2) = 1.679$, $p = .193$, $\eta_p^2 = .041$). There was a significant relationship between completion time and spiral tracing RMSE in young and older adults for Stylus ($r = .744$, $p < .001$ and $r = .504$, $p = .023$, respectively), Finger ($r = .862$, $p < .001$ and $r = .741$, $p < .001$, respectively) and Finger + VS ($r = .635$, $p = .002$ and $r = .460$, $p = .041$, respectively).

Eye Movements. All participants used the same visual strategy during the spiral tracing task. Specifically, both young and older adults used a series of saccades and fixations while tracing the spiral (Fig. 3.1C). This strategy was used for all spiral tracing conditions. Sphericity was violated for total saccade number based on Mauchly's Test of Sphericity. Therefore, Greenhouse-Geisser corrections were used. There was a significant main effect of age on total saccade number ($F(1) = 7.098$, $p = .011$, $\eta_p^2 = .154$) (Fig. 3.4). Young adults made more saccades than older adults while tracing the spiral (mean = 65.97 saccades, 95% CI = [58.77, 73.17] and mean = 47.82 saccades, 95% CI = [42.84, 52.79], respectively). There was no main effect of condition ($F(2) = .747$, $p = .461$, $\eta_p^2 = .019$) or age by condition interaction effect on total saccade number ($F(2) = 1.712$, $p = .192$, $\eta_p^2 = .042$).

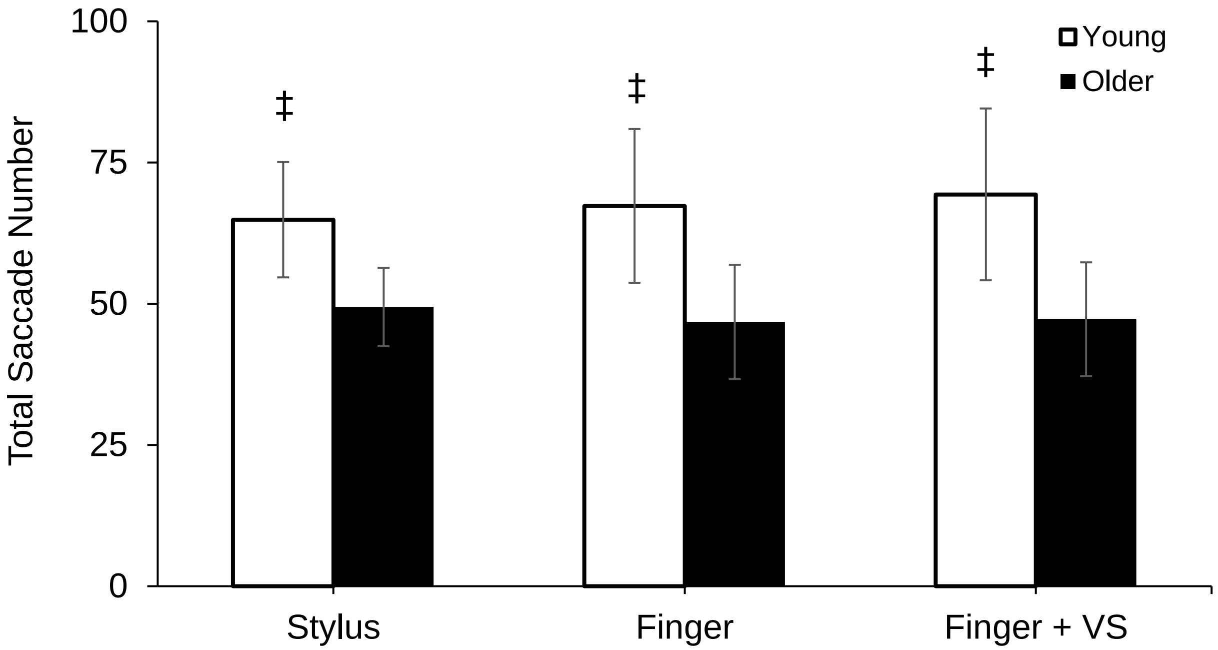


Figure 3.4. Total saccade number in young and older adults during the spiral tracing task. (A) Young adults made more saccades than older adults (‡*p* = .012), though there was no main effect of condition (*p* = .461) or age by condition interaction effect on total saccade number (*p* = .192). Data is reported as mean and 95% CI.

Due to age-associated differences in total saccade number, the relationship between saccade number and spiral tracing error was examined. Pearson's correlations revealed a significant, inverse relationships between total saccade number and RMSE across all conditions in young adults, including Stylus (r = -.868, p < .001), Finger (r = -.670, p = .001), and Finger + VS (r = -.647, p = .002). In older adults, there were no significant relationships between total saccade number and RMSE across all spiral tracing conditions, including Stylus (r = -.261, p = .266), Finger (r = -.270, p = .250), and Finger + VS (r = -.387, p = .092).

Saccade amplitude was significantly greater ($F(1)$ = 5.162, p = .029, η_p^2 = .117) in older compared to young adults (mean = 2.52 °, 95% CI = [2.33, 2.73] and mean = 2.06 °, 95% CI = [1.91, 2.23], respectively) (Fig. 3.5A). There was a significant effect of condition on saccade amplitude ($F(2) = 5.452$, $p = .006$, $\eta_p^2 = .123$). Saccade amplitude was greater for Finger + VS vs. Stylus ($p = .004$). However, there were no differences in saccade amplitude for Finger vs. Stylus ($p = .091$) or Finger vs. Finger + VS ($p = .897$) (Stylus, mean = 2.17 º, 95% CI = [1.98, 2.37]; Finger, mean = 2.30 º, 95% CI = [2.07, 2.57]; Finger + VS, mean = 2.43 º, 95% CI = [2.15, 2.61]. There was no condition by age interaction effect on saccade amplitude ($F(2) = .971$, $p = .383$, $\eta_p^2 = .024$).

Saccade amplitude variability was significantly greater ($F(1) = 7.062$, $p = .011$, $\eta_p^2 = .153$) in older compared to young adults (.71 ± .24 and .57 ± .14, respectively) (Fig. 3.5B). There was a significant condition effect on saccade amplitude variability ($F(2) = 10.039$, $p < .001$, $\eta_p^2 = .205$). Saccade amplitude variability was greater for Finger + VS compared to Stylus ($p < .001$) and Finger ($p = .018$). There was no significant difference in saccade amplitude variability between Stylus and Finger ($p = .501$) (Stylus, .59 ± .20; Finger, .63 ± .16; Finger + VS, .73 ± .26) and no age by condition interaction effect on saccade amplitude variability ($F(2) = .023$, $p = .977$, $\eta_p^2 = .001$).

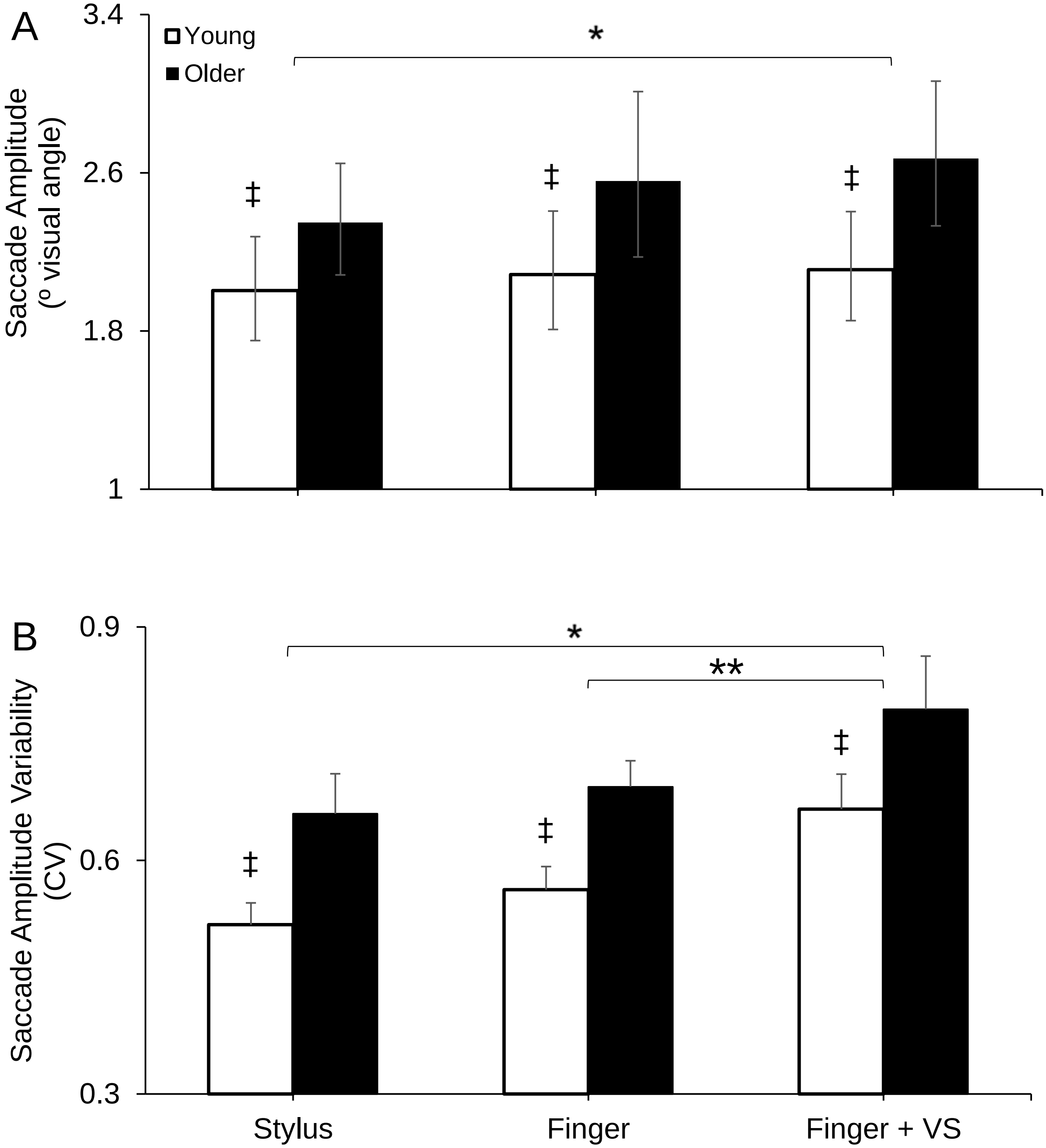
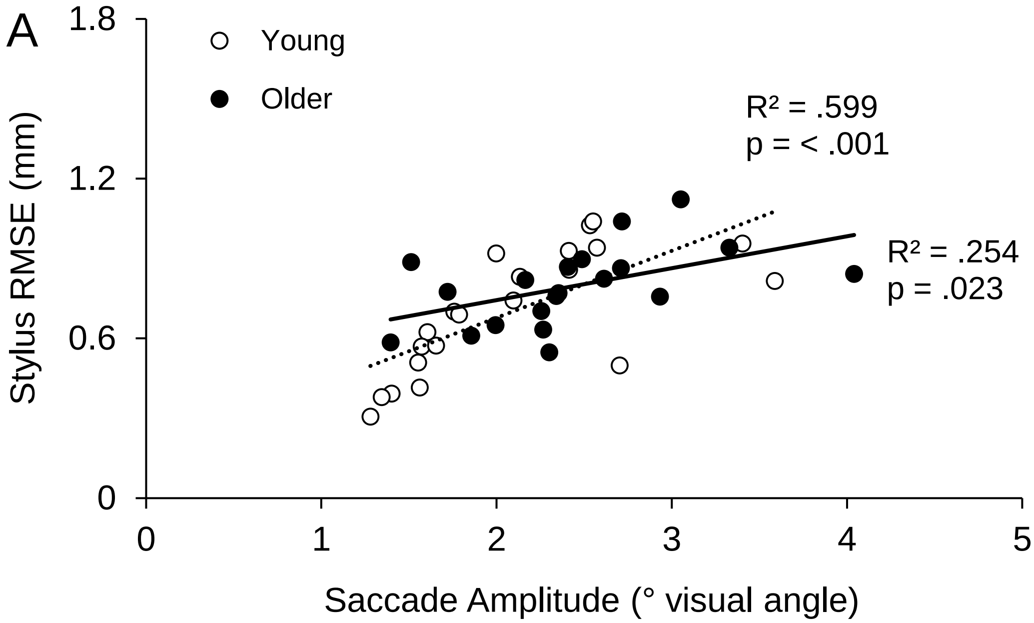


Figure 3.5. Effect of age and condition on saccade amplitude and saccade amplitude variability. (A) There was a main effect of age on saccade amplitude ($^{‡}p$ = .029). Saccade amplitude was greater for older compared to young adults. There was a main effect of condition on saccade amplitude (*p* = .006). Saccade amplitude was greater when tracing with the finger while performing the visuospatial task compared to tracing with the stylus (**p* = .004). Data is reported as mean and 95% CI. (B) There was a main effect of age on saccade amplitude variability, calculated as the coefficient of variability (CV) ($^{‡}p$ = .011). Saccade amplitude

variability was greater for older vs. young adults. There was a main effect of condition on saccade amplitude variability (*p* = .001). Saccade amplitude variability was greater for Finger + VS vs. Stylus (**p* < .001) and Finger + VS vs. Finger (***p* = .018).

Pearson's correlations revealed significant, positive relationships between saccade amplitude and spiral tracing RMSE for all conditions in young adults, including Spiral (*r* = .774, *p* < .001), Finger (*r* = .862, *p* < .001), and Finger + VS (*r* = .635, *p* = .002) (Fig. 3.6). There were significant, positive relationships between saccade amplitude and RMSE for all conditions in older adults, including Stylus (*r* = .504, *p* = .023), Finger (*r* = .741, *p* < .001), and Finger + VS (*r* = .460, *p* = .041). There were no relationships between saccade amplitude variability and spiral tracing RMSE for young and older adults across all spiral tracing conditions (*p* > .309).



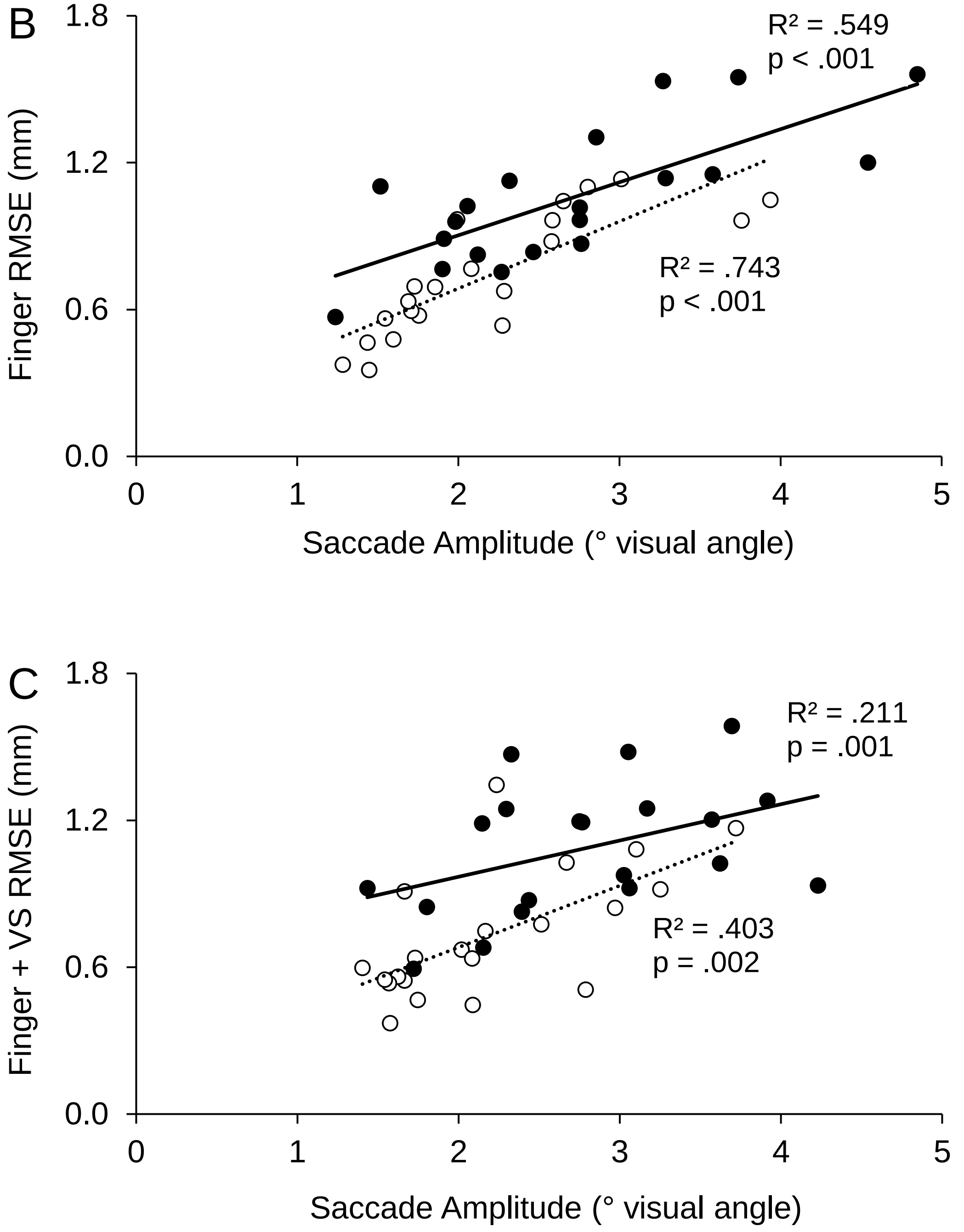
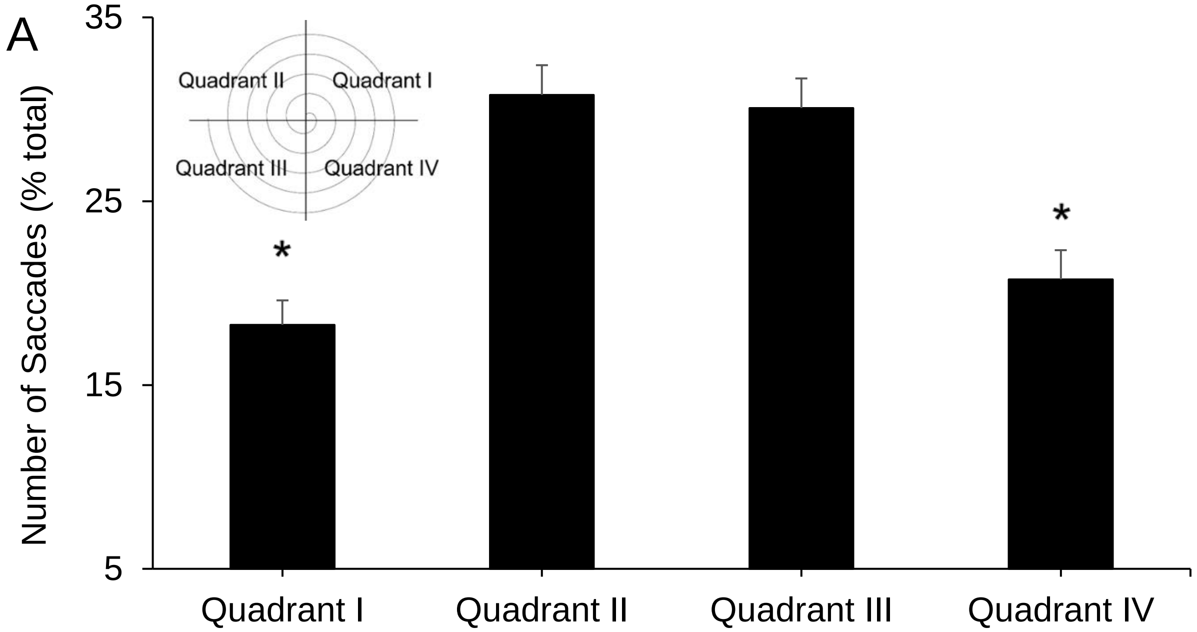


Figure 3.6. Relationship between saccade amplitude and spiral tracing performance. Increased saccade amplitude was related to increased spiral tracing error in young and older adults across all conditions, including (A) Stylus, (B) Finger, and (C) Finger + VS. Data is presented as back-transformed values.

Sphericity was violated for saccade number in each quadrant based on Mauchly's Test of Sphericity. Thus, Greenhouse-Geisser corrections were used. There was a significant main effect of quadrant on saccade number ($F(3) = 14.978$, $p < .001$, $\eta_p^2 = .277$) (Fig. 3.7A). Saccade number was greater for Quadrant II and Quadrant III vs. Quadrant I ($p < .001$ for both), and for Quadrant II and Quadrant III vs. Quadrant IV ($p = .003$ and $p = .006$, respectively). There was no significant difference in saccade number between Quadrant I and Quadrant IV ($p = .730$) and Quadrant II vs. Quadrant III ($p = .942$). There were no other significant main effects or interaction effects on saccade number ($p > .057$). There was no main effect of quadrant ($F(3) = 2.519$, $p = .065$, $\eta_p^2 = .061$), quadrant by age interaction effect ($F(3) = 1.763$, $p = .158$, $\eta_p^2 = .043$) or quadrant by condition interaction effect ($F(3) = 1.346$, $p = .238$, $\eta_p^2 = .033$) on spiral tracing RMSE (Fig. 3.7B).



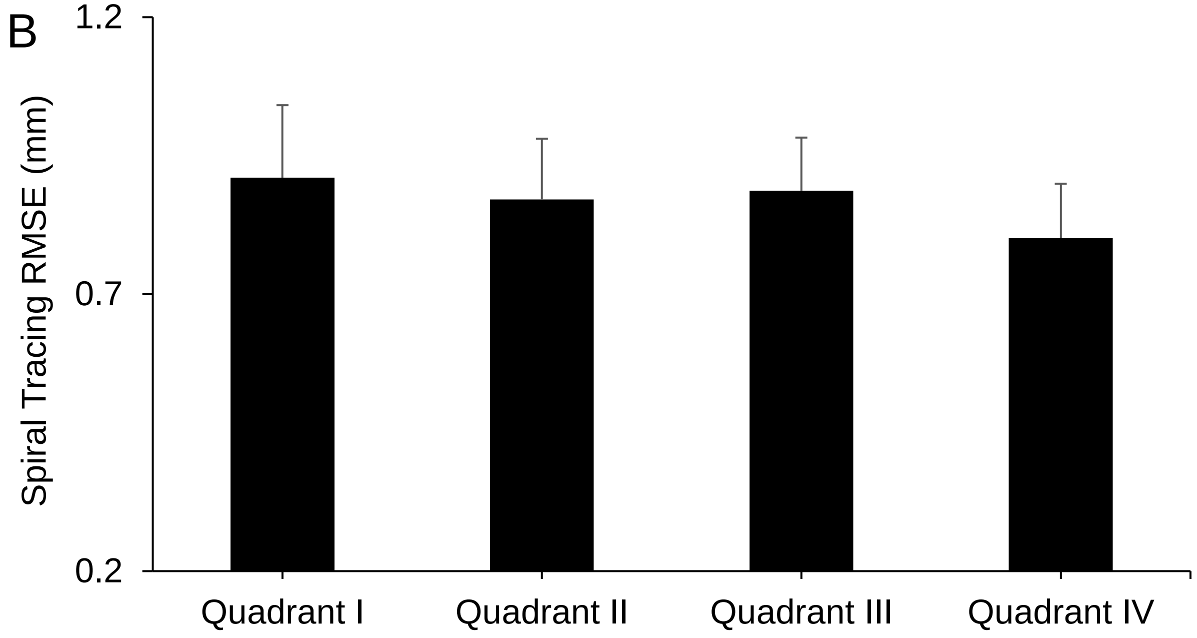


Figure 3.7. Saccade number and spiral tracing performance across the four quadrants. (A) There were more saccades in Quadrant II and Quadrant III compared to Quadrant I and Quadrant IV (*p < .001). Inset image = Quadrants I through IV relative to the spiral template. (B) Despite differences in saccade number across quadrants, there were no significant effects of quadrant on spiral tracing performance, quantified by RMSE ($p > .061$). Data is collapsed across conditions and age groups in both figures.

Grooved Pegboard. Grooved Pegboard completion time was significantly greater ($t(39) = 6.104$, $p < .001$, $d = 2.196$) for older (75.53 ± 11.47 s) vs. young (55.16 ± 6.36 s) adults. In older adults, Pearson's correlations revealed significant, positive correlations between Grooved Pegboard completion time and spiral tracing RMSE for all conditions, including Stylus ($r = .674$, $p = .001$), Finger ($r = .682$, $p < .001$), and Finger + VS ($r = .538$, $p = .014$) (Fig. 3.8). In young adults, there were no significant relationships between Grooved Pegboard completion time and spiral tracing RMSE for all conditions, including Stylus ($r = .316$, $p = .163$), Finger ($r = .061$, $p = .791$), and Finger + VS ($r = -.095$, $p = .684$).

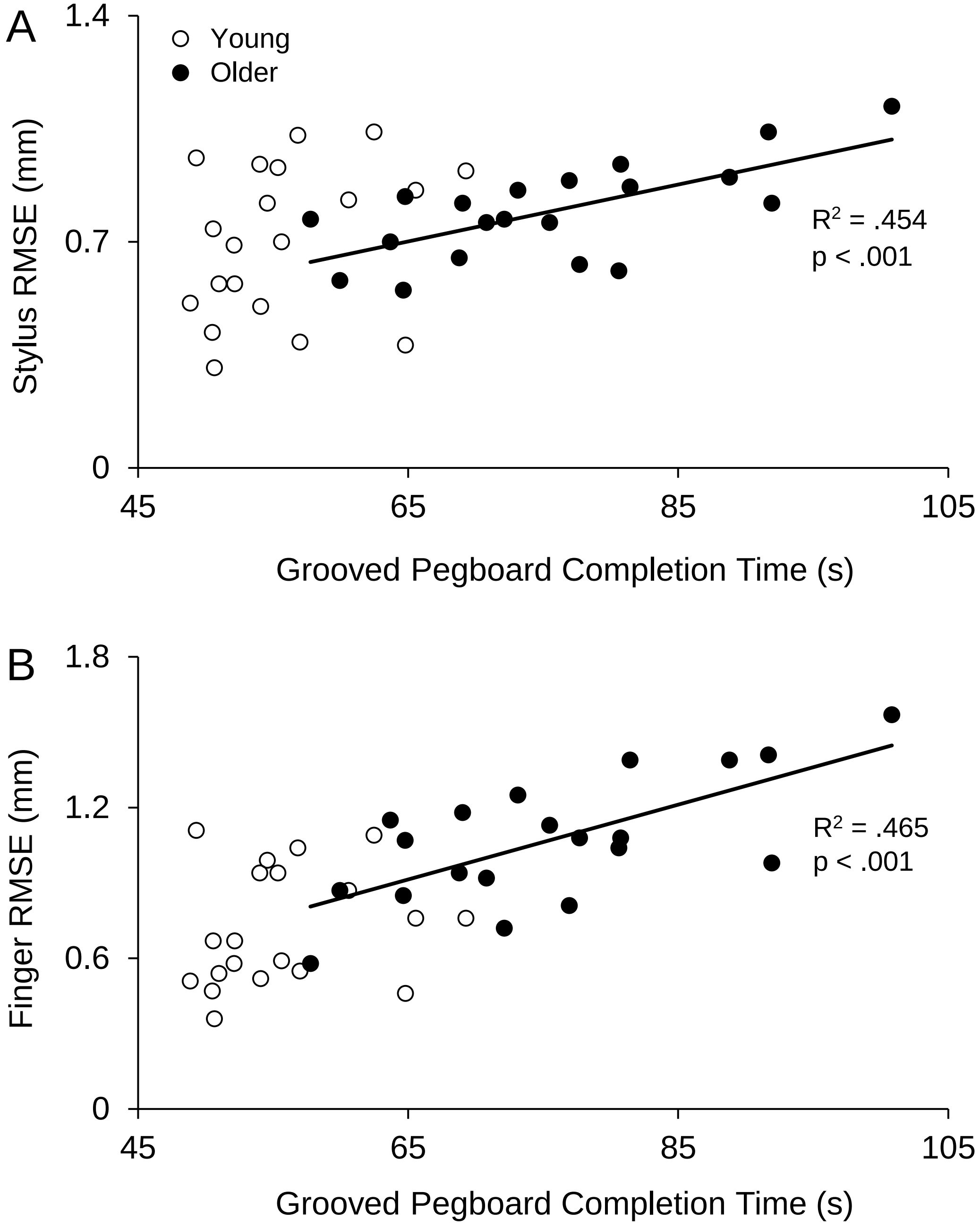


Figure 3.8. Relationship between Grooved Pegboard and spiral tracing performance. There was a significant, positive correlation between Grooved Pegboard completion time and spiral tracing performance when tracing with the (A) stylus (*p* = .001) and (B) finger (*p* < .001) in older but not young (*p* >.163) adults. Data has been collapsed across conditions when tracing with the finger.

Discussion

The primary purpose of this study was to examine age-related changes in eye movements during a touchscreen Archimedes spiral tracing task and to determine if these changes were associated with spiral tracing impairments in older adults. The main findings were 1) age-related changes in eye movements during the spiral tracing task and a relationship with spiral tracing performance in older adults and 2) decreased visual information may not play a critical role in preferential declines in spiral tracing performance when tracing with the finger in older compared to young adults. Though spiral tracing error was greater in older compared to young adults when tracing with the finger, there was no significant difference in spiral tracing performance between young and older adults when tracing with the stylus. Older adults made fewer saccades than young adults. Saccade amplitude and saccade amplitude variability were greater in older compared to young adults, and increased saccade amplitude was related to spiral tracing impairments in older adults. Young and older adults made more saccades when tracing parts of the spiral where vision of the upcoming spiral template was likely less obstructed by the hand. Because saccades are used to orient gaze with areas of interest in the visual field (Henderson, 2003), a greater number of saccades likely reflects a visual strategy that would allow for more up to date visual feedback of the spiral template; however, this had no effect on spiral tracing performance. Together, results provide evidence of age-related changes in eye movements during the spiral tracing task and suggest that decreased visual information may not be the main contributing factor associated with impaired spiral tracing performance when tracing with the finger in older adults.

Older adults exhibited similar performance as young adults when tracing with the stylus however, spiral tracing error was approximately 30% greater in older compared to young adults when tracing with the finger (Fig. 3.3). This is consistent with previous findings (Heintz & Keenan, 2018) and continues to support the use of a stylus for touchscreen manipulation in older adults (Heintz & Keenan, 2018; Leonardi et al., 2010; Motti et al., 2014). Because the finger is larger in diameter and occludes more vision of the touchscreen than a stylus (Vogel & Baudisch, 2007) and because older adults rely more on visual information than young adults for some hand tasks (Coats & Wann, 2011), we examined eye movements to determine whether visual strategy was associated with these age-related spiral tracing impairments in older adults. Both young and older adults used a series of saccades and fixations while viewing the template and trace during the spiral tracing task (Fig. 3.1C). Consistent with previous work (Keenan et al., 2017), older adults made fewer saccades than young adults (Fig. 3.4) and increased saccade number was related to increased spiral tracing performance in young adults. Given that saccades are used to orient gaze with areas of interest in the visual field (Henderson, 2003), increased saccade number in young adults could reflect an optimal visual strategy that would allow gaze to more closely follow the leading edge of the spiral trace and would therefore provide more up to date visual feedback of spiral tracing performance. Though results indicate that a greater number of saccades are beneficial for spiral tracing performance in young adults, this was not true for older adults, evidenced by a lack of relationship between saccade number and spiral tracing performance in this age group. Further, no difference in saccade number when tracing with the stylus versus finger indicates that saccade number was not related to impaired performance when tracing with the finger in older adults.

Differences in saccade amplitude between young and older adults have been shown previously during hand motor tasks and provide evidence for age-related changes in the control of eye movements (Rand & Stelmach, 2011). Similarly, saccade amplitude was greater in older compared to young adults during the spiral tracing task (Fig. 3.5) and increased saccade amplitude was related to decreased spiral tracing performance in older adults (Fig. 3.6). This relationship provides evidence for an association between age-related changes in the control of eye movements and decreased spiral tracing performance in older adults. There were no differences in spiral tracing completion time between young and older adults, which is consistent with our previous study (Heintz & Keenan, 2018). However, increased completion time could have played a role in this relationship given that there was a significant relationship between completion time and spiral tracing performance within the two age groups. Specifically, increased completion time may have led to a greater number of saccades and decreased saccade amplitude within each age group. Though some studies have imposed a time constraint during spiral tracing (Heenan et al., 2014), the task was self-paced based on previous work (Heintz & Keenan, 2018; Marmon et al., 2011; Miralles et al., 2006) and to replicate the traditional, clinical assessment as closely as possible (Bain et al., 1993). Also, we did not impose a time constraint as it could have led to undue stress for some individuals and might deemphasize the goal of the task, which was to complete the spiral as accurately as possible. Future work could control for completion time to determine whether differences in saccade amplitude are a result of age-related changes in eye movements or differences in completion time.

Studies suggest that older adults make more saccade landing errors during hand motor tasks, reflecting a decreased ability to control gaze location with age (Rand & Stelmach, 2011, 2012; Wu et al., 2010). Similarly, increased saccade amplitude variability in older compared to young adults could reflect a greater number of saccade landing errors and decreased ability to control gaze location. Saccade amplitude variability was also greater during the spiral tracing task with versus without simultaneously performing the visuospatial task (Fig. 3.5B). This provides evidence for decreased ability to control gaze location when allocating attentional resources across multiple tasks, which seems reasonable given that changes in eye movements are intimately linked to attentional processes (Hunt et al., 2019). Though these findings reveal the effect of age and attentional processes on eye movements, saccade amplitude variability was not significantly related to spiral tracing performance.

Young and older adults made fewer saccades when tracing in the right quadrants (Quadrants I and IV) compared to the left quadrants (Quadrants II and III) where vision of the upcoming spiral template was likely more obstructed by the hand (Fig. 3.7A). This altered visual strategy is clearly seen by comparing the number of saccades on the right versus left side of the spiral trace in Fig. 3.1C. Saccades are used to orient the area of highest visual acuity with task-relevant information and fixations are used to obtain visual information (Henderson, 2003). Therefore, a greater number of saccades would allow gaze location to stay closer to the upcoming spiral template and would provide more up-to-date visual feedback to guide hand movements (Keenan et al., 2017). If older adults relied more on visual feedback for spiral tracing, decreased saccade number would likely have impaired performance to a greater degree in older compared to young adults. Despite altered visual strategy, there were no differences in spiral tracing error across quadrants for young compared to older adults (Fig. 3.7B). Thus, eye movements and subsequent changes in visual feedback are likely not the main factors associated with spiral tracing impairments when tracing with the finger in older adults as originally anticipated.

Though visual information is important for hand motor tasks, older adults may have also relied on anticipatory parameter control during the spiral tracing task. Anticipatory parameter control is the ability to create and adjust motor programs based on learned and expected task characteristics and is independent of online processing of sensory feedback (e.g., visual feedback) while performing the task (Johansson & Edin, 1993). The symmetrical shape of the spiral template is relatively easy to learn and predict which could facilitate this type of feedforward control. Further, previous work has shown no differences in performance between young and older adults during upper extremity movements that incorporate less online processing of visual information (Seidler-Dobrin & Stelmach, 1998). This could explain the lack of age-related differences when tracing with the stylus in the current study.

Additional factors were assessed to further examine age-related spiral tracing impairments including attentional processes. Attentional processes are impaired in older compared to young adults (Huddleston et al., 2014). However, contrary to previous work assessing the effect of dual tasks during finger force-matching tasks (Pereira et al., 2015; Voelcker-Rehage et al., 2006), there were no differences in error when performing the spiral tracing task with compared to without the visuospatial task. The visuospatial task was selected based on that used previously and is thought to be of moderate difficulty (Peterson & Keenan, 2018). A lack of differences in performance could be due to the difficulty level of the visuospatial task. However, this same task was difficult enough to influence performance on other motor tasks (e.g., pegboard tests, see Chapter 2) and the differential effect of dual tasks on motor performance is not novel (Peterson & Keenan, 2018). Nonetheless, current results provide evidence that attentional demands of the spiral tracing task are less than those of other hand motor tasks and, along with no relationship between other measures of attentional processes and spiral tracing performance in older adults shown previously (Heintz & Keenan, 2018), support the idea that age-related declines in attentional processes do not significantly contribute to spiral tracing impairments.

Grooved Pegboard completion time was greater in older compared to young adults and this was related to decreased spiral tracing performance in older adults (Fig. 3.8). Manual dexterity is defined as a component of hand function associated with speed and accuracy of hand movements (Reuben et al., 2013; Yancosek & Howell, 2009). Results indicate that manual dexterity impairments are associated with decreased spiral tracing performance in older adults. Indeed, accurate control of hand movements would be important to trace the spiral template as closely as possible. Though it is possible that manual dexterity was not associated with spiral tracing performance in young adults, a lack of relationship in young adults may be due to low variability in pegboard completion time within this age group (Fig. 3.8). The relationship between the two measures was similar when tracing with the stylus ($r = .454$) and finger ($r = .465$) in older adults; therefore, age-related declines in manual dexterity were not associated with preferential performance impairments when tracing with the finger in this age group.

The myriad factors examined in the current and previous study (i.e., fingertip sensation, surface friction, hand used) (Heintz & Keenan, 2018) do not completely account for age-related impairments when tracing with the finger. Additional factors could underlie performance deficits in older adults. For example, decreased fingertip sensation in older adults, assessed using the standardized von Frey Anesthesiometer, was not related to spiral tracing performance in our previous study (Heintz & Keenan, 2018). The von Frey Anesthesiometer quantifies fingertip sensation by pressing filaments of different sizes to the participant’s fingertip. It is possible that this assessment was not sensitive to age-related declines in cutaneous sensation that play a role in spiral tracing performance. Additionally, touchscreen ownership and comfort using a touchscreen were not related to performance in our current study. However, a relatively small number of older adults did not own touchscreens (N = 4) making statistical comparisons difficult. Further, experiential differences could impact the ability to interact with touchscreens in ways that are difficult to quantify. Many of today's young adults are exposed to touchscreen devices at an early age. For example, more than one third of all children under 2 have used a touchscreen device and 75% of children live in a home with access to a smartphone or tablet (Rideout & Saphir, 2013). This early exposure was not the case for the older population who were adults before the rise in touchscreen technologies (Holzinger et al., 2007). Touchscreen manipulation using the finger is a relatively unique aspect of many newer technological devices. Use of stylus-like drawing implements, such as a pen or pencil, is not unique to newer technologies. Age-related deficits when tracing with the finger but not the stylus could be the result of less experience manipulating touchscreens with the finger and similar experience using stylus-like drawing implements compared to young adults. More work is needed to understand how this impacts the ability to manipulate touchscreen devices, with the goal of increasing usability of technological devices and benefits associated with their use (e.g., increased social support, self-efficacy, and functional independence) (Mynatt & Rogers, 2011; Wright, 2000). For example, a future study could implement a training paradigm in older adults to examine whether age-related impairments are mitigated with more experience tracing with the finger.

The following limitations should be considered. Our main objective was to examine age-related spiral tracing impairments. However, continuous tracing used for this task is one of many gestures performed on touchscreens. Additional work is needed to examine if results generalize to other touchscreen gestures, particularly those that are less apt to anticipatory parameter control and require more online processing of visual information. Results suggest that amount of visual information influences visual strategy but not spiral tracing performance. Though the objective of this study was to examine age-associated impairments in spiral tracing performance in healthy older adults, changes in the amount visual feedback influence performance on hand tasks in a variety of patient populations (e.g., Parkinson's disease (Ghilardi et al., 2000)). Given that Archimedes spiral tracing task is commonly used as a clinical assessment of tremor, it would be beneficial to examine eye movements and spiral tracing performance in these patient populations. Though not a main objective of our study, assessment of previous touchscreen experience was limited to self-assessment. To our knowledge, no validated assessment currently exists to provide a comprehensive characterization of experience with touchscreen devices. Future work aimed at developing a valid, reliable assessment of experience with touchscreen devices would be beneficial for understanding age-related impairments using these technologies (e.g., mobile phones, tablets, etc.).

Conclusion. The current study provides evidence of age-related changes in eye movements and an association between increased saccade amplitude and decreased spiral tracing performance in older adults. Young and older adults used an altered visual strategy that would allow for less up to date visual information when tracing parts of the spiral where vision of spiral template was likely more obstructed by the hand. This had no effect on spiral tracing performance, indicating that decreased visual information may not play a critical role in spiral tracing impairments when tracing with the finger in older adults. We suggest that other factors could underlie these performance deficits in older adults such as earlier exposure to touchscreen devices in young compared to older adults. Future work could continue to investigate other factors associated with the ability to manipulate touchscreen devices with the goal of increasing touchscreen usability in older adults.

Chapter 4: Visual feedback and declines in attention are associated with altered visual strategy during a force-matching task in older adults

Introduction

The ability to produce steady finger forces decreases with age (Keenan & Massey, 2012; Kornatz et al., 2005; Laidlaw et al., 2000; Marmon et al., 2011; Pereira et al., 2018; Tracy et al., 2005) and is associated with impaired hand function in older adults (Kornatz et al., 2005; Marmon, et al., 2011). The number of older adults (65+ years) living in the United States is increasing (Vespa et al., 2018) and impairments in hand function are well-documented in this population (Desrosiers et al., 1999; Seidel et al., 2009). Impaired hand function is associated with difficulties performing activities of daily living (Carmeli et al., 2003; Seidel et al., 2009; Shiffman, 1992) and contributes to loss of independence and need for living assistance (Falconer et al., 1991; Lubitz et al., 2003; Ostwald et al., 1989; Williams et al., 1982).

Visual information plays an important role in many goal-directed hand motor tasks (Johansson et al., 2001). The effect of visual information on hand motor control is commonly assessed by manipulating the amount of visual feedback during visually guided force-matching tasks (Baweja et al., 2012; Kennedy & Christou, 2011; Sosnoff & Newell, 2006a; Tracy et al., 2007). Specifically, participants are provided visual feedback of their force output relative to a target force level, displayed as a horizontal line in the center of a screen, and asked to maintain a steady force as accurately as possible. Feedback of force output is displayed as a horizontal line that moves up and down with force magnitude (i.e. compensatory feedback) or a force trace that moves up and down with force magnitude while moving left to right with time across the screen (i.e. pursuit feedback). Amount of visual feedback is commonly manipulated by changing the gain of visual feedback (Baweja et al., 2012; Chen et al., 2017; Keenan et al., 2017; Kennedy &

Christou, 2011; Sosnoff & Newell, 2006b). Higher gain leads to greater vertical displacement of the force trace for a given force output than lower gain (Keenan et al., 2017). Studies of age-related changes in force control with altered visual feedback have found increased force fluctuations in older adults with higher compared to lower gain, indicating an association between amount of visual feedback and decreased force control in older adults (Ofori et al., 2010; Sosnoff & Newell, 2006a).

Despite the effect of visual information on the control of steady forces in older adults, to our knowledge only one study has examined eye movements during finger force-matching tasks in young and older adults (Keenan et al., 2017). A pinch force-matching task was performed with pursuit and compensatory feedback. While viewing pursuit feedback, all participants gazed near to the target line and used a series of saccades and fixations to track the force trace from left to right across the screen. Older adults made fewer saccades than young adults and this was related to decreased force steadiness. While viewing compensatory feedback, increased gain was associated with altered visual strategy and decreased force-steadiness in older adults. Despite these findings, the effect of gain on eye movements during pursuit feedback is not known. Furthermore, because older adults had greater force fluctuations than young adults and the force trace moves up and down with the magnitude of force output, visual feedback of force was different between age groups. Characteristics of visual feedback influence eye movements (Huddleston et al., 2013; Rand & Stelmach, 2010). Therefore, it is not known whether decreased saccade number in older versus young adults was due to differences in visual feedback or age-related changes in the control of eye movements.

Attentional processes decline with age (Huddleston et al., 2014) and may contribute to decreased force steadiness in older adults (Keenan et al., 2017; Pereira et al., 2015; Voelcker-

Rehage et al., 2006). For example, decreased attentional prowess, measured with a cued saccade attention test, was related to decreased force steadiness during a pinch force-matching task in older adults (Keenan et al., 2017). Additionally, studies have shown preferential impairments in older adults when performing dual tasks (Hausdorff et al., 2008; Peterson & Keenan, 2018; Schrodt et al., 2004; Voelcker-Rehage et al., 2006). Dual-task paradigms are commonly used to examine age-related changes in the ability to allocate attentional resources across multiple tasks (Woollacott & Shumway-Cook, 2002). However, a majority of studies using dual-task paradigms have targeted falls risk in older adults (Hausdorff et al., 2008; Peterson & Keenan, 2018; Schrodt et al., 2004) and fewer studies have examined the effect of dual tasks on upper extremity motor performance in older adults (Pereira et al., 2015; Voelcker-Rehage et al., 2006). Further, eye movements are intimately linked to attentional processes (Hunt et al., 2019). To our knowledge no studies to date have examined the effect of a dual task on eye movements during force-matching tasks in older adults.

The primary purpose of this study was to examine if visual feedback amount influenced eye movements during a pinch force-matching task and the association with decreased force steadiness in older adults and to determine whether differences in visual strategy between young and older adults were due to age-associated changes in the control of eye movements. In addition, we examined the effect of decreased attentional resources on eye movements during a force-matching task and the relationship with force steadiness in older adults. Eye movements were recorded during a submaximal pinch force-matching task while viewing pursuit feedback of force with higher and lower gain and while simultaneously performing a visuospatial task. Participants also performed a visual-tracking task where they were asked to follow the leading edge of a preprogrammed force trace with their gaze. The trace was presented with higher and lower variability to reflect that produced by older and young adults during the force-matching task, respectively. To further examine attentional processes, the Test of Everyday Attention and Trail Making Test were performed. Both are common, standardized measures of subsystems of attention (Posner & Petersen, 1990; Robertson et al., 1994), including selective attention, sustained attention, attentional switching, and divided attention. We hypothesized that older adults would use fewer saccades than young adults during the force-matching task, especially with increased visual feedback and addition of a visuospatial dual task, and this would be related to increased force fluctuations. During the visual-tracking task, we hypothesized that older adults would make fewer saccades than young adults but there would but no difference in saccade number while visually tracking the preprogrammed trace with higher vs. lower variability. This would indicate that decreased saccade number in older compared to young adults during the force-matching task was due to age-associated changes in the control of eye movements and not differences in visual feedback of force between age groups.

Methods

Participants. A total of 51 participants, 23 young (age, 25.3 ± 4.4 years; range, 20 – 38 years; 12 females) and 28 older (age, 72.6 ± 6.6 years; range, 65 – 90 years; 13 female) adults, were recruited from the surrounding community. Written informed consent was obtained from all participants as approved by the Institutional Review Board at the University of Wisconsin – Milwaukee. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971) and had normal or corrected to normal vision as assessed by the Snellen Eye Chart test for visual acuity (Hallowell, 2008). Exclusion criteria included presence of functional deficiencies or neuromuscular disorders, pain currently in the upper extremities that may limit normal movement, hand pathologies (e.g., arthritis), currently taking medications that influence neuromuscular function or vision, and inability to sit comfortably for extended periods. Participants were asked to abstain from caffeine 12 hours prior to testing (Lorist et al., 1994; Lorist et al., 1995). The Montreal Cognitive Assessment (MoCA) was used to assess cognitive impairments that could influence performance (Nasreddine et al., 2005).

Equipment. Eye movements were recorded with an infrared R6 Remote Optics Eye Tracking System (Applied Science Laboratories, Bedford, MA) at 120 Hz. Sampling rate is consistent with previous studies examining eye movements during force-matching tasks (Huddleston et al., 2013; Keenan et al., 2017). Pinch force was recorded with a force sensor (LSB200, Futek, Irvine, CA) sampled at 121 Hz (NI9237; National Instruments, Austin, TX) (Huddleston et al., 2013; Keenan et al., 2017). Metal pinch contact surfaces were 1.8 cm in diameter and spaced 3 cm apart. Data were collected on a computer (Dell Latitude E6510, Austin, TX) using Eye-Trac 6 User Interface program (Applied Science Laboratories, Bedford, MA). Custom software (BTS, Richfield, WI) written in LabVIEW (National Instruments) was used to display visual feedback and record force data. Participants completed a full-field 9-point eye tracking calibration prior to testing.

Force-Matching Task. Participants sat with their eyes positioned 70.2 cm in front of a screen (Fig. 4.1A), a similar distance compared to previous work (Keenan et al., 2017; Ofori et al., 2010). A headrest was used to facilitate eye movement recordings, decrease extraneous head movement, and control visual angle. The force sensor was held between the distal phalanges of the right thumb and index finger using a tip-to-tip pinch grip. The right forearm and wrist were supported in neutral on a table using a VersaForm pillow (VersaForm Systems Corp., Danbury, CT). Visual feedback was displayed as a 30.8 cm x 40.8 cm image on the screen using an LCD projector (1024 x 768 resolution, 102CP-RX80, Hitachi Consumer Electronics Co. Ltd, Yokohama, Japan).

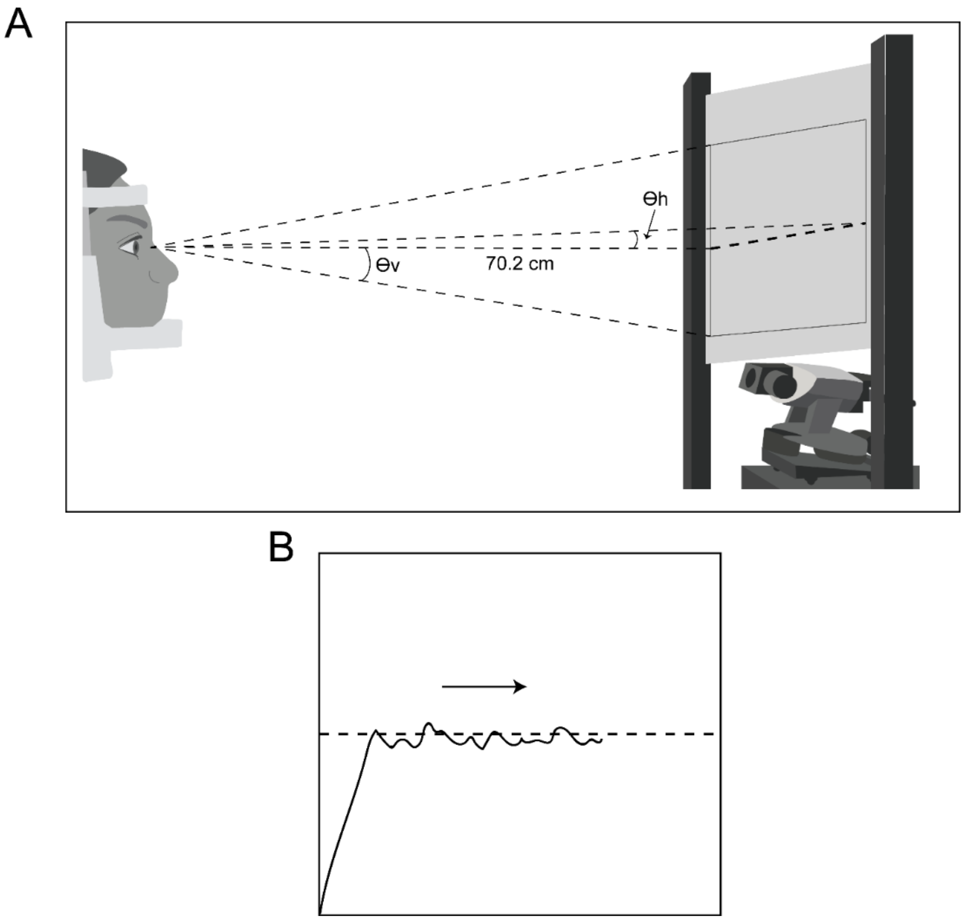


Figure 4.1. Experimental setup and visual feedback for the force-matching task. (A) Participants sat with their head in a headrest and eyes 70.2 cm in front of a screen. Visual feedback was displayed on the screen using a projector. The vertical angle from the middle to bottom of the visual feedback display was 12.6 º (Ɵv), for a total vertical angle of 25.2 º. The total horizontal angle of the visual feedback display was 32.4 º (Ɵh). Participant's view of the visual feedback (B) demonstrates the target force, displayed as a dashed line at 1 N, and participant's force trace, displayed as a solid line that moved up and down in magnitude of force output and left to right in time across the screen.

Participants were instructed to match a 1 N target force as accurately as possible by pinching the force sensor. Target force was presented as a horizontal dashed line and the participant's force was presented as a solid line that moved left to right across the screen (i.e.

pursuit feedback) (Fig. 4.1B). The 1 N target force was selected to allow for comparisons (Huddleston et al., 2013; Keenan et al., 2017), minimize fatigue, is functionally relevant, and because age-associated differences in the ability to hold steady forces are greater for lower compared to higher force levels (Kornatz et al., 2005; Laidlaw et al., 2000; Tracy et al., 2005).

The force-matching task was performed under three conditions including, a 1) lower gain, 2) higher gain, and 3) higher gain + VS condition. Visual feedback was presented under a lower and higher gain by changing the ordinate scale (Huddleston et al., 2013; Keenan et al., 2017). For the lower gain condition, the bottom and top of the screen corresponded to 0 N and 2 N, respectively. For the higher gain condition, the bottom and top of the screen corresponded to 0.8 N and 1.2 N, respectively. These values were used for lower and higher gain conditions during a similar pinch force-matching task that were associated with altered visual strategy in older adults (Keenan et al., 2017).

For the higher gain + VS condition, participants completed the force matching task with higher gain visual feedback while simultaneously performing a visuospatial task based on Brooks' spatial memory task (Brooks, 1967) and that used previously (Peterson & Keenan, 2018). A visuospatial task was selected instead of a nonspatial task because visuospatial tasks impact motor performance to a greater extent in older adults (Sturnieks et al., 2008). Specifically, participants visualized a star moving around four boxes in a 2 x 2 grid, labeled 1 through 4. The star always started in box 1. Participants were told a series of four directions that signified the direction of the star's movement (i.e. right, left, up, down, diagonal). Each series began when the experimenter said, "Start" followed by four randomized locations, and ended when the experimenter asked, "Location?" upon which the participant was instructed to report the final star location by stating the number of the box the star was in. Prior to testing, participants completed five practice trials while viewing the grid followed by a series of practice trials without the visual display. Three consecutive correct practice trials were required before proceeding.

One practice trial and three test trials each lasting 13 seconds were performed for all three force-matching task conditions. Additional practice trials were performed if the participants were not able to maintain a steady force. Test trials were discarded and additional trials were performed if a tip-to-tip pinch grip was not maintained or the force trace exceeded the field of view. Eye movements were recorded in the horizontal (X) and vertical (Y) directions. The sequence of trials was block randomized across force-matching tasks.

Visual-Tracking Task. A visual-tracking task was performed to examine whether decreased saccade number in older vs. young adults (Keenan et al., 2017) was the result of differences in visual feedback or age-related changes in eye movement control. The setup for the visual-tracking task was similar to the force-matching task except that participants did not pinch the force sensor and a pre-programmed force trace was presented to the participants. Participants were told that they would be presented with a series of videos of the force trace and target force as if we had recorded the visual display while they were performing the force-matching tasks. The target force and force trace were displayed as a dashed line and solid line, respectively, equivalent to visual feedback used during the force-matching task. Instructions were to follow the leading edge of the solid line with their eyes as closely as possible as it moved left to right across the screen.

The visual-tracking task was performed under two conditions, including a pre-programmed force trace with 1) higher variability and 2) lower variability. For the higher and lower variability conditions, the force trace fluctuated around the target force with a higher and lower standard deviation of force (SD), respectively. The SD was 0.061 N for the higher variability condition and 0.034 N for the low variability condition. These values were the average force variability of older and young adult participants during the pinch-force matching task while viewing a 1 N target force with an ordinate scale of 0 N to 2 N using pursuit feedback in the aforementioned study, respectively (Keenan et al., 2017). Three test trials each lasting 13 seconds were performed for both conditions. Eye movements were recorded in the X and Y directions. The visual-tracking task was performed after the force-matching task. The sequence of trials was block randomized across visual-tracking tasks.

Measures of attention. Test of Everyday Attention Subtests and the Trail Making Test were performed, as detailed in Chapter 3. Scores for the Test of Everyday Attention subtests were Timing Score for the Visual Elevator (attentional switching), Time per Target Score for the Telephone Search (visual selective attention), and Dual Task Decrement for the Telephone Search While Counting (divided attention and sustained attention). Measures for the Trail Making Test were completion time for Part A and Part B. The sequence of trials was block randomized across attention tests.

Data Analysis. Time was needed to reach a constant force at the beginning of the force-matching trial and changes in force may have occurred due to anticipation at the end of the trial, therefore the first 3 seconds and last 1 second were removed prior to analysis. Thus, data between 3 – 12 seconds were analyzed, as done previously (Huddleston et al., 2013; Keenan et al., 2017). Data between 3 – 12 seconds were analyzed for the visual-tracking task to allow for comparisons. Drift was not expected because visual feedback was provided, therefore force data was not detrended (Huddleston et al., 2013)

Eye position data associated with blinks and artifact were removed, defined as X, Y, or pupil size of zero. Transient spikes were removed, defined as instances when eye position exceeded the field of view. Additional data associated with artifact were removed manually, including instances when vertical eye position exceeded 3 SDs of the trial mean (SD calculated after transients were removed) (Huddleston et al., 2013; Keenan et al., 2017). Similar to previous work, eye position was not filtered (Huddleston et al., 2013; Keenan et al., 2017; Rand & Stelmach, 2011).

All participants made a series of saccades and fixations in the left to right direction while viewing the screen during the lower gain force-matching task, higher gain force-matching task, and visual-tracking tasks. Therefore, saccade number and vertical eye fluctuations were calculated for these conditions. Number of saccades were calculated based on the number of fixations using EyeNal software (Applied Science Laboratories, Bedford, MA). Fixations were defined as times when SD of eye position did not exceed 0.5 degrees in the X and Y directions for a duration ≥ 100 ms (Huddleston et al., 2013; Keenan et al., 2017). Number of saccades were calculated for each trial and averaged across all trials for each condition. Vertical eye fluctuations were calculated as the SD of vertical eye position for each trial in degrees visual angle and were reported as the average across all trials for each condition.

For the force-matching task, force was analyzed offline using custom scripts written in MATLAB (The MathWorks, Inc., Natick, MA). Force fluctuations < 4 Hz represent force fluctuations due to voluntary corrections while those between 4 – 12 Hz represent fluctuations due to tremor/afferent feedback loops (Laine et al., 2014). Thus, force was filtered using a 4th-order low-pass (< 4 Hz) and bandpass (4 – 12 Hz) filter, as done previously (Keenan et al., 2017;

Laine et al., 2014). Force variability was calculated as force SD within the two frequency ranges for each trial and is reported as the average across all trials for each condition, in newtons.

Statistical analysis. Statistical analysis was performed using SPSS 25 (SPSS, Chicago, IL). Statistical significance for all tests was set at $p < 0.05$. Data are reported as mean ± SD in the text and mean + SE in figures unless otherwise noted. Normal distributions of transformed data were confirmed using Shapiro-Wilk's Test and observation of Q-Q plots. A two-sample, independent t-test was used to examine differences in Montreal Cognitive Assessment scores between young and older adults. Force fluctuations were moderately, positively skewed. Therefore, data was transformed using a log transformation (Osborne, 2002). A mixed between-within subjects ANOVA was performed to examine differences in force fluctuations between age groups and across force-matching conditions, with a between subjects factor age (young and older adults) and within subjects factor of condition (lower gain, higher gain, higher gain + VS). Significant results were followed with post-hoc tests with Bonferroni corrections.

Differences in saccade number and vertical eye fluctuations between young and older adults and across force-matching task conditions were also examined using a mixed between-within subjects ANOVA with a between subjects factor of age (older and young adults) and within subjects factor of condition (lower gain and higher gain). Significant omnibus tests were followed with post-hoc tests with Bonferroni corrections. Pearson's correlations were used to examine the relationships between saccade number and force fluctuations and between vertical eye fluctuations and force fluctuations during the higher gain force-matching tasks in older adults.

All young participants and 14 older adults also used a series of saccades and fixations that moved from left to right across the screen during the high gain + VS condition. However, 7 older adults did not make saccades in a left to right fashion. Instead, they used a series of saccades and fixations that moved around the screen in no particular direction. To examine differences in force fluctuations and eye movements between older adults who used the altered visual strategy and those that did not, and because force variability did not conform to a normal distribution in these subgroups, a Kruskal-Wallis test was used to compare non-transformed < 4 Hz force variability, 4 – 12 Hz force variability, saccade number, and vertical eye fluctuations during the higher gain + VS condition. Differences in the attention test scores were also compared between these two groups. Attention test scores did not conform to a normal distribution with transformations. Therefore, a Kruskal-Wallis test was used.

A mixed between-within subjects ANOVA was used to examine differences in saccade number and vertical eye fluctuations during the visual-tracking task between ages and across conditions, with a between-subjects factor of age (young and older) and within subjects factor of condition (lower variability and higher variability).

Results

Participants. A total of 42 participants, 21 young (age, 25.38 ± 4.78 years; range, 20 - 38 years; 11 female) and 21 older (age, 73.57 ± 7.07 years; range, 65 – 90 years, 11 female) adults, were included in this study. This is consistent with an a priori power analysis using G*Power (Faul et al., 2007) and is similar to sample sizes used previously (Keenan et al., 2017). Data from 9 participants, 2 young (age, 25.50 ± 3.54 years; range, 23 - 28 years; 2 female) and 7 older (age, 69.71 ± 4.19 years; range, 67 – 90 years, 4 female) adults, were discarded due to eye data artifact. There was no significant difference in MoCA scores ($t(40) = 1.441$, $p = 0.157$, $d = .542$) between young (28.38 ± 1.16; range, 26 - 30) and older (27.78 ± 1.05; range, 26 - 30) adults. No participants scored below the cutoff suggesting cognitive impairment (i.e. < 26) (Nasreddine et al., 2005).

Force-Matching Task.

Force Variability. Force fluctuations < 4 Hz were significantly greater ($F(1) = 35.191$, $p < .001$, $\eta_p^2 = .468$) for older (mean = .090 N, 95% CI = [.074, .110]) vs. young (mean = .032 N, 95% CI = .029, .035]) adults (Fig. 4.2A). There was a significant effect of condition on < 4 Hz force fluctuations ($F(2) = 3.414$, $p = .038$, $\eta_p^2 = .079$). Force fluctuations < 4 Hz were greater for higher vs. lower gain ($p = .013$). There was no difference between higher gain and higher gain + VS ($p = .809$) or lower gain and higher gain + VS ($p = .534$) (lower gain, mean = .049 N, 95% CI = [.038, .062]; higher gain, mean = .059 N, 95% CI = [.045, .076]; higher gain + VS, mean = .054 N, 95% CI = [.041, .070]). There was no age by condition effect on force fluctuations < 4 Hz ($p = .439$). Force fluctuations 4 – 12 Hz were significantly greater ($F(1) = 38.506$, $p < .001$, $\eta_p^2 = .490$) for older (mean = .028 N, 95% CI = [.023, .035]) compared to young (mean = .009 N, 95% CI = [.008, .010]) adults (Fig. 4.2B). There were no other significant main or interaction effects on 4 – 12 Hz force fluctuations (p > .058).

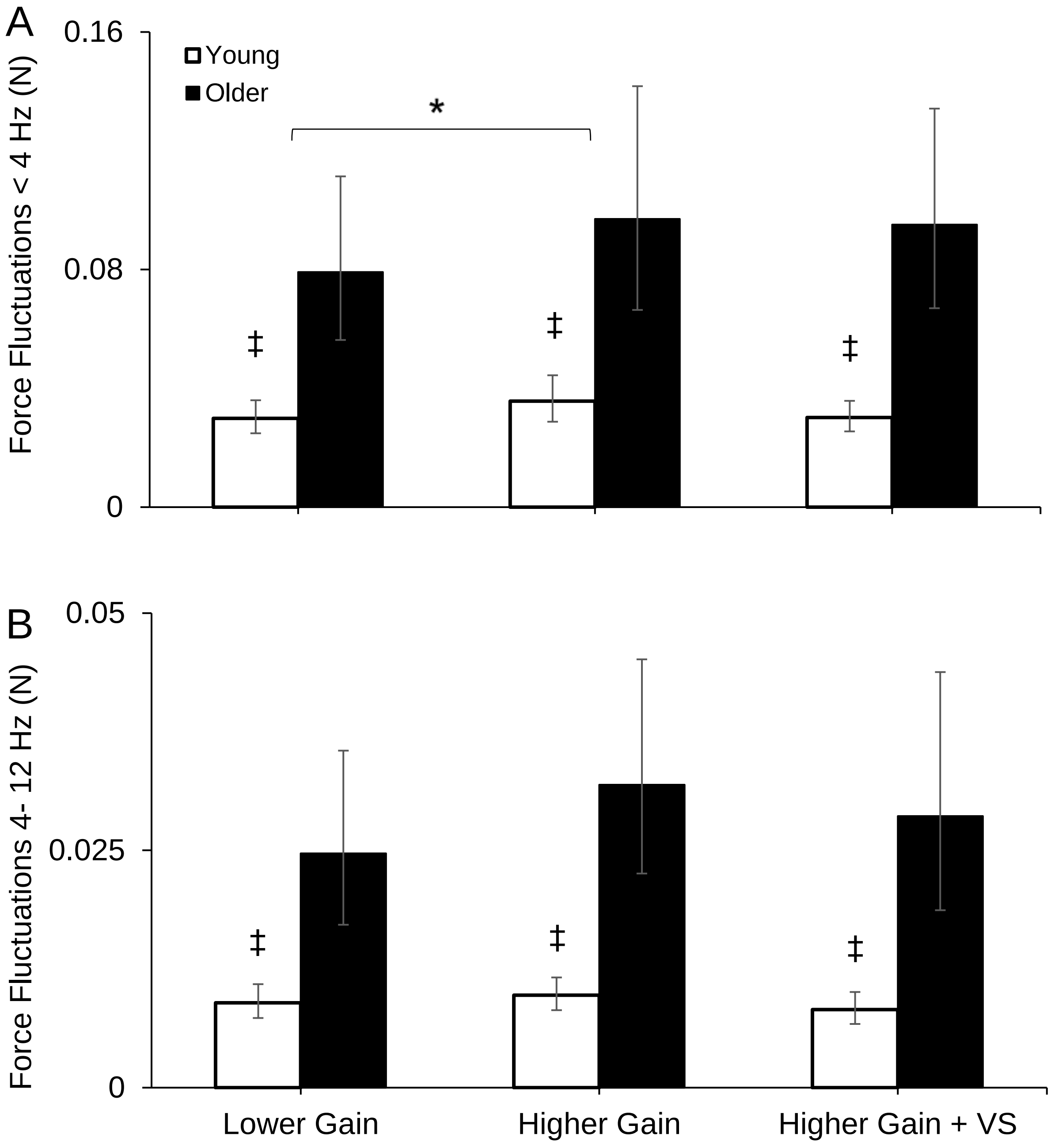


Figure 4.2. Force fluctuations in young and older adults and across force-matching conditions. (A) Force fluctuations < 4 Hz were greater for older compared to young adults ($^{‡}p$ < .001). There was also a condition effect on force fluctuations ($p = .038$). Force fluctuations were greater with higher compared to lower gain visual feedback ($^{*}p = .013$) however, there was no difference in force fluctuations between higher gain and higher gain + VS ($p = .809$) or lower gain and higher gain + VS conditions ($p = .534$). (B) Force fluctuations between 4 – 12 Hz were greater for older compared to young adults ($^{‡}p$ < .001). There were no other significant effects of interactions ($p > .058$). Data is back-transformed mean and 95% CI for both figures.

Eye Movements. All participants used a similar visual strategy during the lower and higher gain conditions. Specifically, participants gazed near the target line and used a series of saccades in the left to right direction to track the force trace as it moved across the screen. Therefore, differences in saccade number and vertical eye fluctuations were examined between these two conditions. Young adults made significantly more saccades ($F(1) = 8.382$, $p = .006$, $\eta_p^2 = .173$) than older adults (23.60 ± 4.48 saccades and 21.04 ± 2.88 saccades, respectively) (Fig. 4.3A). Saccade number was significantly greater ($F(1) = 20.622$, $p < .001$, $\eta_p^2 = .340$) during the lower vs. higher gain condition (23.73 ± 3.45 saccades and 20.91 ± 3.97 saccades, respectively). There was no age by condition interaction effect on saccade number ($p = .208$). There was a significant main effect of condition on vertical eye fluctuations ($F(1) = 4.854$, $p = .033$, $\eta_p^2 = .108$) (Fig. 4.3B). Vertical eye fluctuations were greater during the higher compared to lower gain conditions (.71 ± .50 º and .55 ± .21 º, respectively). There was no significant main effect of age ($p = .423$) or condition age by condition interaction effect ($p = .723$) on vertical eye fluctuations.

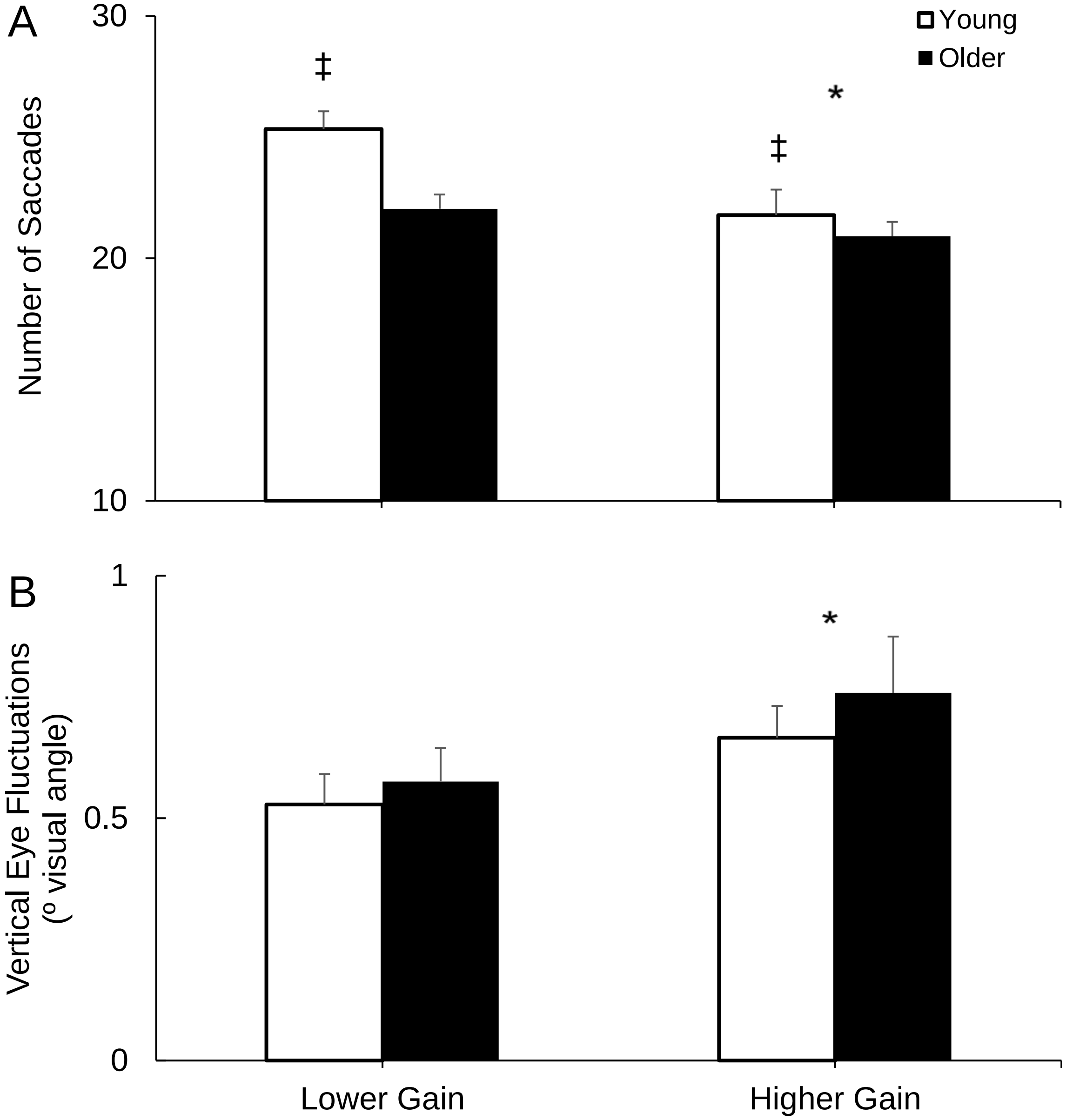


Figure 4.3. Saccade number and vertical eye fluctuations in young and older adults with lower and higher gain. (A) Saccade number was greater for young vs. older adults (‡p = .006) and during the lower vs. higher gain (*p < .001) condition. (B) Vertical eye fluctuations were greater during the higher vs. lower gain condition (*p = .033).

Because saccade number and vertical eye fluctuations were different for the lower compared to higher gain condition, we wanted to determine whether they were related to increased force fluctuations during the higher gain condition in older adults. There was no significant relationship between saccade number and < 4 Hz force fluctuations (*r* = -.199, *p* = .388) or 4 – 12 Hz force fluctuations and (*r* = -.182, *p* = .430) during the higher gain condition in older adults. Similarly, there was no significant relationship between vertical eye movements and < 4 Hz force fluctuations (*r* = -.067, *p* = .776) or 4 – 12 Hz force fluctuations (*r* = -.106, *p* = .648) during the higher gain condition in older adults.

All young participants and 14 older adults used a series of saccades and fixations that followed the direction of the force trace (i.e. left to right) while performing the force-matching task with the visuospatial task (Fig. 4.4A). Seven older adults used an altered visual strategy during this condition where, despite using a series of saccades and fixations, gaze did not stay near the target line and did not travel exclusively from left to right with the force trace (Fig. 4.4B). There was no significant difference in < 4 Hz force fluctuations ($K(1) = .941$, $p = .332$, $\varepsilon^2 = .047$), 4 – 12 Hz force fluctuations ($K(1) = .089$, $p = .765$, $\varepsilon^2 = .067$), saccade number ($K(1) = 2.015$, $p = .156$, $\varepsilon^2 = .317$), or vertical eye fluctuations ($K(1) = 2.455$, $p = .117$, $\varepsilon^2 = .350$) between older adults who did and did not use this altered visual strategy (Table 4.1).

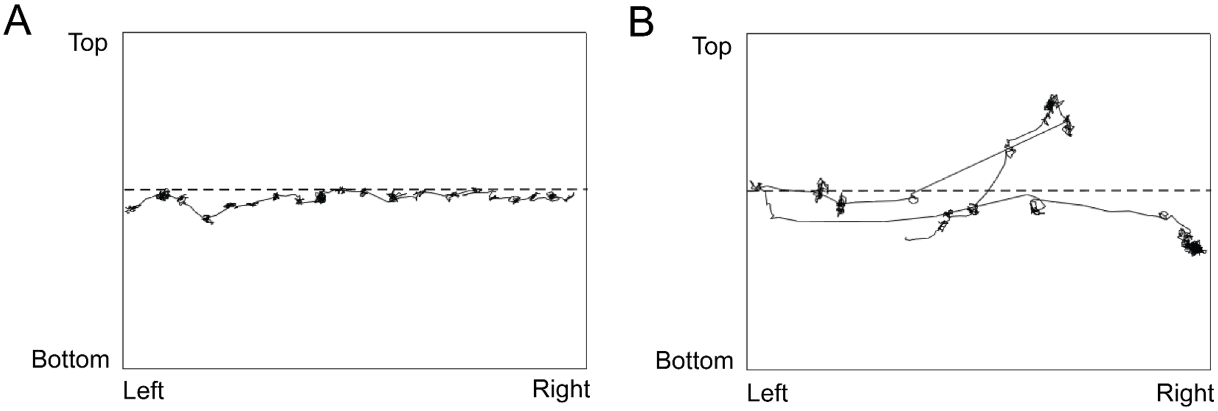


Figure 4.4. Representative eye movement data from two older adults while performing the force-matching task with the visuospatial task. (A) All young adults and 14 older adults used a series of saccades and fixations moving in the left to right direction while viewing visual feedback during the force-matching task. However, (B) 7 older adults made saccades and

fixations that did not move solely in the left to right direction. Top, Bottom, Left, Right correspond to the top, bottom, left, and right of the visual display. Dashed line = target line, solid line = participant's eye movements.

	Saccades Left to Right	**Altered Visual Strategy**
< 4 Hz Force Fluctuations (N)	Mdn = .082 IQR = .042 - .15	Mdn = .14 IQR = .089 - .180
4 – 12 Hz Force Fluctuations (N)	Mdn = .025 IQR = .016 - .048	Mdn = .033 IQR = .013 - .072
Saccade Number	Mdn = 18.41 IQR = 16.50 - 20.37	Mdn = 22.00 IQR = 17.00 - 23.50
Vertical Eye Fluctuations (º)	Mdn = .75 IQR = .50 - 1.35	Mdn = 1.27 IQR = .86 - 2.38

Table 4.1. Force fluctuations, saccade number, and vertical eye fluctuations for older adults who made saccade exclusively in the left to right direction and those that used an altered visual strategy.

Because this altered visual strategy was found only during the force-matching condition that required allocation of attentional resources across multiple tasks (i.e. higher gain + VS), we were interested in determining whether there were differences in performance on the measures of attention between these two groups. There were significant differences between older adults who did and did not saccade left to right on the TMT B ($H(1) = 5.699$, $p = .017$, $\varepsilon^2 = .240$), Telephone Search while Counting ($H(1) = 6.818$, $p = .009$, $\varepsilon^2 = .318$), and Visual Elevator ($H(1) = 5.009$, $p = .025$, $\varepsilon^2 = .312$) (Fig. 4.5). Specifically, attention test scores were greater (i.e. decreased performance) for those who did not use the left to right saccade pattern vs. those who did for TMT B (Mdn = 84.49 s, IQR = 52.37 - 136.45 and Mdn = 50.82 s, IQR = 42.70 – 61.40, respectively), Dual Task Decrement (Mdn = 2.56, IQR = .73 - 3.84 and Mdn = .48, IQR = -.03 - 2.20, respectively), and Timing Score (Mdn = 5.07 s, IQR = 4.39 - 5.64 and Mdn = 4.25 s, IQR = 3.69 – 4.50, respectively). There were no differences in attention test scores between older adults who did not use the left to right saccade pattern and those who did for TMT A ($H(1) = 1.091$, $p = .296$, $\varepsilon^2 = .111$) (Mdn = 36.38 s, IQR = 26.41 – 45.29 and Mdn = 28.65 s, IQR = 23.96 – 38.57, respectively) and Time per Target Score (H(1) = 3.206, $p = .073$, $\varepsilon^2 = .155$) (Mdn = 4.42 s, IQR = 3.82 – 4.59 and Mdn = 3.74 s, IQR = 3.49 – 3.99, respectively).

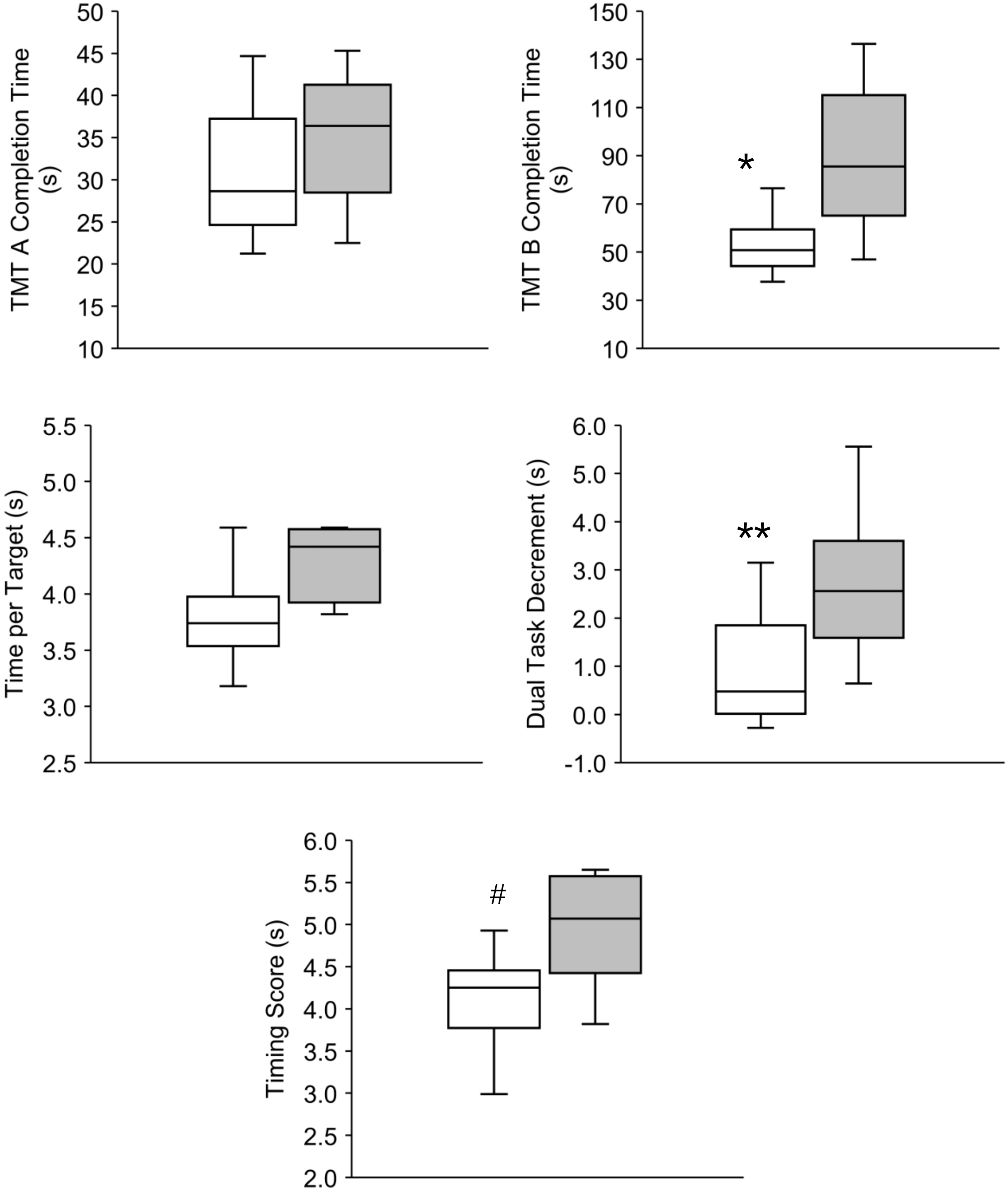
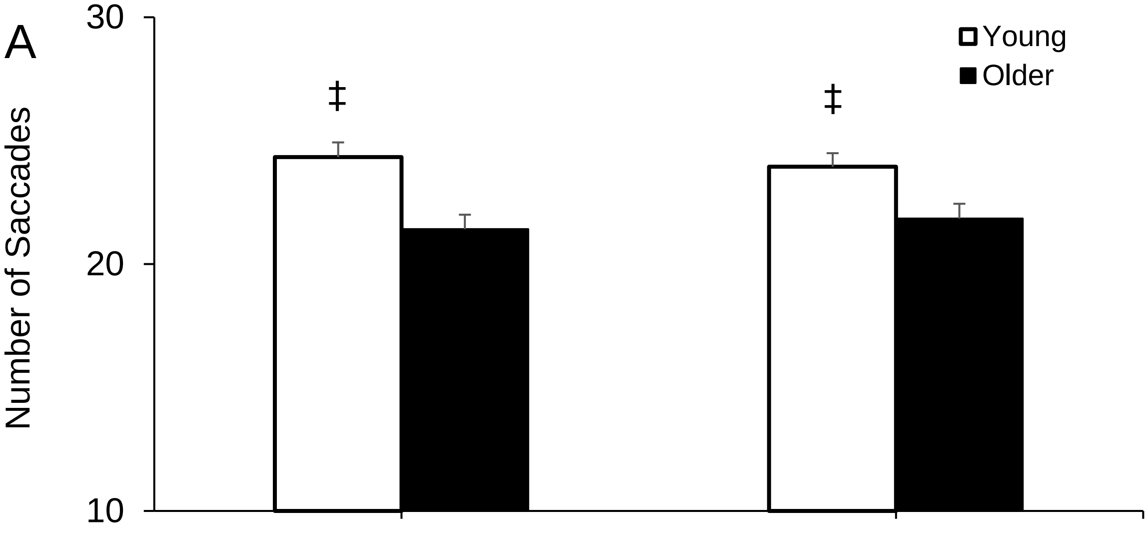


Figure 4.5. Attention test scores for older adults based on visual strategy during the force-matching task while performing the visuospatial task. Attention test scores were greater (i.e. decreased performance) for older adults who did not make saccades in the left to right direction and those who did for TMT B completion time (*p = .017), Dual Task Decrement (**p = .009), and Timing Score ($^{\#}p$ = .025). There were no differences in attention test scores between these two groups for TMT A completion time and Time per Target. Open box = older adults that

used the left to right saccade pattern; Filled box = older adults that used the altered visual strategy. Data is presented as median and IQR.

Visual-Tracking Task. All young and older adults made saccades and fixations in the left to right direction during the visual-tracking test. Number of saccades was significantly greater ($F(1) = 7.628$, $p = .009$, $\eta_p^2 = .160$) in younger (24.33 ± 2.73 saccades) compared to older (21.41 ± 3.60 saccades) adults (Fig. 4.6A). There was no significant effect of condition ($F(1) = .004$, $p = .948$, $\eta_p^2 < .001$) or significant age by condition interaction effect ($F(1) = 1.639$, $p = .208$, $\eta_p^2 = .039$) on saccade number. Vertical eye fluctuations were significantly greater ($F(1) = 7.153$, $p = .011$, $\eta_p^2 = .152$) for the higher (.627 ± .39 º) compared to lower (.483 ± .16 º) variability condition (Fig. 4.6B). There was no significant main effect of age ($F(1) = .033$, $p = .857$, $\eta_p^2 = .001$) or age by condition interaction effect ($F(1) = 1.082$, $p = .305$, $\eta_p^2 = .031$) on vertical eye fluctuations.



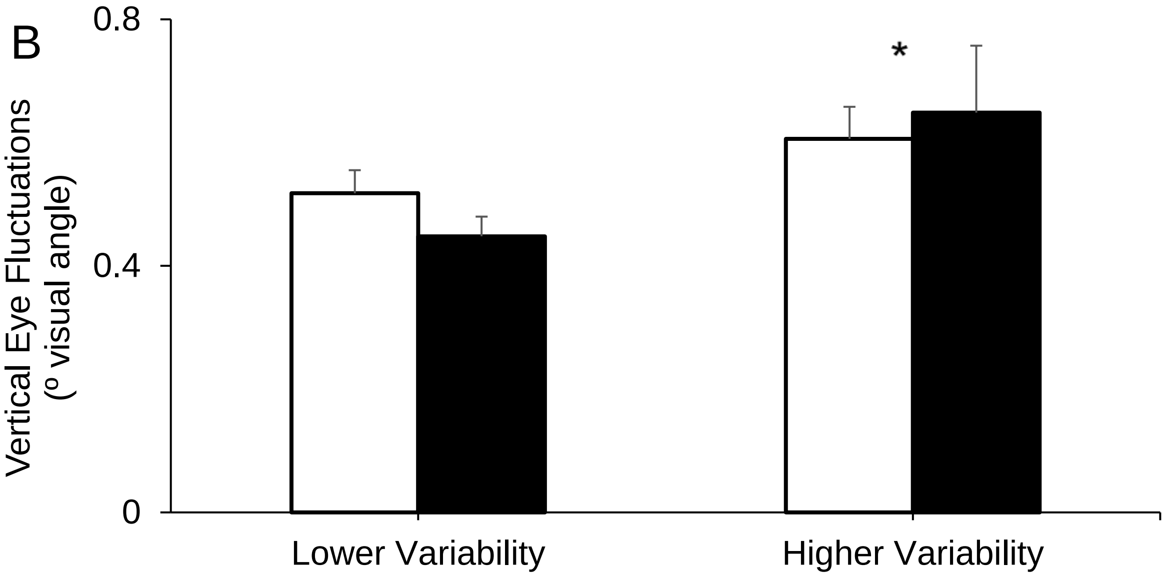


Figure 4.6. Number of saccades and vertical eye fluctuations during the visual-tracking task. (A) Young adults made more saccades than older adults (‡p = .009) and (B) vertical eye fluctuations were greater during the higher compared to lower variability condition (**p* = .011) during the visual-tracking task. There were no other significant effects on saccade number (*p* > .208) or vertical eye fluctuations (*p* > .305).

Discussion

Main findings from this study of age-related changes in eye movements during a visually guided force-matching task were 1) decreased saccade number during the higher gain condition in older adults, 2) decreased saccade number in older compared to young adults was likely due to age-associated changes in the control of eye movements (Fig. 4.6), and 3) an altered visual strategy was used while simultaneously performing a visuospatial task by older adults who also exhibited declines in attentional processes. Older adults made fewer saccades than young adults and during the higher compared to lower gain condition. A lack of relationship with increased force fluctuations during the higher gain condition supports the idea that older adults may have relied more on other processes (e.g., proprioception and cutaneous afferent feedback (Tracy et al., 2007)). There were no differences in saccade number when visual-tracking force traces with higher and lower variability, indicating that use of fewer saccades in older adults was primarily due to age-related changes in eye movement control and not differences in force trace variability between age groups. A subset of older adults used an altered visual strategy when performing the force-matching task with a visuospatial task. Given that these older adults demonstrated poorer performance on measures of attention, this could have been a maladaptive visual strategy used by older adults that were performing near their attentional capacity. Taken together, this study contributes to existing literature by providing further evidence of age-related changes in control of eye movements, which is important given the association between force steadiness and impaired hand function in the older adult population (Kornatz et al., 2005; Marmon et al., 2011). Future work should continue to examine why some older adults used an altered visual strategy during force-matching with a dual task and whether this could serve as an indicator of motor and/or cognitive impairments in older adults and patient populations.

Force-Matching Task and Amount of Visual Feedback. Findings support the well-established idea that the ability to produce steady finger forces declines with age (Keenan & Massey, 2012; Laidlaw et al., 2000; Tracy et al., 2007), evidenced by increased force fluctuations in older compared to young adults (Fig. 4.2). Force fluctuations < 4 Hz were greater during the higher compared to lower gain condition (Fig. 4.2A) supporting previous work demonstrating increased force fluctuations with greater amounts of visual information (Baweja et al., 2012; Tracy et al., 2007). There was no difference in 4 - 12 Hz force fluctuations for the higher compared to lower gain condition (Fig. 4.2B), which is consistent with findings from a similar pinch force-matching task with higher and lower gain compensatory feedback (Keenan et al., 2017). Because force fluctuations < 4 Hz represent fluctuations due to voluntary corrections, mainly due to visual feedback processing (Freund & Hefter, 1993), and force fluctuations 4 - 12

Hz represent fluctuations due to tremor/afferent feedback loops (Laine et al., 2014), it seems reasonable that changes in visual feedback had a greater effect on 0 - 4 Hz force fluctuations than 4 - 12 Hz force fluctuations. However, another study found increased 4 - 12 Hz force fluctuations during an ankle dorsiflexion force-matching task with increased visual feedback. These authors suggest that changes in visual feedback influence nearly the entire frequency spectrum of force fluctuations (Laine et al., 2014). Contradictory findings are likely due to methodological considerations, including increased visual feedback by a factor of 10 in the study by Laine et al. (1994) versus 5 in the current study and that by Keenan et al. (2017). Future work could continue to examine the effect of altered visual feedback on frequency ranges of force fluctuations that reflect different sources of input onto the motor neuron pool.

Results from eye movement recordings in the current study support several of the findings by Keenan et al. (2017). For example, all young and older adults used a similar visual strategy during both the lower and higher gain conditions. Specifically, participants gazed near the target line and used a series of saccades and fixations that moved in the left to right direction, likely to track the leading edge of the force trace as it moved across the screen. Additionally, young adults made more saccades than older adults (Fig. 4.3A), which could reflect an optimal visual strategy used by young adults to maintain gaze near the leading edge of the force trace (Keenan et al., 2017), and there were no age-related differences in vertical eye fluctuations (Fig. 4.3B).

The current study adds to previous findings by demonstrating the effect of visual feedback amount on vertical eye fluctuations and saccade number. Vertical eye fluctuations were greater during the higher compared to lower gain condition (Fig. 4.3B). The higher gain condition led to greater vertical displacement of the participant’s force trace for a given force output than the lower gain condition. Though there was no relationship between vertical eye fluctuations and force fluctuations, greater vertical eye fluctuations during the higher gain condition likely reflects a visual strategy used to visually track the force trace as it fluctuated in magnitude about the target line. Altered gain of visual feedback had no effect on vertical eye fluctuations during a force-matching task with compensatory feedback in a previous study (Keenan et al., 2017). Given that gain of visual feedback was altered to the same degree in the current and aforementioned study (i.e. ordinate scale of 0 N to 2 N and 0.8 to 1.2 N for lower and higher gain, respectively), results indicate that altered gain of visual feedback has a differential effect on eye movements depending on the type of visual feedback (i.e. pursuit versus compensatory). Participants made fewer saccades during the higher compared to lower gain condition (Fig. 4.3A) and this could be due to 1) greater vertical eye fluctuations or 2) changes in visual strategy. First, greater vertical eye fluctuations during the higher compared to lower gain condition could lead to greater saccade amplitude. This could result in decreased number of saccades given that duration of the force-matching task was consistent across participants. Second, findings could reflect an altered visual strategy when presented with greater amounts of visual information and subsequent increase in task demands.

Regardless, older adults may rely less on visual feedback of force for force-matching tasks than originally anticipated. Saccades are used to orient the area of highest visual acuity with important areas of the visual field and fixations are used to obtain task-relevant visual information (Henderson, 2003). Greater saccade number likely reflects an optimal visual strategy used to maintain gaze near the leading edge of the force trace and to obtain more up to date visual feedback of force output (Keenan et al., 2017). A lack of relationship between increased saccade number, and therefore more up to date visual feedback of force output, and decreased force fluctuations during the higher gain condition in older adults indicates that older adults rely less on visual feedback to produce steady forces during visually force-matching tasks than originally anticipated. Instead, older adults may have relied more on proprioceptive and cutaneous feedback to produce steady finger forces, which is consistent with conclusions from a previous study demonstrating no difference in force-fluctuations between young and older adults when there was no visual feedback of force (Tracy et al., 2007).

Visual-Tracking Task. During the force-matching task, vertical displacement of the force trace corresponded to magnitude of force output. Therefore, greater fluctuations in force output in older compared to young adults (Fig. 4.2) led to increased fluctuations in the force trace and thus, different visual feedback between age groups. Because visual feedback can influence eye movements, fewer saccades in young compared to older adults in the previous (Fig. 6 in Keenan et al. (2017)) and current study (Fig. 4.3A) could have been due to age-related changes in the control of eye movements or differences in visual feedback between age groups. When visually tracking force traces with higher and lower variability to imitate force traces produced by older and young adults, respectively, older adults made fewer saccades than young (Fig. 4.6A); however, changes in variability of the force trace had no effect on eye movements in young and older adults. Therefore, decreased saccade number in younger compared to older adults during the pinch force-matching task may be primarily due to age-related changes in the control of eye movements and not differences in visual feedback between age groups. Furthermore, there were no differences in vertical eye fluctuations between age groups (Fig. 4.6B). Thus, when asked to gaze at the force trace, older adults were able to increase vertical eye movements to a similar degree to young adults when visually-tracking the force trace with greater vertical displacement, supporting the idea that the ability to make vertical eye movements does not decrease with age (Pratt et al., 2006).

Attention. Visuospatial attention is impaired in older compared to young adults (Huddleston et al., 2014); however, there were no differences in performance during the force-matching task with vs. without simultaneously performing the visuospatial task. The visuospatial task was selected based on that used previously and is thought to be of moderate difficulty (Peterson & Keenan, 2018). A lack of differences in performance could be due to the difficulty level of the visuospatial task though this same task was difficult enough to influence performance on other motor tasks and the differential effect of dual tasks on motor performance is not novel (Peterson & Keenan, 2018). Nonetheless, though all young participants and 14 older adults used a similar visual strategy during the force-matching task with vs. without the visuospatial task (Fig. 4.4A), seven older adults used an altered visual strategy where, despite using a series of saccades and fixations, eye movements did not stay near the target line nor did they exclusively travel in the left to right direction with the force trace (Fig. 4.4B). Performance on the force-matching task was no different between these groups, nor were saccade number or vertical eye fluctuations. However, the median of < 4 Hz force fluctuations in those that used the altered strategy was almost two times higher than that in older adults who made saccades exclusively left to right (.14 N vs. .08 N, respectively) and a lack of significance could have been due to the relatively small number of participants who used this alternate strategy, which made statistical comparisons difficult (VanVoorhis & Morgan, 2007).

Although it is not clear why the subset of older adults adopted this alternate visual strategy, older adults who used this altered visual strategy in the current study had poorer performance on measures of attention compared to older adults who did not, specifically the

TMT B (Completion Time), Telephone Search While Counting (Dual Task Decrement Score), and Visual Elevator (Timing Score) (Fig. 4.5). Telephone Search While Counting is an assessment of divided attention and sustained attention. Visual Elevator is an assessment of attentional switching (Robertson et al., 1994). TMT B is different from TMT A, of which there were no differences between the two groups of older adults, due to an attentional switching component (Sanchez-Cubillo et al., 2009). Therefore, results indicate that older adults who used this unique strategy demonstrated declines in divided attention, sustained attention, and attentional switching, and this could have been a maladaptive visual strategy used by some older adults that were performing near their attentional capacity. Future studies could continue to examine why some older adults used this altered visual strategy, for example, by reevaluating these older adults after an extended period of time (e.g., 10 years) or in patient populations to determine whether it this visual strategy could be an early indicator of motor and/or cognitive impairment.

Limitations. The following limitations should be considered. Increased visual feedback amount during steadiness tasks are associated with age-related changes in neuromuscular control, including impaired modulation of agonist muscle activity (Baweja et al., 2012; Chen et al., 2017; Kennedy & Christou, 2011) and increased motor unit discharge variability (Chen et al., 2017). Though the main objective of the current study was to examine eye movements during a force-matching task, simultaneous electromyography-eye tracking recordings could further our understanding of how visual information is incorporated into hand motor control and the ability to produce steady forces. The current study assessed how altered gain of visual feedback influenced eye movements in young and older adults. A variety of approaches can be used to manipulate visual feedback including removal of visual feedback (Tracy et al., 2007), altered frequency of visual feedback (Slifkin et al., 2000), or increasing gain by a greater factor than that used here (Ofori et al., 2010). Though this study aimed to determine the effect of gain and replicate previous work to examine the mechanisms underlying performance, these could influence eye movements and performance differently in young and older adults. The current study aimed to examine healthy older adults and exclusion criteria was selected to minimize effect of other age-related changes on eye movements and force-matching performance. However, this resulted in a relatively high functioning sample of older adults. Future studies could use other patient populations who demonstrate impaired steadiness and less healthy older adults.

Conclusion. The current study revealed age-related changes in the control of eye movements during a visually guided force-matching task. Older adults used fewer saccades than young adults and with higher compared to lower gain visual feedback. A lack of relationship between saccade number and increased force fluctuations during the higher gain condition may indicate a reliance on proprioception and cutaneous feedback in older adults, based on the idea that a greater number of saccades allowed for more up to date visual information of force feedback. Findings also revealed a unique visual strategy used by a subset of older adults while performing the force-matching task with a dual task, and these older adults also demonstrated declines in attentional processes. Taken together, this study provides more detailed information regarding the use of visual information to control steady finger forces in older adults. Future work could continue to investigate the relationship between visual strategy, attentional processes, and hand motor control in the older adult population.

Chapter 5: Summary and Conclusions

Objectives

Visual information is critical for many goal-directed movements. Changes in visual information have been associated with hand motor decrements in older adults (Tracy et al., 2007). However, eye movements and the relationship with impaired hand motor control in older adults are relatively understudied. Therefore, this dissertation examined age-related changes in eye movements and the association with hand motor impairments in older adults. Given that attention plays a role in motor performance and declines with age, the relationship between attentional processes and performance on hand motor tasks was also assessed.

Summary of Methods

A total of 51 participants, 23 young (age, 25.3 ± 4.4 years; range, 20 – 38 years; 12 females) and 28 older (age, 72.6 ± 6.6 years; range, 65 – 90 years; 13 female) adults, were recruited for this study. Eye movements were recorded during common hand tasks including pegboard tests of manual dexterity (Chapter 1), a touchscreen Archimedes spiral tracing task (Chapter 2), and a visually guided pinch force-matching task (Chapter 3). Measures of the subsystems of attention (i.e. Test of Everyday Attention and TMT) and a dual task were performed.

General Conclusions

Consistent with the central hypothesis, current findings demonstrate age-related changes in eye movements, attention, and the association with hand motor impairments in older adults. First, results provide evidence that the ability to control gaze location decreases with age, including a greater number of corrective saccades during the pegboard tests and greater saccade amplitude variability during spiral tracing in older compared to young adults. Second, young adults may use optimal visual strategies during hand motor tasks when compared to older adults. For example, young adults spent a greater percentage of time gazing at the pegboard holes during the pegboard tests and used more saccades during spiral tracing and force-matching tasks than older adults, which would allow greater amounts of visual feedback during the more complex part of the pegboard task and more up to date visual feedback of performance during the spiral tracing and force-matching tasks. Third, these age-related changes in the control of eye movements may be associated with hand motor impairments in older adults, evidenced by an association between increased saccade amplitude and increased spiral tracing error in older adults. Fourth, the relationship between decreased pegboard performance and TMT B completion time in older adults demonstrates the association between declines in attentional processes and manual dexterity impairments in older adults.

Visual information is important for many goal-directed hand motor tasks. However, the degree to which visual information and attention contribute to successful motor performance likely varies across tasks. The visual strategy used by older adults during the pegboard test indicates a reliance on visual information for both peg placement and peg pickup, which was not the case for all young adults. Therefore, and consistent with previous research (Coats & Wann, 2011), visual information may be critical for pegboard test performance in older adults. Second, both young and older adults used a visual strategy that would allow for less up to date visual information when tracing parts of the spiral where vision was likely more obstructed by the hand; however, this had no effect on spiral tracing performance. Given the predictable nature of the spiral template, older adults may depend more on anticipatory feedforward than visual information when compared to the pegboard test. A lack of relationship between increased saccade number and decreased force fluctuations in older adults indicates that older adults may rely less on visual feedback to produce steady forces during force-matching tasks. Instead, older adults may also rely on proprioceptive and cutaneous feedback to produce steady finger forces, which is consistent with conclusions from a previous study demonstrating no difference in force-fluctuations between young and older adults when there was no visual feedback of force (Tracy et al., 2007). Further, performance on the pegboard test, but not the spiral tracing task and force-matching task, was not impaired when allocating attentional resources across multiple tasks. Therefore, the attentional demands of the pegboard test may be greater than those of the spiral tracing task and force-matching task.

Together, these findings have important implications regarding hand motor impairments in older adults. First, tasks that are under more anticipatory feedforward control or sensitive to age-related changes in proprioception and cutaneous feedback, such as the Archimedes spiral tracing task and force-matching task, respectively, may be less sensitive to age-related changes in visuomotor processing and attentional processes than the pegboard test of manual dexterity. Second, given the age-related differences in visual strategy and idea that visual information is critical for the pegboard tests of manual dexterity, visual cueing may decrease age-related performance impairments in older adults. Future studies could examine whether cueing older adults to gaze at and attend to the pegboard holes for a greater percentage of time improves pegboard performance and manual dexterity in older adults.

In summary, this dissertation contributes novel findings regarding age-associated impairments in hand motor control as they relate to eye movements and attention, offering more insight into decreased hand function and loss of independence in the rapidly increasing older adult population. Additionally, results inform future studies assessing the relatively under-explored role of eye movements in hand motor control in older adults and patient populations. Future work should continue to seek a more comprehensive understanding of how eye movements and attention contribute to movement impairments with advancing age, with the goal of informing interventions targeting impaired hand function. For example, studies could examine why some older adults used an altered visual strategy during force-matching with a dual task and whether this could serve as an indicator of motor and/or cognitive impairments in older adults and patient populations.

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APPENDICES

APPENDIX A: Review of Literature

Aging and Changes in Motor Control

Overview

The United States population is aging rapidly. An older adult is typically defined as an individual 65 years of age and older, and according to the 2017 National Populations Projections one in five people in the United States will fit this description by 2030 (Vespa et al., 2018). This same year represents an important turning point, in that the older adult population is projected to exceed that of children for the first time in United States history (Vespa et al., 2018). Furthermore, the number of individuals 85 years of age and older is expected to almost double from 2016 to 2035 from 6.4 million to 11.8 million, respectively, and this population will grow by approximately 200% by 2060 (Vespa et al., 2018). This trend is not unique to the United States, and the demographics of other industrialized countries such as Japan, Germany and France are aging also (Anderson & Hussey, 2000). The rapidly growing aging population has important implications in terms of a greater need for health-related services and long-term care. For example, according to data from the most recent National Nursing Home Survey, 88% of nursing home residents are 65 years of age and older and the number of nursing home residence grew by approximately 40% from 1974 to 2004 (Jones et al., 2009).

Advancing age is associated with declines in motor control and function. Decreased mobility, dexterity, and strength, for example, contribute to loss of function in older adults. In one study, 72% of older adults reported at least one functional limitation (Lubitz et al., 2003) and many older adults face difficulties on instrumental activities of daily living such as cooking, housework, shopping, and use of transportation (Seidel et al., 2009). Such difficulties are associated with loss of independence in this population. Specifically, it has been estimated that 43% of those 65 years of age and older will spend some time in a nursing home (Kemper & Murtaugh, 1991), and motor impairments are strongly related to increased likelihood of admittance to a long-term care facility (Ostwald et al., 1989; Williams et al., 1982). Functional impairments have significant financial consequences and are strongly associated with an increase in health care expenditure. In fact, average yearly health care expenditure rose from $4,600 to $45,400 for older adults with no functional limitation and those living in a long-term care setting, respectively (Lubitz et al., 2003). Thus, with the increasing older adult population and significant motor impairments with advancing age, an understanding of age-related changes in motor control is important to inform interventions targeting decreased function and loss of independence in this population.

Hand Motor Control

Impairments in hand function increase with advancing age and significantly contribute to a loss of independence in older adults (Carmeli et al., 2003; Ostwald et al., 1989). Hand function is relatively stable until age 65, after which it progressively declines even in healthy older adults (Carmeli et al., 2003; Shiffman, 1992), including impaired performance on tasks of manual dexterity, grasping, spiral tracing, and object manipulation, among others (Cole, 1991; Desrosiers et al., 1999; Heintz & Keenan, 2018). Decreased hand function in older adults is associated with difficulties performing activities of daily living and other common tasks, such as taking money from a wallet, pouring milk (Shiffman, 1992), opening a jar, placing a stamp on an envelope, opening a pill container, shuffling cards (Desrosiers et al., 1999), and tying a knot (Seidel et al., 2009). These age-related impairments in hand function negatively impact functional independence and decrease the ability to live independently (Falconer et al., 1991;

Ostwald et al., 1989; Williams et al., 1982). For example, performance on a timed manual dexterity task was found to be one of the main determinants of admittance to nursing homes in older adults (Ostwald et al., 1989) and manual ability was found to be the best marker of dependency when compared to a plethora of other factors (e.g., socioeconomic status, education, medications, and medical problems) (Williams et al., 1982).

Measures of Hand Motor Control

Numerous measures sensitive to age-related impairments in hand function are commonly used to examine hand motor control in older adults. For example, declines in object manipulation and manual dexterity in older adults are commonly assessed using tasks such as card turning (Cole, 1991), coin handling (Desrosiers et al., 1999), the Box and Block test of gross manual dexterity (Desrosiers et al., 1999), and pegboard tests (Desrosiers et al., 1999; Marmon et al., 2011; Ranganathan et al., 2001). For example, one study found that older adults took approximately 62% longer than young adults to turn over a series of five playing cards (Cole, 1991), and a longitudinal study found a 13% reduction in performance on the Box and Block test after a three year span in older adults (Desrosiers et al., 1999). Declines in performance in older versus young adults have also been demonstrated on tasks of writing (Contreras-Vidal et al., 1997), Archimedes spiral tracing (Heintz & Keenan, 2018; Marmon et al., 2011), and tapping (Bowden & McNulty, 2013; Martin et al., 2015). For example, when asked to tap a surface as quickly as possible, tapping frequency decreased by 34% for older versus younger adults (Bowden & McNulty, 2013). Steadiness tasks are also common in the literature, including both force-matching tasks and position-matching tasks, and decreased steadiness has been well-documented with advancing age (Kornatz et al., 2005; Marmon et al., 2011). Three of these well-established measures selected for use in the present investigation are discussed in more detail below, including 1) Archimedes spiral tracing 2) pegboard tests, and 3) steadiness tasks.

Archimedes spiral tracing is a common, clinical assessment used in various populations such as essential tremor (Deuschl et al., 2015), Parkinson's disease (Westin et al., 2010), and multiple sclerosis (Heenan et al., 2014), among others. Spiral tracing has also been reported as a sensitive measure of age-associated changes in manual dexterity for a wide range of age groups, including both older adults (Heintz & Keenan, 2018; Hoogendam et al., 2014; Marmon et al., 2011) and young children (Louis et al., 2011). To complete the task, individuals are asked to trace an Archimedes spiral template as accurately as possible. The traditional, clinical assessment is completed using a pen/pencil on paper and subjectively scored by a rater based on visual inspection using a numerical scale, such as the 0 – 10 scale created by Bain et al. (1993) or the 0 – 4 Tremor Rating Scale (Fahn et al., 1988). However, scoring using these methods is subjective, may not quantify small changes in performance, and has low to moderate reliability (Bain et al., 1993; Miralles et al., 2006).

More recently, studies have implemented the spiral tracing assessment on digitizing tablets and other technologies, which can provide a more objective, sensitive measure of motor performance (Heintz & Keenan, 2018; Hoogendam et al., 2014; Marmon et al., 2011; Westin et al., 2010). For example, a recent study implemented the Archimedes spiral tracing task on a touchscreen in young and older adults, and performance was quantified by calculating tracing error to the millimeter through automated code (Heintz & Keenan, 2018). The studies implementing Archimedes spiral tracing on digitizing technologies in older adults have quantified age-related impairments using various performance metrics. Specifically, studies have quantified decreased performance in older adults as increased total deviation from the spiral template, number of times crossing the spiral template line, total movement time, increased length of participant trace (Hoogendam et al., 2014), standard deviation (SD) from the spiral template to spiral trace (Marmon et al., 2011), and RMS error from spiral template to spiral trace (Heintz & Keenan, 2018).

Pegboard tests measure fine manual dexterity by asking individuals to place small pegs into holes on a pegboard. While numerous types of pegboard tests exist (e.g., Purdue Pegboard, Grooved Pegboard, 25-Hole Pegboard, 9-Hole Pegboard) two commonly used, standardized versions are the 9-Hole Pegboard and the Grooved Pegboard (Reuben et al., 2013; Wang et al., 2011). 9-Hole Pegboard requires participants to place and remove nine plastic pegs, one at a time and as quickly as possible, into nine holes on the pegboard. This test is recommended by the NIH due to its reliability, validity, and ease of implementation for all age groups (Reuben et al., 2013; Wang et al., 2011). Grooved Pegboard consists of 25 grooved metal pegs and a pegboard with 25 grooved holes oriented in different directions. Participants are asked to place the pegs into the holes one at a time and as quickly as possible by rotating the pegs so that the groove matches the orientation of the holes. This reliable and valid measure of manual dexterity presents with greater cognitive and visual perceptual task demands compared to 9-Hole Pegboard, is related to cognitive functioning in older adults (Ashendorf et al., 2009), and may be more challenging for older adults than 9-Hole Pegboard (Reuben et al., 2013; Wang et al., 2011). Normative data for ages 3 – 85 has been published for performance on both 9-Hole Pegboard and Grooved Pegboard and using the right and left hand (Reuben et al., 2013; Wang et al., 2011).

Age-related performance impairments on pegboard tests are well documented in the literature. Performance on 9-Hole Pegboard and Grooved Pegboard begins to decline around age 45 (Wang et al., 2011), with studies reporting an approximately 33% (Marmon et al., 2011) to

47% (Bowden & McNulty, 2013) increase in completion time for older versus young adults. Numerous studies have examined potential factors underlying these age-related impairments. Decreased performance on pegboard tests has been related to declines in attentional prowess (Keenan et al., 2017), tactile sensation (Bowden & McNulty, 2013), hand strength (Marmon et al., 2011), force steadiness (Hamilton et al., 2017; Marmon et al., 2011), and cognition (Hamilton et al., 2017) in older adults.

Steadiness-tasks ask participants to match a target force or position as accurately as possible. Older adults are less steady than young adults during force-matching tasks and position-matching tasks, especially for relatively low-level forces, lengthening contractions, and when interacting with low-friction surfaces (Keenan & Massey, 2012; Kornatz et al., 2005; Laidlaw et al., 2000; Marmon et al., 2011; Pereira et al., 2018; Tracy et al., 2005). Moreover, older adults have trouble producing precisely directed finger forces, with more misdirected forces than young adults on various finger pressing and object manipulation tasks (Cole et al., 2010; Kapur et al., 2010; Keenan & Massey, 2012).

Decreased steadiness with age reflects age-related neuromuscular changes (Kornatz et al., 2005; Laidlaw et al., 2000; Tracy et al., 2005) and is associated with impairments on more functional measures (Kornatz et al., 2005; Marmon et al., 2011). For example, one study found that decreased force steadiness in older adults during submaximal index finger abduction and precision pinch tasks was associated with impaired performance on spiral tracing, Grooved Pegboard, scissors cutting, and the game Operation (Marmon et al., 2011). A second study found a relationship between decreased force steadiness and impaired performance on Purdue Pegboard in older adults. Specifically, increased steadiness on an index finger position matching task post a training intervention explained 56% of the improvements in performance on the pegboard test (Kornatz et al., 2005).

Neuromuscular Changes and Impaired Hand Motor Control

Purposeful, well-controlled hand movements are the result of complex processes that take place throughout the neuromuscular system, including both the central and peripheral nervous systems. To voluntarily activate a muscle and produce movement, motor areas of the brain (e.g. primary motor cortex) innervate motor neurons by sending signals through spinal cord pathways that synapse onto motor neuron cell bodies located in the ventral horn of the spinal cord. Upon activation from higher centers, the motor neuron sends efferent action potentials from the cell body, along its axon, and to a group of muscle fibers located in the target muscle. The motor unit is the motor neuron and all muscle fibers it innervates, and the fundamental component of the neuromuscular system. Degree of muscle activation is controlled by the nervous system through recruitment of motor units and/or increased motor unit firing rate (McNulty et al., 2000). Additionally, sensory information is important for the control of movement and influences motor unit activation. Sensory receptors are activated by a given stimulus, which then send afferent signals to motor neurons or through spinal pathways to higher centers for conscious processing. Both efferent signals from higher centers and afferent signals from peripheral sensory feedback innervate the motor unit either directly or through spinal interneurons to activate the muscle and control movements. Thus, as termed by Charles Sherrington, the motor unit is the “final common pathway” of muscle activation (Burke, 2007).

Widespread age-related changes occur throughout the neuromuscular system leading to impaired hand function in older adults. The motor unit is one such location, where degenerative processes contribute to decreased strength, steadiness, and a general slowing of movements with age. Motor neuron degeneration and associated loss of motor units begins around age 60 in healthy older adults (Campbell et al., 1973; Sica et al., 1974), with one study reporting less than half of the original motor units remaining by the 9th decade of life in small muscles of the hand (Sica et al., 1974). This age-related loss of motor units has been suggested to be the most important factor contributing to muscle wasting and loss of strength in healthy older adults (Campbell et al., 1973; Sica et al., 1974), which is associated with impaired hand function in this population (Marmon et al., 2011; Martin et al., 2015). For example, maximal voluntary contraction force on handgrip tests declines by approximately 30% in older versus young adults (Marmon et al., 2011; Ranganathan et al., 2001), and decreased handgrip strength has been shown to be associated with impaired performance on tasks of aiming, tapping (Martin et al., 2015), tracing, and grooved pegboard (Marmon et al., 2011).

A restructuring of the peripheral nervous system follows motor neuron degeneration, such that de-innervated muscle fibers are re-innervated by surviving motor neurons. A resultant increase in innervation ratio (i.e. the number of muscle fibers per motor neuron) and motor unit size may contribute to decreased force steadiness in older adults (Galganski et al., 1993; Stalberg & Fawcett, 1982). Furthermore, demyelination of the motor axon leads to decreased action potential conduction velocity in older adults (Campbell et al., 1973). This along with preferential atrophy of Type II muscle fibers (Lexell et al., 1988) contributes to a general slowing of movements. Increased movement time has been demonstrated on a wide range of timed tasks related to hand function, for example those requiring fine manual dexterity, gross manual dexterity, and special accuracy (Desrosiers et al., 1999; Parikh & Cole, 2012; Ranganathan et al., 2001). A slowing in movement initiation time also has significant implications for hand function tasks, especially those requiring fast responses and quick adjustments.

Decreased steadiness with age is also the result of other age-related neuromuscular changes. First, motor unit discharge rate variability increases with age. Studies using electromyography (EMG) to investigate age-related changes in muscle activity report greater variability in motor unit discharge rate in older adults, which is associated with decreased force steadiness, especially at relatively low-force contractions (Enoka et al., 2003; Kornatz et al., 2005; Laidlaw et al., 2000; Tracy et al., 2005). Second, it has been suggested that increased common drive in older versus young adults contributes to decreased steadiness (Semmler et al., 2003). Common drive refers to the common modulation of motor unit discharge rates by oscillatory inputs from higher centers (e.g., motor cortex, brainstem) onto motor neurons. Increased common drive, quantified by increased levels of coherence, has been associated with decreased steadiness in young adults and those with tremor. However, fewer studies have assessed common drive in older versus young adults and results from those studies are conflicting. Specifically, some studies report that increased coherence (Semmler et al., 2003) or decreased ability to modulate common drive (Semmler et al., 2006) is associated with decreased force steadiness in older adults. However, other studies have reported no difference in coherence between young versus older adults despite decreased force steadiness in older adults (Keenan et al., 2012). Conflicting results may be due to methodological considerations such as electrode placement (Keenan et al., 2012) and signal processing techniques (Farina et al., 2004), and further research is necessary to determine whether common drive plays a role in age-related impairments in force steadiness and tasks of hand function.

Coordination is essential for successful movement output, however the ability to control a number of movement segments or body parts in a well-timed manner decreases with age. For example, a study by Contreras-Vidal et al. (1997) found decreased coordination of wrist and hand movements along with decreased straightness, smoothness, and movement speed on handwriting tasks in older versus younger adults. The authors suggest these impairments to be the result of improperly timed initiation and disproportionate activation of independent muscles controlling the wrist and hand (Contreras-Vidal et al., 1997). Moreover, tasks with greater coordination requirements preferentially impair performance in older adults. For example, decreased smoothness and larger endpoint errors where found on a pointing task requiring multi-joint versus single-joint coordination in older but not young adults (Seidler et al., 2002). Other studies suggest that impaired coordination leads to a reduced ability to produce well-directed finger forces and moments in older adults (Cole 2006; Kapur et al., 2010; Keenan & Massey, 2012; Olafsdottir et al., 2007; Parikh & Cole, 2012), thus impairing performance on hand tasks requiring precisely directed finger forces. For example, Kapur et al. (2010) report greater misdirected forces in older versus young adults on a multi-finger force-matching task and suggest this to be reflective of impaired coordination of intrinsic and extrinsic hand muscles, including less flexible coordination patterns and more elemental versus synergistic control (Kapur et al., 2010). Other studies have made similar conclusions based on tasks of finger force-matching (Cole, 2006), finger moment-matching (Olafsdottir et al., 2007), gripping and lifting, and placing a key into a slot (Parikh & Cole, 2012).

Age-related declines in somatosensation, including cutaneous sensation and proprioception, are also associated with impaired hand motor function in older adults. Sense of touch plays a critical role in hand motor control, and decrements in cutaneous sensation are well-documented in older adults, including decreased touch sensitivity, touch discrimination, and haptic object recognition (Bowden & McNulty, 2013; Cole, 1991; Desrosiers et al., 1999; Dunn et al., 2013; Stevens & Patterson, 1995; Thornbury & Mistretta, 1981). For example, Bowden and McNulty (2013) report that a 73% decrease in touch sensitivity of the palm and fingertips in older versus young adults accounts for approximately 36% of impairments in performance on hand motor tasks (i.e. Grooved Pegboard, finger tapping). Decreased tactile sensibility may also impair finger force control on hand tasks such as grasping (Cole, 1991) and finger pressing (Keenan & Massey, 2012), which is essential for controlled manipulation of small objects during many everyday tasks (Carmeli et al., 2003). Proprioception provides feedback of limb position and also decreases with age. Loss of proprioception leads to significant motor impairments (Gordon et al., 1995) and age-related declines in proprioception have been demonstrated in the upper extremity and hands in older adults (Adamo et al., 2007; Ferrell et al., 1992). Specifically, detection of finger (Ferrell et al., 1992) and elbow joint position (Adamo et al., 2007) decrease with age and have been suggested to impair the ability to perform many functional tasks in the older adult population.

Vision is also important for hand motor control. Increasing age is associated with numerous impairments in visual input, including decreased visual acuity and contrast sensitivity, which are related to impaired motor performance in this population (Lord et al., 1991). Furthermore, the integration of visual information into motor control is critical for many goal-directed tasks. However, while much literature exists demonstrating the effect of sensory detection impairments on declines in hand motor function, relatively less is known as to how age-related changes in the processing of sensory information impacts hand motor control. Accordingly, further investigation of age-related changes in sensorimotor processing is necessary to understand hand motor control and hand function in older adults.

Visuomotor Processing and Motor Control

Overview

Vision is inextricably linked to movement. For the simple, everyday tasks to the exceedingly complex, the visual system gathers relevant information and integrates it into motor control and output (Foulsham, 2015; Hayhoe & Ballard, 2005; Henderson, 2003). To make a cup of tea, for example, an individual uses vision to locate an object, direct movements of the limb and hand towards the object, and provide feedback of their actions (Land et al., 1999). The visual and motor systems are so intricately linked, in fact, it has been suggested that the two systems be studied together in order to gain a complete understanding of motor control and output (Goodale, 1998).

The translation of visual information into motor output occurs through a series of steps referred to as visuomotor processing. Specifically, the eyes move to orient the center of gaze, or fovea, to a target (Henderson, 2003). Visual stimuli are detected by photoreceptors of the retina (i.e. rods and cons) before being sent to the central nervous system, wherein this information is transformed into motor commands through complex cortical and subcortical pathways. Interestingly, signals from photoreceptors begin the transformation into motor commands the moment they enter the central nervous system (Goodale, 1998). Ultimately, these commands travel to motor units by way of spinal pathways to influence muscle activity and motor output.

Visuomotor processing plays a critical role in dexterous manipulation and common tasks of hand function (Hayhoe, 2000; Hayhoe & Ballard, 2005; Johansson et al., 2001; Land & Hayhoe, 2001). Furthermore, changes in visuomotor processing take place with age and contribute to impaired motor control and function in older adults. For example, studies provide evidence for delays in visuomotor processing (Young & Hollands, 2012) and changes the use of visual information for the performance of hand motor tasks in older versus young adults (Ofori et al., 2010; Sosnoff & Newell, 2006). Despite these findings, however, age-related changes in visuomotor processing and mechanisms associated with decreased hand function in older adults remain unclear. Thus, further work is necessary to elucidate visuomotor contributions to impaired hand motor function in this population.

Visual Feedback and Information Processing

Visual information plays a central role in visually guided movement and age-related changes in the use of visual information are associated with impaired hand function in older adults. Decreased amounts of visual information, for example, have been shown to preferentially impair older adult's performance on tasks of manual dexterity, grasping, and tracing (Coats & Wann, 2011; Heintz & Keenan, 2018). On a simplified pegboard task, for example, older adults were just as good as young adults when vision of the hand was provided, but performance was worse in older adults when vision of the hand was removed (Coats & Wann, 2011). A second study found age-related impairments on Archimedes spiral tracing on a touchscreen when provided less visual information of the spiral template (Heintz & Keenan, 2018). Specifically, performance was worse for older versus young adults when tracing with the index finger that blocked more of the template from view. However, there were no differences in performance for young versus older adults when tracing with a relatively smaller stylus that blocked less of the template from view. Together, these studies provide evidence that older adults are more dependent on visual information to guide arm and hand movements and support the idea that the amount of visual information plays a critical role in age-related impairments in hand function.

Additional studies have used aiming paradigms to examine age-related changes in the use of visual information during arm and hand movements. To do so, investigators divide the aiming movement into two phases based on the use of sensory information, including 1) an initial, ballistic phase and 2) a secondary, corrective phase. The initial phase is assumed to be under preprogrammed, feedforward control and is less dependent on sensory information. The secondary, corrective phase is assumed to be under closed-loop, feedback control and is more dependent on sensory information (Seidler-Dobrin & Stelmach, 1998). Thus, visual information is processed and integrated into movement control during the secondary phase. Studies have shown that while there are no differences in time spent in the initial phase between young and older adults, older adults make more movement corrections and spend a greater amount of time than young adults in the secondary phase (Haaland et al., 1993; Pohl et al., 1996; Pratt et al., 1994; Seidler-Dobrin & Stelmach, 1998). This suggests that older adults have a greater reliance on visual feedback for movement control compared to young adults, which may contribute to movement slowing with advancing age. These results have also been interpreted as evidence for age-related impairments in visual information processing. Specifically, increased time in the second phase may be the result of decreased sensory information processing speed in older adults (Seidler-Dobrin & Stelmach, 1998). Thus, a greater reliance on visual information and impairments in visual information processing may be related to impaired hand function in older adults.

Numerous studies have also used finger steadiness tasks with different amounts of visual feedback to determine age-associated changes in visual information processing. Specifically, participants are typically asked to maintain a target force or position while viewing live feedback of their performance. Type and amount of visual feedback is manipulated and changes in steadiness are quantified. Amount of visual feedback has been manipulated by changing the visual feedback gain (Baweja et al., 2012; Chen et al., 2017; Keenan et al., 2017; Kennedy & Christou, 2011; Sosnoff & Newell, 2006) or by using a vision versus no vision protocol (Critchley et al., 2014; Vaillancourt et al., 2002). Gain of visual feedback is typically manipulated by changing the ordinate scale (Keenan et al., 2017; Schmied et al., 2000; Sosnoff & Newell, 2006), while some authors suggest that changing the visual angle may be a more appropriate way to manipulate visual gain (Baweja et al., 2012; Kennedy & Christou, 2011; Vaillancourt et al., 2006). Furthermore, the type of visual feedback has been manipulated using pursuit or compensatory feedback (Ofori et al., 2010). During pursuit feedback, the force trace moves from left to right with time and vertically with force. This provides more preview information about the required force trajectory over time and more feedforward or anticipatory display. Conversely, during compensatory feedback the force trace appears as a horizontal line that fluctuates vertically with force and provides no information about the upcoming force trajectory, therefore necessitating a greater reliance on feedback versus feedforward control. Thus, pursuit feedback is suggested to provide greater amounts of visual information (Ofori et al., 2010).

Results from these studies provide further support for age-associated impairments in visual information processing. Specifically, greater amounts of visual feedback are associated with age-related impairments on finger steadiness tasks. Studies using vision versus no vision conditions found that force steadiness decreased in older versus young adults when visual feedback was provided, but older adults were just as steady as young adults when visual feedback was not provided (Critchley et al., 2014). Other studies have shown decreased force steadiness in older versus young adults with increased visual gain during index finger abduction (Sosnoff & Newell, 2006) and pinch tasks (Keenan et al., 2017). Type of feedback is also associated with decreased steadiness in older adults. Specifically, studies demonstrate greater impairments in force steadiness for older versus young adults during pursuit versus compensatory feedback (Ofori et al., 2010). Because pursuit feedback presents a greater amount of visual information compared to compensatory feedback (Ofori et al., 2010), these findings support the notion that steadiness is impaired in older adults with greater amounts of visual feedback. Furthermore, they suggest that older adults have a decreased capacity to process greater amounts of visual information and support the notion that visual information processing is impaired in older adults.

Interestingly, changes in visual feedback during steadiness tasks are also associated with age-related changes in neuromuscular control, which likely contribute to decreased steadiness with greater amounts of visual feedback. Studies examining decreased steadiness with age report changes in muscle activity with altered visual feedback in older adults (Baweja et al., 2012; Chen et al., 2017; Kennedy & Christou, 2011). For example, studies have shown impaired modulation of agonist muscle activity with greater gain of visual feedback during a finger force-matching task (Kennedy & Christou, 2011) and a finger position matching task (Baweja et al., 2012). Furthermore, motor unit discharge variability increased in older but not young adults with greater gain of visual feedback during a finger abduction task (Chen et al., 2017).

Eye Tracking and Eye Movements

In normal vision, visuomotor processing involves stereotypical eye movement patterns. Though often unaware of such movements, our eyes jump from place to place as we obtain information from world around us. This rapid relocation of gaze occurs up to three times per second and is known as saccadic eye movement (Foulsham, 2015; Land, 1999). Saccades are used to orient the area of highest visual acuity (i.e. fovea) with important stimuli in the visual field and are generated by three pairs of muscles surrounding the eye (Foulsham, 2015; Henderson, 2003; Land, 1999). Between periods of saccadic movement, the eyes are relatively stationary as they fixate on certain elements of interest. Fixations are used to obtain important information by creating a relatively still image of the element on the fovea and occur as a result of neural saccade suppression (Land, 1999). Smooth pursuit eye movements are slow, continuous movements of the eye used to track moving objects in the visual field. These eye movements are used to maintain visual acuity that would otherwise be compromised by movement of the object (Krauzlis, 2004).

While normal gaze control is characterized by periods of quick saccades, stable fixations, and smooth pursuit, these eye movements are not random. Instead, eye movements are actively controlled as the individual seeks out task-relevant information and saccades and fixations are incorporated in a goal-oriented way (Henderson, 2003). For example, during motor tasks saccades are aimed in the direction of relevant points as the visual system obtains important visual information for the desired motor output (Foulsham, 2015; Tatler et al., 2011).

Eye movements were first captured over 50 years ago by a Russian scientist named Alfred Yarbus, whose seminal work used a mirror system affixed to the eye to track gaze location (Henderson, 2003; Yarbus, 1967). Since that time, numerous advancements have led the development of more sophisticated eye-tracking devices that are commonly used to today. These devices can be used to determine various measures associated with eye movement behavior such as gaze location, number of saccades, and fixation duration, and have been used during various hand tasks including those of object manipulation (Johansson et al., 2001), force-matching (Huddleston et al., 2013; Keenan et al., 2017), making a cup of tea (Land et al., 1999), and making a sandwich (Hayhoe, 2000). Examining eye movement behavior is important because it reflects the moment-to-moment input into the visual system and provide important insight into human behavior (Foulsham, 2015). Furthermore, these measures shed light on the interaction between the visual and motor systems, which allows for a more complete understanding of motor control and output.

Eye-tracking technology has been used to examine age-related changes in eye movement behavior. The ability to perform rapid eye movements is relatively resistant to the normal effects of aging (Pratt et al., 2006; Rand & Stelmach, 2011). However, eye movement patterns do change with age and may be related to impaired motor control (Coats et al., 2016; Keenan et al., 2017; Rand & Stelmach, 2011). For example, one study used eye-tracking technology to assess age-related changes in eye movements during a submaximal pinch force-matching task with altered visual feedback. During pursuit feedback, all participants followed the force trace left to right using saccades. However, the number of saccades was less in older versus young adults, and this was related to increased force fluctuations. Furthermore, older adults used a unique eye movement strategy during compensatory feedback, which resulted in 2.5 times greater force fluctuations. The number of older adults exhibiting this unique strategy was altered by amount of visual feedback. Specifically, only four older adults made saccades during a lower gain condition while 9 older adults made saccades during a higher gain condition (Keenan et al., 2017). Thus, changes in amount of visual feedback during Force-matching tasks may lead to changes in eye movements in older adults.

A limited number of studies have also examined age-related impairments in the concurrent control of eye and hand movements during manual aiming tasks (Coats et al., 2016; Rand & Stelmach, 2011). Gaze anchoring is a prominent eye movement behavior used during aiming movements, where gaze is fixed to a reaching location until the hand arrives (Neggers & Bekkering, 2000; Neggers & Bekkering, 2001; Rand & Stelmach, 2010). Studies calculate dwell time as a measure related to gaze anchoring that can be used to examine the coordination of eye and hand movements, quantified as the time from when the hand stops moving at a target location to the time the eyes begin to saccade to the next target location. Older adults have shown longer dwell times than young adults during complex manual aiming tasks. A study using aiming tasks, for example, assessed the effect of task complexity on eye and hand coordination by manipulating the number of targets. Results show that eye-movements were similar for young and older adults during the least complex task. However, older versus young adults took a longer time to shift their gaze from one target to the next during the complex task (Rand & Stelmach, 2011). A second study found similar age-related changes in older adults when picking up and placing small objects onto designated target locations (Coats et al., 2016). Authors suggest that these eye movement behaviors may be the result of age-related impairments in the consecutive control of eye and hand movements. First, older adults may have difficulty inhibiting one action and initiation another across the oculomotor and limb motor systems. Second, they may reflect a strategy to simplify visuomotor control during complex movements that involves concurrent control of two motor systems (Rand & Stelmach, 2011).

Attention, Eye Movements, and Hand Motor Control

The systems of attention are intimately linked to the motor systems and are thought to play a critical role in the performance of motor tasks (Posner & Petersen, 1990). For example, attention facilitates the selection of relevant information from extraneous information and is associated with the ability to perceive, distinguish, remember, and react more quickly (James, 1890; Posner & Petersen, 1990). During visually guided movements, specifically, attention to visual stimuli (i.e. visual attention) facilitates the selection of visual information critical to the task at hand. Furthermore, attention is allocated to the movement being performed and the upcoming movement (i.e. motor attention), which aids in the control of movement and selection of motor commands. Both visual attention and motor attention have been shown to impact performance on a variety of tasks, and the ability to select relevant visual information and initiate appropriate motor commands are important for the successful completion of visually guided movements. For example, on visual tracking tasks, performance improves when visual attention is focused either directly surrounding an object (Lovejoy et al., 2009) or directly in front of an object (Khan et al., 2010), and performance has been shown to improve when attention is focused on the movement being performed (Tipper et al., 1992) and upcoming movements (Snyder et al., 1997). Further, previous work illustrates age-related changes in the allocation of attentional resources between the visual and motor attentional systems. Challenging either visual or motor attentional system and no effect on the other in young adults indicating separate attentional resources for these two systems in this age group (Huddleston et al., 2013). Conversely, evidence suggests a shared attentional resource for visual and motor attention in older adults and allocation of attentional resources to one of these systems could negatively impact the other (Huddleston et al., 2014).

Attentional processes are also related to eye movement behaviors. Evidence suggests that eye movements and attention share common neural structures and a strong link exists between the orientation of attention and eye movements (Chelazzi et al., 1995; Posner, 1980; Hunt et al., 2019). For example, studies have shown that attention is oriented to the location of an upcoming saccade just prior to the actual eye movement (Chelazzi et al., 1995; Hunt et al., 2019), and similar relationships exist between eye movements and attention during the performance of motor tasks (Posner, 1980). Moreover, gaze location is thought to provide insight into attentional processes and has served as an indirect measure of overt shifts in attention in numerous studies (Doshi & Trivedi, 2012; Henderson, 2003; Schmidt et al., 2018). For example, a study assessing shifts in attention with painful stimuli recorded eye movement behaviors, including saccades and durations of fixations, to determine changes in focus of attention (Schmidt et al., 2018). Thus, an understanding of the relationships between eye movements, attention, and motor performance may reveal important information about motor control and behavior.

Though the word “attention” is commonly used to refer to a singular mechanism or resource, authors suggest that this is not necessarily the case (Pashler, 1994; Posner & Petersen, 1990). According to the multi-system model of attention by Posner and Petersen (1990), the system of attention can be divided into multiple subsystems associated with different, but interrelated functions, critical to everyday tasks (Robertson et al., 1994). This is consistent with findings demonstrating a network of multiple anatomical areas involved in attention (Hunt et al., 2019) each associated with performing different functions of attention (Posner & Petersen, 1990). Examples of subsystems of attention include selective attention, sustained attention, attentional switching, and divided attention. Visual selective attention is associated with difficulty ignoring irrelevant information or selecting visual stimuli from complex environments and is often used during movements when interacting with the environment, such as reaching to pick up a singular glass among others (Tipper et al., 1992). Impairments in visual selective attention may be associated with difficulties filling out forms, finding an item on a store shelf, or looking up transportation timetables (Robertson et al., 1994). Attentional switching is related to the ability to change the focus of attention from one item to another. Sustained attention is related to the ability to attend to stimuli for an extended period of time, and impairments in sustained attention may be associated with loss of concentration while reading or watching television, or while holding a conversation. Divided attention is related to the ability to attend to multiple stimuli at once and is the related to the ability handle complex, everyday demands such as holding a conversation with multiple people, or writing notes while speaking to someone on the telephone (Robertson et al., 1994).

Attention has also been defined by Woollacott and Shumway-Cook (2002) as the, "information processing capacity of an individual" (p. 1), which is commonly assessed using dual-task paradigms. This definition assumes that individuals possess a finite mental capacity for information processing. When two tasks are performed concurrently, this resource must be split between the two, leaving less mental capacity for each individual task. Subsequently, performance on one or both tasks is often impaired (Woollacott & Shumway-Cook, 2002). In dual-task paradigms, participants are typically required to perform two tasks at once to determine how performance of one task interferes with the other (Pashler, 1994). Such paradigms are similar to everyday task demands (e.g., having a conversation while driving, walking across the street while listening to music), and have been suggested to be one of the best experimental paradigms to examine how parts of systems function together (Pashler, 1994)

Age-related declines in motor performance with the addition of dual tasks are well documented with advancing age. A majority of these studies have targeted falls risk in older adults by incorporating different types of dual tasks during measures of balance, posture, and locomotion (Hausdorff et al., 2008; Peterson & Keenan, 2018; Schrodt et al., 2004). For example, nonspatial dual tasks such as counting backwards have led to changes in gait (Hausdorff et al., 2008; Schrodt et al., 2004) and functional mobility (Shumway-Cook et al., 2000) in older adults. Visuospatial tasks and have been associated with age-related impairments in stepping response time (Peterson & Keenan, 2018), postural stability (Shumway-Cook et al., 1997), and dorsiflexion force steadiness (Peterson & Keenan, 2018). Interestingly, studies comparing the effect of dual task type have shown that visuospatial tasks impair motor performance on tasks of balance and posture to a greater degree in older adults than nonspatial tasks (Menant et al., 2014; Sturnieks et al., 2008).

Despite these findings, few studies have assessed the relationship between age-related changes in attention and impairments on hand motor tasks in older adults. For example, while numerous studies have demonstrated a greater effect of dual tasks on performance of balance, posture, and gaits tasks in older versus young adults, few studies have used dual task paradigms during hand motor tasks. For example, one study found that age-related impairments during a precision grip force matching task increased in older versus young adults when performing a backwards counting task, and that older adults who made an error during the task showed greater variability than those who did not (Voelcker-Rehage et al., 2006). Another study found a relationship between decreased performance on the Trail Making Test and impaired force steadiness during a cognitively challenging elbow flexor task in older adults (Pereira et al., 2018). Specifically, increased time to complete both Part A and Part B of the Trail Making Test was related to decreased force steadiness in older adults, but only when the elbow flexor task was accompanied by counting backwards by 13's. Furthermore, one study has demonstrated a relationship between a visual attention test and hand motor control in older adults (Keenan et al., 2017). Specifically, decreased performance on a cued saccade attention test was associated with decreased performance on the Grooved Pegboard and decreased force steadiness on a pinch force-matching task in older adults (Keenan et al., 2017). While these studies suggest that declines in attention may be related to hand motor impairments in older adults, a comprehensive understanding regarding the role of age-related changes in hand motor control is not clear, and further work is necessary to determine how attentional processes contribute to hand motor impairments in older adults.

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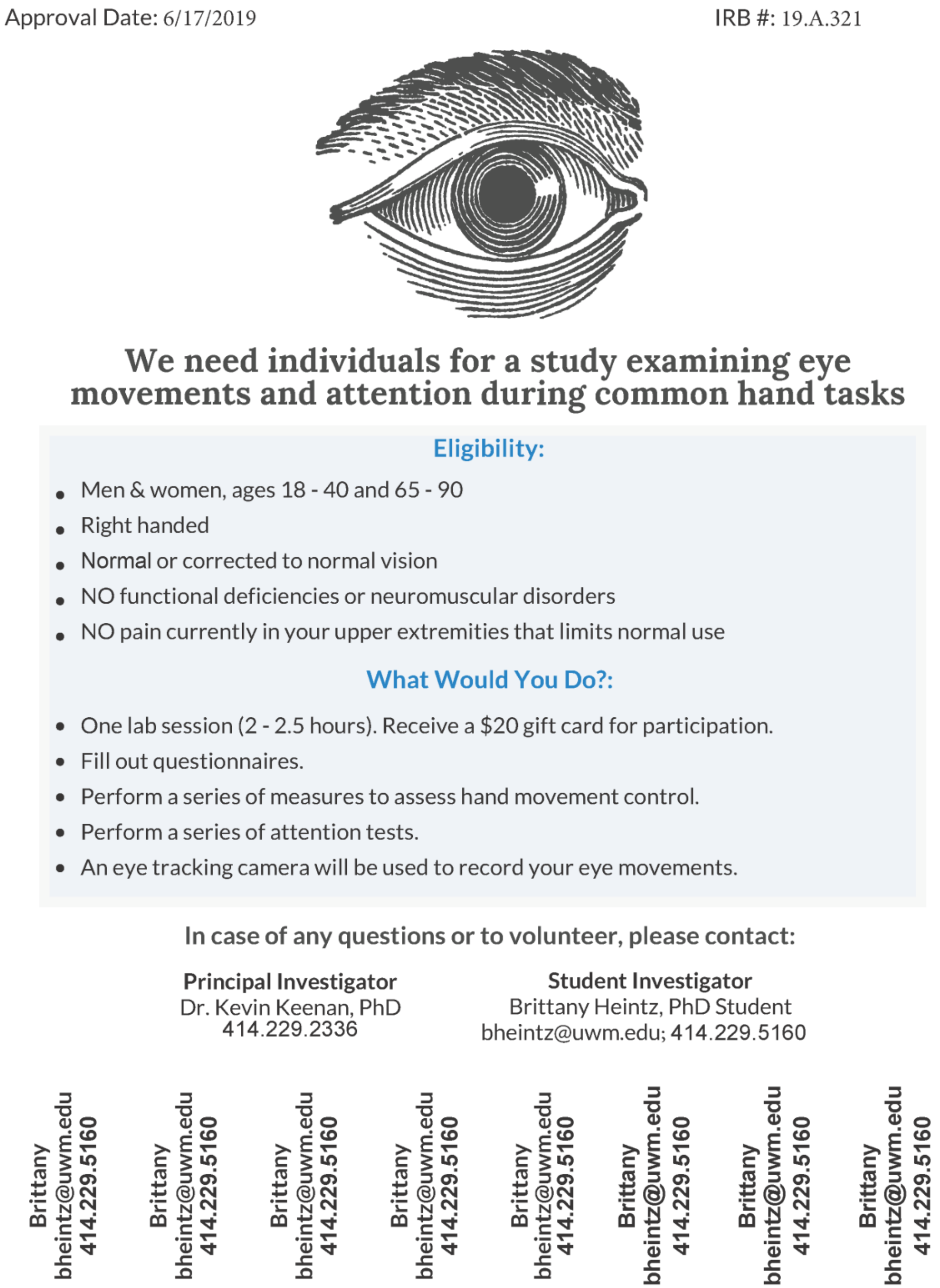
APPENDIX B: Recruitment Flyer



Approval Date: 6/17/2019 IRB #: 19.A.321

We need individuals for a study examining eye movements and attention during common hand tasks

Eligibility:

- Men & women, ages 18 - 40 and 65 - 90
- Right handed
- Normal or corrected to normal vision
- NO functional deficiencies or neuromuscular disorders
- NO pain currently in your upper extremities that limits normal use

What Would You Do?:

- One lab session (2 - 2.5 hours). Receive a $20 gift card for participation.
- Fill out questionnaires.
- Perform a series of measures to assess hand movement control.
- Perform a series of attention tests.
- An eye tracking camera will be used to record your eye movements.

In case of any questions or to volunteer, please contact:

Principal Investigator
Dr. Kevin Keenan, PhD
414.229.2336

Student Investigator
Brittany Heintz, PhD Student
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APPENDIX C: Prescreening Questionnaire

Prescreening Questionnaire

The following questions will help determine if you meet the criteria for inclusion into this study. It is important that you answer each question accurately. Please consider your response to each of the four questions below.

☐ Yes ☐ No Are you between the ages of 18 and 40 years or 65 and 90 years?

☐ Yes ☐ No Are you right-handed?

☐ Yes ☐ No Do you have normal or corrected to normal vision?

☐ Yes ☐ No Are you able to sit comfortably for extended periods of time?

If you answered 'no' to any of the above four questions, unfortunately you do not qualify for this study. If you answered 'yes' to all of the above questions, you may qualify for the study. Please answer the next four questions:

☐ Yes ☐ No Do you have functional deficiencies that involve your arms or hands? Specifically, do you have difficulties performing everyday tasks such as reaching for an object, opening a jar, picking up objects, etc.?

☐ Yes ☐ No Do you have pain in your arms, wrists, or hands that limits normal movement?

☐ Yes ☐ No Have you previously been diagnosed with any disorder(s) that may limit normal movement of your hands?

☐ Yes ☐ No Are you currently taking any medications that may alter your nervous system function, muscular function, or vision?

If you answered 'no' to the last four questions and 'yes' to the first four questions, you qualify for this study. Please contact us to set up an appointment.

If you were unable to answer these questions accordingly, you will not be able to participate. We do thank you for your willingness to be part of your study.

Comments/Notes:

APPENDIX D: Vision Screen

Participant Vision Screening

Researcher will ask the participants the following questions…

1) Do you use corrective eyewear (either glasses or contact lenses)?

Yes_______ No_______

2) If yes to question #1, are you currently wearing your corrective eyewear?

Yes_______ No_______

Hand participant the vision test card.

Have her hold the test card 14 inches from her eyes. If the participant uses corrective eyewear, make sure she is wearing them for the test.

Check each eye separately, first the right and then the left. Keep both eyes open and cover one eye with the palm of the hand.

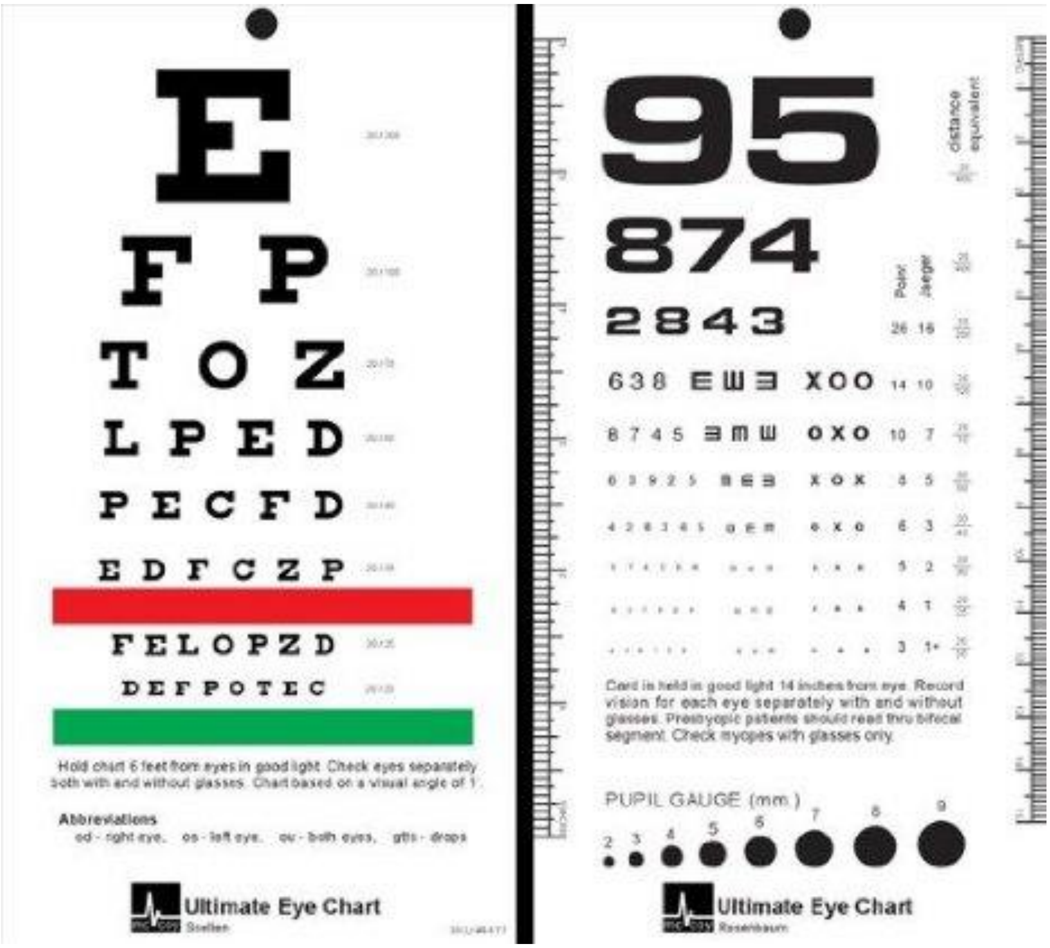
Read the card, beginning with the top line and moving down the lines until it is too difficult to read the letters.

Record the number of the smallest line (below) that the participant read correctly.

Repeat with the other eye

RIGHT EYE ________________

LEFT EYE _________________



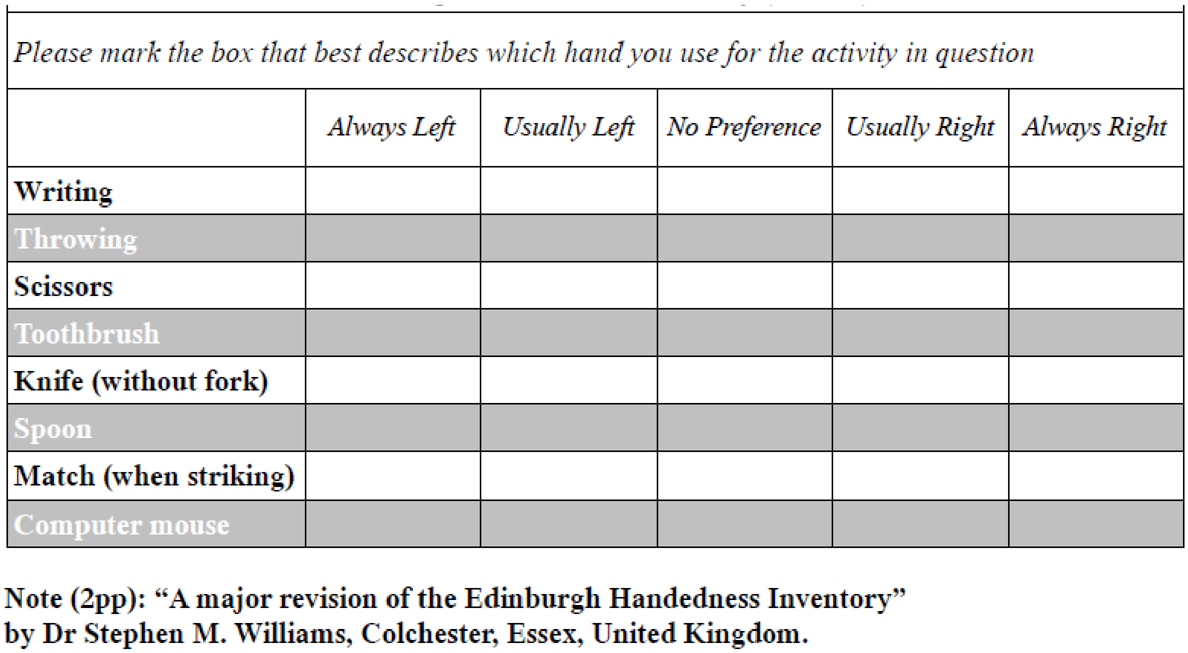
Hold chart 6 feet from eyes in good light. Check eyes separately both with and without glasses. Chart based on a visual angle of 1'.

Abbreviations

od - right eye, os - left eye, ou - both eyes, gtts - drops

Card is held in good light 14 inches from eye. Record vision for each eye separately with and without glasses. Presbyopic patients should read thru bifocal segment. Check myopes with glasses only.

APPENDIX E: Edinburgh Handedness Inventory



Please mark the box that best describes which hand you use for the activity in question

	Always Left	*Usually Left*	*No Preference*	*Usually Right*	*Always Right*
Writing					
Throwing					
Scissors					
Toothbrush					
Knife (without fork)					
Spoon					
Match (when striking)					
Computer mouse					

Note (2pp): “A major revision of the Edinburgh Handedness Inventory”
by Dr Stephen M. Williams, Colchester, Essex, United Kingdom.

Calculation of Laterality Quotient (LQ):
(To be completed by research staff)

1. Total points for left (x 2 for always) = ____________
2. Total points for right (x 2 for always) = ____________
3. Right – Left = ____________
4. Right + Left = ____________
5. #3 divided by #4 x 100 LQ = ____________

APPENDIX F: Health and Activity Inventory

Health and Activity Inventory

DATE OF BIRTH: ________ AGE: _______

GENDER: ____ M ____ F HEIGHT: ______ WEIGHT: _______

Have you been told, or are you aware that you have any of these medical conditions?

			Notes
Circulation Problems	___yes	___no	
Diabetes	___yes	___no	
Excessive Callous Formation	___yes	___no	
High Blood Pressure	___yes	___no	
Peripheral Neuropathy	___yes	___no	
Carpal Tunnel Syndrome	___yes	___no	
Broken Bones (arm or hand)	___yes	___no	
Surgery (specify)	___yes	___no	
Are you currently taking medication If “yes” please specify:	___yes	___no	

Any other medical conditions that may influence your hand use or manual dexterity?

Yes_____ No______ Choose not to answer______

If yes, please specify:

Have you been told, or are you aware of any medical conditions that may influence your vision?

Yes_____ No______ Choose not to answer______

If yes, please specify:

Have you been told, or are you aware of any conditions that may cause deficits in attention?

Yes_____ No______ Choose not to answer______

If yes, please specify:

Do you have significant hearing loss?

Yes_____ No______ Choose not to answer______

If yes, do you wear hearing aids or other assistive devices? Please specify:

Do you have an allergy to adhesives (e.g., those used in Band-Aids)?

Yes_____ No______ Choose not to answer______

Please list all athletic activities you have participated in during the last five years and indicate the skill level and duration of these activities (i.e. recreational, collegiate, master's level, etc.)**:**

Activity	Skill Level	Duration

Please list all manual dexterity skills (e.g., playing the piano or guitar, knitting, video gaming with a joystick, etc) that you have participated in during your life (and you had to perform the skill for over 6 months) and indicate the skill level and duration of these activities:

Activity	Skill Level	Duration

APPENDIX G: Lifestyle Questionnaire

Lifestyle Questionnaire

Please fill out the survey below to the best of your ability.

1. Do you own an electronic device with a touchscreen?
(e.g. iPad, iPhone)

☐ Yes ☐ No

If answered yes, approximately how many hours do you use the device per day? _____

2. Have you ever used an electronic device with a touchscreen?

☐ Yes ☐ No

3. How comfortable do you feel using a touchscreen device? Please select your comfort level by placing an X at the appropriate point along the line below.

Not at all Comfortable

Extremely Comfortable

4. What is the highest level of education you have completed, in years?

Number of years _____ Choose not to answer _____

5. Have you consumed caffeine within the last 12 hours?

☐ Yes ☐ No

If answered yes, approximately how many ounces (1 cup = 8 ounces)? _____

CURRICULUM VITAE

FORMAL EDUCATION

Ph.D. Candidate, Kinesiology (Current)
University of Wisconsin - Milwaukee, Milwaukee, WI
Dissertation: *Eye movements and attention are related to impaired hand motor control in older adults*
Graduate Certificate in Applied Gerontology
Advisor: Dr. Kevin G. Keenan

Studies in Doctor of Physical Therapy (May 2013-August 2015)
University of Texas Southwestern Medical Center, Dallas, TX

M.S., Kinesiology (Graduated May 2013)
University of Wisconsin - Milwaukee, Milwaukee, WI
Primary Concentration: Neuromechanics, Secondary Concentration: Exercise Physiology
Advisor: Dr. Kevin G. Keenan

B.S., Kinesiology (Graduated August 2011)
University of Wisconsin - Milwaukee, Milwaukee, WI
Primary Concentration: Pre-Physical Therapy
Certificate of Nutrition

RESEARCH PUBLICATIONS

Heintz BD & Keenan KG (2018). Spiral tracing on a touchscreen is influenced by age, hand, implement, and friction. PloS one, 13(2), e0191309.

PROFESSIONAL PRESENTATIONS

Heintz BD, Huddleston WE, Keenan KG (2019). Eye movements during a touchscreen Archimedes spiral tracing task. Annual Meeting of the Society for Neuroscience, Chicago, IL, October 19-23.

Joshi M, **Heintz B,** Negro F, Keenan K (2018). Association between manual dexterity and motor unit activity. Annual Meeting of the Society for Neuroscience, San Diego, CA, November 3-7.

Keenan KG, **Heintz BD**, Peterson J, Morgan A, Fueger C, Rodriguez K, Cobb S (2018). EMG activity and function of abductor halluces during fatigue and postural sway. International Society of Electrophysiology and Kinesiology, Dublin, Ireland, June 30-July 2.

Heintz, BD & Keenan, KG (2018). Performance on the Box and Block Test is reduced by low surface friction in older but not young adults. University of Wisconsin - Milwaukee Health Sciences Research Symposium, Milwaukee, WI, May 4.

Heintz, BD (2018). A vision of independence in the elderly. Three Minute Thesis (3MT) Competition, University of Wisconsin - Milwaukee, Milwaukee, WI, April 4.

Heintz BD & Keenan KG (2017). Tracing on a touchscreen: Influence of age, implement, hand, and friction. American Society of Biomechanics Annual Meeting, Boulder, CO, August 8-11.

Joshi M, **Heintz B**, Keenan K (2017). Force fluctuations during hybrid force/motion tasks in young and older adults. American Society of Biomechanics Annual Meeting, Boulder, CO, August 8-11.

Cobb SC, **Heintz BD**, Keenan KG, Cho C (2016). Lower extremity neuromuscular factors associated with postural stability in older adults. Gait and Clinical Movement Analysis Society Annual Conference, The University of Tennessee, Memphis, TN, May 17-20.

Heintz BD & Keenan KG (2013). Motor performance in older adults while using mobile computing devices. University of Wisconsin - Milwaukee Health Sciences Research Symposium, Milwaukee, WI, May 3. (Awarded first place podium presenter).

Heintz B, Coenen SK, Walters TJ, Strath SJ, Swartz AM, & Keenan KG (2012). Choice step response times: Step direction, age, and predictor variables. Annual Meeting of the Society for Neuroscience, New Orleans, LA, 184.21, October 13-17.

Heintz BD, Coenen SK, Walters TJ, Strath SJ, Swartz AM, Keenan KG (2012). Choice step response times are slower while stepping backwards compared with forwards in young and older adults. National Strength and Conditioning Association Wisconsin State Chapter Symposium, April 14.

GRANT SUBMISSIONS

Heintz BD & Keenan KG (2018). A vision of independence in the elderly. Grants-in-Aid of Research Program, Sigma Xi Scientific Research Honor Society, Research Triangle Park, NC.

Heintz BD & Keenan KG (2017-2018). Neuromuscular mechanisms underlying motor performance in older adults. College of Health Sciences Student Research Grant Award, College of Health Sciences, University of Wisconsin - Milwaukee, Milwaukee, WI ($2,000) [Funded May 2017].

Heintz BD & Keenan KG (2017). Assessment of free-living muscle activity and neuromuscular function in older adults with knee osteoarthritis. Grants-in-Aid of Research Program, Sigma Xi Scientific Research Honor Society, Research Triangle Park, NC.

Heintz BD & Keenan KG (2016). Neuromuscular mechanisms underlying motor performance on mobile devices in older adults, College of Health Sciences Student Research Grant Award, College of Health Sciences, University of Wisconsin - Milwaukee, Milwaukee, WI.

Heintz BD & Keenan KG (2012-2013). Choice step response times: Step direction, age, and predictor variables. College of Health Sciences Student Research Grant Award, College of Health Sciences, University of Wisconsin - Milwaukee, Milwaukee, WI ($1,000) [Funded March 2012].

ADDITIONAL RESEARCH-RELATED ACTIVITES

Manuscript Reviewer: Ergonomics (2017), Graphics Interface (2019).

HONORS AND AWARDS

Graduate Student Excellence Fellowship (GSEF), Graduate School, University of Wisconsin - Milwaukee, Milwaukee, WI (Academic Year 2018-2019).

Chancellor's Graduate Student Award, Department of Kinesiology, College of Health Sciences, University of Wisconsin - Milwaukee, Milwaukee, WI (Fall Semester 2016, Academic Year 2017-2018, Academic Year 2018-2019).

Giorgio Sanna Memorial Scholarship, College of Health Sciences, University of Wisconsin - Milwaukee, Milwaukee, WI (May 2018).

3MT Finalist, A vision of independence in the elderly. Three Minute Thesis (3MT) Competition, University of Wisconsin – Milwaukee. One of 14 finalists out of 85 competitors (April 2018).

Graduate Student Travel Award, Graduate School, University of Wisconsin - Milwaukee (May 2017, November 2018).

Kinesiology Association Student Travel Grant, Department of Kinesiology, College of Health Sciences, University of Wisconsin - Milwaukee (April 2017, November 2018)

Helen Bader Age & Community Scholarship, Center for Aging and Translational Research, University of Wisconsin - Milwaukee (Academic Year 2016-2017, Fall Semester 2017)

Dean's Scholarship Award, Doctor of Physical Therapy Program, University of Texas Southwestern Medical Center, Dallas, TX (Academic Years 2013-2015).

First Place Student Research Podium Presenter, College of Health Sciences Research Symposium, University of Wisconsin - Milwaukee (May 2013).

Graduate Teaching Assistantship, Department of Kinesiology, College of Health Sciences, University of Wisconsin - Milwaukee.

- Fall Semester 2019
- Summer Semester 2018
- Summer Semester 2017
- Spring Semester 2017
- Summer Semester 2016
- Spring Semester 2016
- Spring Semester 2013
- Fall Semester 2012

Graduate Research Assistantship, Neuromechanics Laboratory, Department of Kinesiology, College of Health Sciences, University of Wisconsin - Milwaukee.

- Fall Semester 2013
- Spring Semester 2012
- Fall Semester 2011

Support for Undergraduate Research Fellow (SURF), Undergraduate Research Opportunities Program, Office of Undergraduate Research, University of Wisconsin - Milwaukee.

- Summer Semester 2011

TEACHING

2019

a. **Fall 2019**
   Undergraduate Course: KIN360
   Graduate Teaching Assistant
   Motor Development Across the Lifespan (3 credits)

   Undergraduate Course: CHS100
   Teaching Fellow
   New Student Seminar in Health Professions (1 credit)

b. **Summer 2019**
   Undergraduate Course: KIN400 Online
   Lecturer
   Ethics and Values in the Health and Fitness Professions (3 credits)

c. **Spring 2019**

Undergraduate Course: KIN400 Online
Lecturer
Ethics and Values in the Health and Fitness Professions (3 credits)

2018

a. **Fall 2018**
Undergraduate Course: KIN400 Face to Face
Lecturer
Ethics and Values in the Health and Fitness Professions (3 credits)

Undergraduate Course: CHS100
Teaching Fellow
New Student Seminar in Health Professions (1 credit)

b. **Summer 2018**
Undergraduate Course: KIN400 Online
Lecturer
Ethics and Values in the Health and Fitness Professions (3 credits)

Undergraduate Course: KIN461
Graduate Teaching Assistant
Principles of Motor Learning (3 credits)

c. **Spring 2018**
Undergraduate Course: KIN400 Online
Lecturer
Ethics and Values in the Health and Fitness Professions (3 credits)

Undergraduate Course: KIN245
Lecturer, Co-Taught
Client Diversity in Health Sciences: An Interdisciplinary Perspective (3 credits)

2017

a. **Fall 2017**
Undergraduate Course: KIN400 Face to Face
Lecturer
Ethics and Values in the Health and Fitness Professions (3 credits)

b. **Summer 2017**
Undergraduate Course: KIN400 Online
Lecturer
Ethics and Values in the Health and Fitness Professions (3 credits)

Undergraduate Course: KIN461
Graduate Teaching Assistant
Principles of Motor Learning (3 credits)

c. **Spring 2017**
Undergraduate Course: KIN245
Lecturer, Co-Taught
Client Diversity in Health Sciences: An Interdisciplinary Perspective (3 credits)

Undergraduate Course: KIN461
Graduate Teaching Assistant
Principles of Motor Learning (3 credits)

2016

a. **Fall 2016**
   Undergraduate Course: KIN400 Online
   Lecturer
   Ethics and Values in the Health and Fitness Professions (3 credits)

   Undergraduate Course: KIN460
   Lecturer
   Motor Development Across the Lifespan (3 credits)

b. **Summer 2016**
   Undergraduate Course: KIN325
   Graduate Teaching Assistant
   Anatomical Kinesiology (3 credits)

c. **Spring 2016**
   Undergraduate Course: KIN325
   Graduate Teaching Assistant
   Anatomical Kinesiology (3 credits)

2013

a. **Spring 2013**
   Undergraduate Course: KIN461
   Graduate Teaching Assistant
   Principles of Motor Learning (3 credits)

2012

a. **Fall 2012**
   Undergraduate Course: KIN460
   Graduate Teaching Assistant
   Motor Development Across the Lifespan (3 credits)

   Graduate Course: KIN561
   Graduate Teaching Assistant
   Neuromechanics of Goal-Directed Voluntary Movement (3 credits)

Guest Lecturer

a. University of Wisconsin - Milwaukee
   HMS200: Introduction to Kinesiology
   Topic: Introduction to Motor Behavior and Perspectives in Research
   Fall 2017

b. University of Wisconsin - Milwaukee
   HMS325: Anatomical Kinesiology
   Topic: An Introduction to Lower Extremity Muscles
   Summer 2016

c. University of Wisconsin - Milwaukee
   HMS325: Anatomical Kinesiology
   Topic: An Introduction to Lower Extremity Muscles
   Spring 2016

SERVICE

Master of Ceremony, Health Sciences Research Symposium, College of Health Sciences, University of Wisconsin - Milwaukee (May 2019).

Health Sciences Research Symposium Planning Committee, College of Health Sciences, University of Wisconsin - Milwaukee (December 2018-May 2019).

Graduate Student Representative, Graduate School Open House, Department of Kinesiology, College of Health Sciences, University of Wisconsin - Milwaukee (November 2018, November 2017).

Graduate Student Representative, Kinesiology Graduate Orientation, Department of Kinesiology, College of Health Sciences, University of Wisconsin - Milwaukee (August 2018).

Poster Judge, Undergraduate Research Symposium, Office of Undergraduate Research, University of Wisconsin – Milwaukee (April 2018, April 2017).

Graduate Student Representative, MS Kinesiology Program Review Site Visit, Department of Kinesiology, University of Wisconsin - Milwaukee (October 2016).

Camp John Marc Camp Counselor, Muscular Dystrophy Association, Dallas, TX (June 2014).

Hearts in Motion Physical Therapy Volunteer, Kevin O'Halloran Rehabilitation Center, Zacapa, Guatemala (August 2012).

Study of Global Healthcare Abroad, Miqlat Orphanage, Malawi, Africa, through the University of Wisconsin - Milwaukee Nursing Program (January 2010).

PROFESSIONAL & STUDENT ORGANIZATIONS

Society for Neuroscience, Student Member	October 2018 - Present
The Scientific Research Society, Student Member	January 2017 - Present
Graduate Human Movement Sciences Association, Treasurer	November 2016 - August 2020
National Strength and Conditioning Association, Student Member	March 2015 - March 2016
American Physical Therapy Association, Student Member	May 2013 - August 2015
Graduate Human Movement Sciences Association, Treasurer	September 2012 - May 2013
Mortar Board Senior National Honor Society, Social Committee	February 2010 - May 2013
Undergraduate Human Movement Sciences Association, Member	January 2011 - June 2011

CERTIFICATIONS & SPECIAL TRAINING

Graduate Certificate of Aging, Center for Aging and Translational Research, University of Wisconsin - Milwaukee, Milwaukee, WI (August 2017).

An Introduction to Evidence-Based STEM Undergraduate Teaching, The Center for The Integration of Research, Teaching & Learning Network, Boston University, Boston, MA (May 2017).

Undergraduate Certificate of Nutrition, College of Health Sciences, University of Wisconsin - Milwaukee, Milwaukee, WI (August 2011).