Control of Goal-Directed Reaches in Older Adults

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Statement of Contribution

I, Sajida Khanafer, was primarily responsible for the research program and experimental design for all of the included experiments, with input and oversight by my thesis committee consisting of Dr. Heidi Sveistrup and Dr. Erin K. Cressman (Co-Supervisors), Dr. Martin Bilodeau, and Dr. Yves Lajoie. Participant recruitment, experimental set-up, including data collection, data analysis, data reduction, and statistical analysis were primarily completed by myself, Sajida Khanafer. Manuscript preparation for all chapters was completed by me, Sajida Khanafer, with input and/or editorial contributions from Dr. Heidi Sveistrup, Dr. Erin K. Cressman, and Dr. Mindy Levin.

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Glossary of Terms

UL	Upper limb
RT	Reaction time
MT	Movement time
CNS	Central nervous system
SHT	Stationary Hand task
RHT	Reaching Hand Task
PV	Peak velocity
pTAPV	Proportional time after peak velocity
PC	Path curvature
DFs	Degrees of freedom
Min	Minutes
G	Gain
cm	Centimeter
A/P	Anterior-posterior
D	Difference in final hand position
2D	Two dimensions
R	Ratio
Dn	Normalized difference in final hand position
RM ANOVA	Repeated measures analysis of variance
S	seconds
EMG	Electromyography
r^2	Coefficient of determination
ms	Milliseconds
mm/s	Millimetre per second
m/s	Meter per second
vs.	Versus
V+S	Visual + Somatosensory feedback
V	Visual feedback only
AE	Angular error

PVAE	Angular error at peak velocity
CCW	Counter-clockwise
CW	Clockwise
Fig	Figure
B1	Block 1
B2	Block 2
B3	Block 3
B4	Block 4
SD	Standard deviation

Abstract of the Dissertation

Healthy individuals can adjust their movements when changes arise to the body or the environment. Advanced age is associated with central and peripheral changes that may negatively impact one's ability to adapt motor performance, such us upper-limb (UL) reaching movements. In this thesis, we conducted four studies to address the impact of aging on coordination and adaptation of goal-directed reaches.

In the first experiment, we examined compensatory arm–trunk coordination in older adults during trunk-assisted reaching, using two motor tasks : 1) the Stationary Hand Task (SHT) in which older and young participants were asked to maintain a fixed hand position while flexing forward at the trunk, and 2) the Reaching Hand Task (RHT) in which participants were instructed to reach to a within-arm's reach target while simultaneously flexing forward at the trunk (Raptis et al., 2007; Sibindi et al., 2013). We found that in SHT, young and older participants were able to maintain a stable hand position and compensate for trunk movement by appropriate angular rotations at the elbow and shoulder joints. As well, in the RHT, both groups made similar small overshoot errors. However, older participants performance was significantly more variable compared to young adults. These results suggest that older adult preserve their ability to coordinate arm and trunk movements efficiently during reaching but are not as consistent as young adults.

In the second experiment, we sought to determine the ability of older adults to adjust shoulder and elbow coordination in response to changing task demands. Thus, we asked young and older adults to perform the RHT of Raptis et al. (2007) from the first experiment. A detailed comparison of UL kinematics during reaches in the presence and absence of trunk motion (i.e., free- vs. blocked-trunk trials) was performed and compared between young and older adults. We

found that participants in both age group were able to coordinate motion at the elbow and shoulder joints in accordance with motion at the trunk. However, the extent of changes at the UL joints was smaller and more variable in older adults compared to young ones, especially when trunk motion was involved. These results imply that older adults can coordinate their UL movements based on task requirements, but with less consistent performance compared to young adults.

In the third experiment, we investigated the preservation of intermanual transfer and retention of implicit visuomotor adaptation in older adults. We had young and older participants train to reach with visual feedback rotated 30° counter-clockwise relative to their actual hand motion. Furthermore, we examined whether providing augmented somatosensory feedback regarding movement endpoint would enhance visuomotor adaptation. We found that older adults demonstrated a comparable magnitude of implicit adaptation, transfer, and retention of visuomotor adaptation as observed in young adults, regardless of the presence of augmented somatosensory feedback. These results indicate that intermanual transfer and retention do not differ significantly between young and older adults when adaptation is driven implicitly, regardless the availability of augmented somatosensory feedback.

In the fourth experiment, we looked to determine age-related differences in the engagement of offline and online control processes during implicit visuomotor adaptation. A detailed analysis of reaching performance was conducted ~~and~~ between young and older adults, during and after visuomotor adaptation. We found that when rotation was introduced, participants in both age took longer time to complete their movements, reached with a lower peak velocity and spent more time homing in on the target compared to reaches with aligned cursor feedback. Additionally, older adults had more curved paths with rotated cursor feedback compared to their reaches with aligned cursor feedback. Moreover, these changes in reaching performance continued following adaptation for both groups. These results suggest that young and older adults engage more in online control processes during implicit visuomotor adaptation.

Together, these studies show that older adults: 1) maintain the ability to use compensatory arm-trunk coordination to maintain reaching accuracy, 2) preserve the ability to adjust the coordination between UL joints to meet task demands, 3) maintain the ability to adjust reaches to meet changes in the reaching environment, as well as transfer and retain the newly acquired movement, and 4) preserve the ability to modify the control processes underlying these adapted movements to meet the demands of the reaching environment. In conclusion, the flexibility to coordinate and adapt upper limb reaching performance to meet changes in task demands is maintained across lifespan.

1. Chapter 1 General Introduction

Aging is the process of growing older. The population of individuals over the age of 65 is growing worldwide, such that it is expected to reach 1.6 billion by 2050 (Ferrucci et al., 2020). In Canada, over 6 million Canadians were over the age of 65 in 2014, representing 15.6% of Canada's population. By 2030, it is expected that there will be 9.5 million Canadians over the age of 65, representing 23% of our population (Statistics Canada, 2014). Advanced age is associated with deterioration in sensorimotor control and functioning (Diggles-Buckles, 1993), including declines in fine motor control (Emborg et al., 1998; Floel et al., 2008b) and deficits in gait and balance (Tang & Woollacott, 1996). This deterioration impacts the ability of older adults to perform activities of daily living independently (Welford, 1977; Salthouse, 1985; Stelmach & Worringham, 1985).

The origins of sensory and motor deficits are multi-factorial, as central nervous system declines and changes in sensory receptors, muscles and peripheral nerves arise with advanced age (Welford, 1977; Salthouse, 1985; Stelmach & Worringham, 1985). Degradation of upper limb functionality is prominent with aging (Carmeli, Patish, & Coleman, 2003). In this thesis, we studied the influence of aging on goal-directed upper limb (UL) movements. In particular, *we investigated how age-related changes hinder one's ability to adapt goal-directed reaches to meet changes in task demands, where changes in task demands include sudden changes within the body or more consistent changes in the environment.*

Before outlining our specific research questions in more detail, this literature review first summarizes cognitive, sensory, and motor impairments associated with aging, including the impact of such impairments on reaching. This is followed by a discussion of the influence of aging on one's ability to adapt goal-directed reaches.

1.1. Age-Related Impairments

1.1.1. Cognitive Impairments

Cognition refers to a mental action or processes associated with the selection, acquisition, understanding and/or retention of information required to perform a task (Salmon & Butters, 1995). The prevalence of cognitive impairment among older adults is greater than 40% (Yaffe et al., 2011). In general, aging may impact multiple aspects of cognitive function including attention, memory, visuospatial processing, and executive functions (Salmon & Butters, 1995). Attention deficits may lead to decreases in mental flexibility (i.e., ability to respond effectively to new, complex, and problematic situations), decreased concentration, and impaired performance while dual tasking (i.e., performing two tasks simultaneously) (Salmon & Butters, 1995). Memory problems may influence initial processing and storage of information, as well as affect the retrieval of information, such that the ability to use information and feedback from a previous movement is impaired when performing a similar subsequent movement (Salmon & Butters, 1995). Deficits associated with visuospatial processing in older adults are reflected in a slower processing of spatial information (Meadmore, Dror, & Bucks, 2009) and reduced efficiency of encoding spatial stimuli compared to young adults (Hartley, Speer, Jonides, Reuter-Lorenz, & Smith, 2001). Finally, problems in executive function include the inability to plan and initiate goal-directed activity (Salmon & Butters, 1995).

1.1.2. Sensory Impairments

Sensation is essential for exploring and interacting with the environment for effective and efficient performance of motor skills (Carey, 1995; Carey, & Matyas, 2005). Processing of sensory input refers to the way one manages incoming sensory information, including its reception, modulation, and integration with other brain areas to generate an adaptive output to meet environmental demands (Miller, Anzalone, Lane, Cermak, & Osten, 2007). Deficits in sensory processing may lead to diminished sensitivity to stimuli (i.e., problems in detecting sensory stimuli), such that the minimum level of sensation needed for detection is increased. This increase in stimulus (i.e., threshold) needed for detection has been shown with advanced age (Stuart et al., 2003).

More specific declines in sensory processing with aging can be seen with respect to the sense of proprioception. Proprioceptive information arising from receptors in the muscles, tendons, joints, and cutaneous receptors, play a critical role in the control and coordination of goal-directed movement (Adamo, Martin, & Brown, 2007), as well as the learning of new motor skills (Ingram, van Donkelaar, Cole, Vercher, Gauthier, & Maill, 2000; Shabbott & Sainburg, 2010). The decline in proprioception with aging arises due to changes in the peripheral and central nervous systems. At the peripheral level, deterioration in proprioception is in part because of changes in the function and structure of muscle spindles (i.e., proprioceptors located within the muscles). Functional changes are demonstrated as a decrease in the receptors' dynamic response (i.e., response to muscle stretch) (Miwa, Miwa, & Kanda,1995), while structural changes include decreases in the total number of intrafusal muscle fibers and nuclear chain fibers per spindle, and increases in spindle capsule thickness (Kararizou et al., 2005; Liu et al., 2005). Moreover, aging leads to the atrophy of axons and declines in nerve conduction velocity causing deficits in the detecting and processing of sensory input (Hashizume & Kanda, 1995; Verdu et al., 2000). At the central level, age-related changes in proprioception arise due to a progressive decline of dendrites in the motor cortex (Scheibel, 1975), losses in the number of neurons and receptors, and neurochemical modifications in the brain (Masliah & Terry, 1993; Pakkenberg & Gundersen, 1997). Deficits in proprioception due to aging impact movement quality as movements become slow, clumsy, poorly coordinated, and inadequate adaption to complex tasks is observed (Rothwell et al., 1982; Ghez & Sainburg, 1995). Furthermore, both balance and motor coordination problems associated with advanced age could be partially related to a decline in proprioception (Ribeiro & Oliveira, 2007). Finally, proprioception deterioration causes poorer perception of the position of the body in space, leading to inadequate biomechanics of joints during everyday activities, and subsequently results in degeneration of joints over time (Ribeiro & Oliveira, 2007).

In addition, aging is associated with deterioration in the vestibular system (Agrawal et al., 2009; Liston et al., 2014) including a decrease in the number of vestibular hair cells in the sensory end organs (i.e., sensory receptors in the inner ear) (Rosenhall & Rubin, 1975), a decline in the size of neurons that make up the vestibular nucleus (Lopez, Honrubia, & Baloh, 1997), and a loss in vestibular nerve fibers (Park, Tang, Lopez, & Ishiyama, 2001). Vestibular information plays a role in maintaining balance and orientation in space through sensing head movement and coordinating eye and postural movements (Blouin, Bresciani, Guillaud, & Simoneau, 2015). Moreover, vestibular input is involved in tasks requiring interjoint coordination, as well as tasks requiring e stable hand position while the trunk is in motion (Adamovich et al., 2001).

1.1.3. Motor Impairments

Motor control refers to one’s ability to direct and regulate goal-directed movement (Shumway-Cook & Woolacott, 2007). Impairments in motor performance associated with aging usually include slowed and variable movement initiation and execution (i.e., reaction time (RT) and movement time (MT) are increased; Welford, 1977; Spirduso, 1975), irregular reaching trajectories towards a visual target (Darling, Cooke, & Brown, 1989; Seidler-Dobrin, He, &

Stelmach, 1998), decreased postural stability (Woollacott, Shumway-Cook, & Nashner, 1986; Alexander, Shepard, Gu, & Schultz, 1992), and diminished locomotor function (Sakari-Rantala, Heikkinen, & Ruoppila, 1995).

The decline in motor performance in older adults is attributed to reduced processing speed and higher movement variability due to the shift in control mechanisms with age. That is, control switches from lower-level automatic control to higher-level attentional control (Wishart, Lee, Murdoch, & Hodges, 2000, Wu & Hallett, 2005; Seidler et al., 2010). In addition, motor performance may decline due to functional and structural changes in the peripheral and central nervous system. Specifically, motor impairments with aging have been suggested to arise due to changes in the muscles themselves, which include a loss of muscle tissue, decrease in number and size of muscle fibers, and reduced muscle twitch time and twitch force. These changes lead to reduction in the force generation capacity of muscle over a series of repeated contractions or sustained contractions. Thus, older adults have muscles that are weaker, slower, less powerful, less steady, and more fatigable (Hunter, Pereira, & Keenan, 2016). As muscles strength levels decline with advanced age, movements begin to deteriorate until, eventually, older adults perceive that they are slow or unable to perform the task as frequently as they once did, and a modified strategy is then adopted (Hunter, Pereira, & Keenan, 2016). Functional and structural changes in the central nervous system include changes in the brain, such as shrinkage of the cerebellum and prefrontal regions (Raz et al., 2005), which impact movement control, timing, and coordination (Ivry et al., 2002).

Having established typical age-related declines in cognitive, sensory, and motor processing, we now turn our discussion to arm reaching movements and subsequently explore age-related differences in adapting goal-directed reaches.

1.2. Goal-Directed Reaches

Throughout the day we are constantly engaged in goal-directed actions (i.e., movements of the body performed in order to achieve a specific goal or task; Kröger, Kopp, & Lowit, 2009). Examples of these goal directed movements include activities such as reaching for a cup of tea, lifting a laundry basket, opening the refrigerator, picking up a pencil, climbing a set of stairs, or even walking around the room. The ability to execute an organized and controlled movement is achieved through the integration of sensory information from the environment and/or the body in order to select the proper set of muscle forces and joint activations needed for the production of purposeful, coordinated movements (Schmidt & Lee, 1998; Shumway-Cook & Woollacott, 2007). For example, to execute an appropriate movement towards an object (e.g., to reach for a cup of tea and bring it up to one's mouth), the central nervous system (CNS) typically integrates visual information about the target and hand position with limb somatosensory information (i.e., haptic and proprioceptive information defined as one's sense of limb position and movement in space). The CNS then translates these sensory inputs into appropriate motor commands (van Beers, Sittig, & Gon, 1999; Sober & Sabes, 2005).

In general, literature focussing on goal-directed reaches has shown that older adults demonstrate significant decline in arm movements compared to young adults (Wallace *et al.*, 1980; Janicke & Wrobel, 1984). For example, UL movements involving multiple joints have been shown to be 15–30% slower and less smooth in older adults compared to young adults (Diggles-Buckles, 1993). Moreover, older adults require more time to initiate (RT) and execute (MT) their movements (Yan et al., 1998), have greater spatial and temporal variability (Contreras-Vidal et al., 1998), and execute more inaccurate multi-joint movements (Poston et al., 2013; Seidler-Dobrin, Alberts, & Stelmach, 2002) compared to young adults.

The reaching deficits just discussed outline performance differences between young and older adults when reaching in a typical environment, where task demands do not change. That said, task demands are continuously changing, and we may need to unexpectedly adapt our movements or learn new movements to accommodate for these changes. Limited research has suggested that older adults have difficulty adapting their movements to changing task requirements (Vaillancourt & Newell, 2002; Newell et al., 2006; Kapur et al., 2010; Verrel et al., 2012). *In this thesis, we looked to establish age-related differences in adaptation of goal-directed reaches to changes in task demands arising within the body and the environment.*

1.3. Reach Adaptation to Changes within the Body

The same motor outcome can be achieved by recruitment of different combinations of body segments, a characteristic known as “motor equivalence” (Lashley, 1951; Bernstein, 1967; Latash et al., 2007). This redundancy in the body permits flexibility and adaptability in how movements are executed, including reaching to a target (Bernstein, 1967). For example, during reaching, healthy individuals can reach for a target by moving only their arm or move their arm in combination with active forward trunk motion. It has been found that the shape and velocity profile of the hand trajectory during reaching remains invariant regardless of trunk involvement (Ma & Feldman, 1995; Pigeon & Feldman, 1998). Moreover, the influence of the trunk movement on the hand position is neutralized by appropriate compensatory rotations of the elbow and shoulder joints (Ma & Feldman, 1995; Pigeon & Feldman, 1998). In such situations, the trunk is recruited slightly prior to or simultaneously with the arm, only contributing to the hand movement after the hand achieves peak velocity (Shaikh, Goussev, Feldman, & Levin, 2014). Trunk motion is minimized through compensatory arm joint rotations in the opposite direction at the shoulder and elbow in order to prevent transferring trunk motion to the hand (Shaikh et al., 2013). Once the target is achieved, this compensatory arm–trunk coordination is seen again when the arm is maintained at the same position (i.e., at the target), while the trunk continues moving forward for several milliseconds due to momentum (Kaminski, Bock, & Gentile, 1995). In order for the hand to remain motionless, angular modifications at the elbow and shoulder joint are made until trunk movement ceases (Rossi, Mitnitski, & Feldman, 2002).

Adamovich et al. (2001) referred to these angular modifications in trunk-assisted reaching as ***"compensatory arm–trunk coordination" or "compensatory arm-trunk synergy"***. Based on these findings, it was proposed that arm-trunk coordination involves two different movement synergies: the arm-transport synergy, moving the hand along a trajectory to the target, and the compensatory arm-trunk synergy, minimizing the deflections from this trajectory elicited by recruitment of trunk (Ma & Feldman, 1995; Archambault et al., 1999; Pigeon & Feldman, 1998).

Engagement of movement synergies during multi-joint tasks have been further studied by comparing motor performance of healthy individuals and individuals with sensorimotor deficits. For example, Tunik et al. (2003) examined compensatory arm-trunk coordination in deafferented patients, who lacked cutaneous and proprioceptive afferent sensitivity, by having participants make reaching movements without vision. The arm motion was to be accompanied by forward bending of the trunk. Unbeknownst to participants, trunk motion was unexpectedly blocked at the start of the movement on a small subset of trials. Results indicated that the hand trajectory remained invariant regardless of whether the trunk was or wasn't blocked. This invariance in hand trajectory was achieved by changes in arm inter-joint coordination, which indicates that patients were able to perform the required adaptive changes in UL inter-joint coordination in response to the presence or absence of trunk motion even in the absence of proprioceptive feedback.

In contrast, Raptis et al. (2007) showed that patients with unilateral vestibular lesions had deficits in adapting arm joint motion in trunk-assistant reaching. In their study, participants were asked to lean forward with the trunk, in the absence of vision, while maintaining the same hand position or while moving the hand to a target. In randomly selected trials, the trunk motion was prevented by an electromagnetic device. While healthy participants were able to maintain the required hand position or trajectory to targets by modifying elbow and shoulder joint rotation after trunk movement onset, patients did not compensate for 30–100% of the trunk displacement, leading to alterations in the final hand position or arm trajectory.

Recently, arm-trunk coordination deficits in vestibular patients have been characterized by Sibindi et al. (2013) using the same tasks of Raptis et al. (2007). Sibindi et al. (2013) assessed arm-trunk coordination by measuring the difference in hand end point position in free and blocked trunk motion trials in both a 1) Stationary Hand Task (SHT), in which participants maintained their hand position while flexing their trunk, and 2) Reaching Hand Task (RHT), in which participants reached to a target while simultaneously flexing their trunk. It was found that vestibular patients had lower and more variable gains, reflecting an increase in the influence of trunk motion on hand position in the Stationary Hand Task. In the Reaching Task, vestibular patients had larger and more variable arm deviations (i.e., greater deviation of the finger position in the free- compared to blocked-trunk trials) compared to age-matched healthy participants. Thus, it was concluded that the arm-trunk gain score in the Stationary Hand Task and hand deviations in the Reaching Task can be used to assess the efficiency of movement adaptability mechanisms (i.e., ability to adapt arm-trunk compensatory synergy based on trunk motion condition) in vestibular-deficient patients and assess recovery following therapeutic interventions.

While literature has investigated adaptation in arm-trunk coordination in healthy young adults and impaired populations (e.g., deafferented patients and vestibular patients), it is unclear whether older adults are able to quickly modify their arm-trunk coordination to unexpected changes within the body. Advanced aging has been hypothesized to decrease individuals' ability to adapt their behavior to changes in task requirements (Vaillancourt & Newell, 2002, Newell, Vaillancourt, & Sosnof, 2006). Moreover, literature examining goal-directed reaches has demonstrated that older adults execute slower and more variable arm movements compared to young adults (Darling et al., 1989, Yan et al., 1998) and have higher levels of muscle coactivation (Seidler-Dobrin et al., 1998). Finally, age-related deficits in movement smoothness and end-point accuracy are generally more pronounced for movements requiring shoulder-elbow coordination than for single-joint actions (Seidler et al., 2002), indicating impairment in multi-joint coordination among older adults.

The *first goal of this research was to assess compensatory arm-trunk coordination during trunk-assisted reaching in healthy older adults using the Stationary Hand Task (SHT) and the Reaching Hand Task (RHT) in which participants must adapt their reaches to unexpected changes within the body. These motor tasks will provide insight into how sensorimotor changes that occur with aging may influence one's ability to quickly adapt how movements are coordinated.*

1.4. Reach Adaptation to Changes within the Environment

Consistent, extrinsic changes within the environment (e.g., changes in visual mapping) have been shown to lead to motor adaptation. In this case, motor adaptation refers to a form of motor learning and is defined as a reduction in systematic movement errors in order to return to a desired level of performance (Krakauer, 2009). Motor adaptation demonstrates the flexibility of the motor system in its ability to modify its structure and function, which is necessary to interact in a meaningful way with an ever-changing environment (Ungerleider, Doyun, & Karni, 2002).

The ability of the motor system to adapt to novel environments has been studied extensively in healthy young adults. Motor adaptation can be assessed by altering the visual environment by having participants reach to visual targets while wearing (laterally-displacing) prism goggles or in a virtual environment while seeing a cursor on the screen that misrepresents the position of the hand in space (Redding & Wallace, 1993, 1996, 1997**b**; Simani, McGuire & Sabes, 2007; Ostry, Darainy, Mattar, Wong, & Gribble, 2010). In both types of paradigms, reaching movements are typically first performed in the absence of an external distortion (or perturbation) to establish *"baseline"* characteristics of the movement. Then, the distorted visual feedback is introduced, which modifies the seen position of the hand, i.e., the position of the hand is translated left or right or rotated clockwise or counter- clockwise relative to its actual position. Initially participants tend to make large initial reaching errors, however, they quickly adapt their movements to compensate for the distortion. Moreover, when participants are asked to reach to visual targets in the absence of visual feedback following the distortion trials, they tend to make reaching errors on these trials, such that they continue to reach as if they were still influenced by the distortion. These reach-errors are referred to as "*aftereffects",* and they indicate that a persistent change in the motor system (i.e., visuomotor adaptation) has occurred (Krakauer, 2009; Sainburg & Wang, 2002; Vetter, Goodbody, & Wolpert, 1999; Wolpert, Ghahramani, & Jordan, 1995a).

It has been proposed that the motor system adapts implicitly (i.e., unconsciously) to a change in environmental conditions due to experiencing a sensory prediction error, such that predicted and actual sensory feedback do not match (Wolpert et al.,1995a; Baraduc & Wolpert, 2002). The discrepancy between desired and actual sensory feedback is diminished through adaptation of the inverse (i.e., motor command) and forward (i.e., expected sensory feedback) models, such that the models are updated to accommodate for environmental perturbations (Wolpert & Kawato, 1998; Wolpert & Ghahramani, 2000). These changes in the motor system are robust in that they have been shown to be: 1) transferred from the trained to untrained hand (Sainburg & Wang, 2002; Wang & Sainburg, 2003, 2006; Thompson & Henriques, 2010; Taylor et al., 2011; Mostafa et al., 2014; Poh et al., 2016), and 2) retained for a long period of time (e.g., from 24 hours up to a year following initial visuomotor adaptation) (Yamamoto et al., 2006; Nourouzpour et al., 2015; Maksimovic & Cressman, 2018). Retention of visuomotor adaptation has been examined by observing recall of aftereffects at the start of a second testing session (Krakauer et al., 1999; Baraduc & Wolpert, 2002; Yamamoto et al., 2006) and/or savings within a second testing session, i.e., faster relearning upon exposure to a previously experienced visuomotor rotation compared to initial training performance (Krakauer et al., 1999; Bock et al., 2001; Tong, Wolpert, & Flanagan, 2002; Caithness et al., 2004; Krakauer et al., 2005).

Adaptation to changes in the environment remains crucial throughout the lifespan, and research has looked to examine the impact of aging on visuomotor adaptation. Results of this work, including research examining intermanual transfer and retention of visuomotor adaptation, are limited and findings controversial (Buch et al., 2003; Bock, 2005; Seidler, 2007; Cressman, Salomonczyk, & Henriques, 2010; Wang, Przybyla, Wuebbenhorst, Haaland, & Sainburg, 2011; Leow et al., 2012, 2013; Pan & Van Gemmert, 2013). Several studies have reported no age-related adaptation deficits (e.g., Seidler, 2006; Heuer & Hegele, 2008; Cressman et al., 2010; Vachon, Modchalingam, ‘t Hart, & Henriques, 2020), while others found that aging results in slower and reduced adaptation (e.g., McNay & Willingham, 1998; Bock, 2005; Bock &

Girgenrath, 2006; Heuer & Hegele, 2008, 2009, 2010a). However, older adults have consistently demonstrated aftereffects that are similar in magnitude to those observed in young participants (McNay & Willingham, 1998; Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon et al., 2020).

Age-related declines in visuomotor adaptation have typically been reported in studies using large cursor rotations (such as 60° or 90°; McNay & Willingham, 1998; Bock, 2005; Bock & Girgenrath, 2006; Heuer & Hegele, 2008, 2009, 2010a). It has been suggested that larger rotations tend to evoke more explicit processes than smaller rotations do, such that participants engage in cognitive strategies in order to counteract the cursor rotation (Buch et al., 2003; Bock, 2005; Neville & Cressman, 2018). Thus, age-related cognitive decline may explain age related differences in visuomotor adaptation (Buch et al., 2003; Bock, 2005). It remains to be determined how aging will impact the transfer and retention of visuomotor adaptation, as recent literature has suggested that explicit processes underlie transfer and retention of visuomotor adaptation in young adults (Morehead et al., 2015; Haith et al., 2015; Bouchard & Cressman, 2021).

The *second goal of this research was to investigate the preservation of intermanual transfer and retention of implicit visuomotor adaptation in older adults.*

1.5. Outline of Thesis

As stated previously, the overall goal of this dissertation was to study how age-related changes influences one's ability to adapt goal-directed reaches. In general, we looked at older adults' capability to modify coordination between shoulder and elbow joints during trunk-assisted reaches to meet unexpected changes within the body (i.e., with or without trunk movement). Then, we examined reaching performance in a visuomotor adaptation paradigm to determine the ability of older adults to adjust their reaches to meet changes in the reaching environment, as well as transfer and retain the newly acquired movement. The main objectives (bolded) and hypotheses (italicized) for each experiment (Chapters 2 to 5) are outlined briefly below.

Experiment 1: In Chapter 2, we investigated **compensatory arm–trunk coordination during trunk-assisted reaching in healthy older adults over the age of 60, using the SHT and the RHT**. Within our experimental design we considered the influence of movement speed and hand used. Specifically, participants performed the task at two speeds, a comfortable speed (similar to Sibindi et al., 2013) and a fast speed (i.e., as fast as possible). Since aging is characterized by slowness in motor performance, performance at two speeds allowed us to compare performance across older and young adults when performing the tasks at a similar speed (e.g., the fast speed for older adults and the comfortable speed for young adults). As well, participants completed all movements with their dominant and non-dominant arms, since reaching and rapid aiming movements are typically more accurate when completed with the dominant compared to the non-dominant arm (Roy & Elliott, 1989; Carson et al., 1993). *We hypothesized that, compared to healthy young adults, older individuals would: (1) in the SHT, show an increase of the influence of trunk motion on hand position; i.e., decrease in the ability to compensate for trunk movement* *with appropriate angular modifications at the elbow and shoulder joints, and (2) in the RHT, exhibit greater endpoint deviation; i.e., greater deviation of the index finger position when the trunk was involved in the reaches (free-trunk trials) compared to reaches without the trunk (blocked-trunk trials). Moreover, based on previous literature, we hypothesized that both groups would perform the tasks better with their dominant hand (Roy & Elliott, 1989; Carson et al., 1993) and when moving at their preferred speed (Seidler-Dobrin & Stelmach, 1998; Messier et al., 2003) (i.e., better compensation for trunk movement in the SHT and less arm deviation in the RHT).*

Experiment 2: In Chapter 3, we investigated **the ability of older adults to modify shoulder and elbow coordination in response to changing task demands.** A detailed comparison of UL kinematics during reaches in the presence and absence of trunk motion (i.e., free- vs. blocked-trunk trials) was performed and compared between young and older adult**s.** Specifically, from Experiment 1, young and older adults performed the Reaching Hand Task (RHT) of Raptis et al. (2007). Given that aging is characterized by slowness in motor performance, reaches were performed at two speeds, participants' comfortable speed (similar to Sibindi et al., (2013)) and a fast speed (i.e., as fast as possible). Additionally, participants performed each task with their dominant arm and non-dominant arm to examine the effect of handedness. Since successful completion of the task necessitated rapid adaptive changes in UL inter-joint coordination in response to the presence or absence of trunk motion and aging is accompanied by deterioration in adaptive motor behaviour (Kapur et al., 2010; Verrel et al., 2012) and a decline in coordination of multi-joint movements (Poston et al., 2013; Seidler et al., 2002), *we expected older participants to demonstrate: (1) decreased UL coordination between the elbow and shoulder joints during performance of the RHT (e.g., delayed onset and magnitude of* *compensatory modifications), (2) decreased movement consistency (e.g., varied onset and magnitude of compensatory modifications among older participants), and (3) impaired ability to modify UL inter-joint coordination to account for changes in the availability of trunk motion (e.g., decreased motor equivalence).*

Experiment 3: In Chapter 4, we investigated **the preservation of intermanual transfer and retention of implicit visuomotor adaptation in older adults**. According to previous literature, adaptation to small perturbations (i.e., 30° or less) arises implicitly (Neville & Cressman, 2018; Vachon et al., 2020), In this experiment, young and older participants were trained to reach when a small 30° visuomotor distortion was introduced. Participants were not made aware of the introduction of the visuomotor distortion, nor instructed on how to counteract it. Based on previous results, we *expected both young and older participants to adapt their reaches to the 30° in the training trials and demonstrate aftereffects when reaching in the absence of visual feedback (e.g., McNay & Willingham, 1998; Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon et al., 2020)*. Given that adaptation was expected to be driven implicitly, *we hypothesized that both young and older participants would demonstrate minimal transfer and retention of implicit adaptation, and that the overall extent would not differ across ages.* Additionally, we investigated **whether providing augmented somatosensory feedback regarding movement endpoint would enhance intermanual transfer and retention of visuomotor adaptation.** Augmented somatosensory feedback was provided to half of the young and older participants at the end of their reach during training trials via the robotic handle that participants held, providing an additional external afferent signal indicating actual hand position. We *expected to observe the greatest intermanual transfer and retention of visuomotor adaptation for participants in the augmented somatosensory feedback group, as motor learning has been* *shown to benefit from augmented somatosensory feedback (Emken et al., 2005; see also see Sigrist et al., 2013).*

Experiment 4: In Chapter 5, we investigated **the influence of aging on reaching performance during implicit visuomotor adaptation**. A detailed analysis of reaching performance was conducted by comparing reaction time (RT), movement time (MT), peak velocity (PV), proportional time after peak velocity (pTAPV), and path curvature (PC), between young and older adults, during and after visuomotor adaptation. *We expected a decline in older adults reaching performance regardless of reaching in a typical or novel environment. On the other hand, given that adaptation was presumed to be driven implicitly, we expected young and older adults to adapt their movements to a similar extent and in a similar manner. Specifically, we expected a larger contribution of online control processes when reaching with a rotated cursor compared to when reaching with aligned cursor feedback. A greater engagement of online control processes would be evident through increased MT, decreased PV, increased pTAPV and increase PC of reaches with a rotated cursor compared to aligned cursor.*

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2. Chapter 2 Age differences in arm-trunk coordination during trunk-assisted reaching

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2.1. Abstract

Reaching for an object is a basic motor skill that requires precise coordination between elbow, shoulder, and trunk motion. The purpose of this research study was to examine age-related differences in compensatory arm-trunk coordination during trunk-assisted reaching. To engage the arm and trunk, an older and young group of participants were asked to (1) maintain a fixed hand position while flexing forward at the trunk (Stationary Hand Task (SHT)) and (2) reach to a within-arm's reach target while simultaneously flexing forward at the trunk (Reaching Hand Task (RHT)) (Raptis et al., 2007; Sibindi et al., 2013). Both tasks were completed with eyes closed. Participants completed the two tasks with their dominant and non-dominant arms, and at both a fast and a preferred speed. On average, young and older participants performed in a similar manner in the SHT, such that they maintained their hand position by compensating for trunk movement with modifications of the elbow and shoulder joints. In the RHT, young and older participants had similar endpoint accuracy. This similarity in performance between young and older participants in the SHT and RHT tasks was observed regardless of the arm used or movement speed. However, for both tasks, movements in older adults were significantly more variable compared to young adults as shown by the larger variability in arm-trunk coordination performance (gain scores) in the SHT and higher MT variability in the RHT. Thus, results imply that older adults maintain their ability to coordinate arm and trunk movements efficiently during reaching actions but are not as consistent as young adults.

2.2. Introduction

In our daily life, we are constantly engaged in actions that can be performed by numerous combinations of joint rotations (degrees of freedom (DFs)), a characteristic known as "motor equivalence" (Lashley, 1951; Bernstein, 1967; Latash et al., 2007). The fundamental question of how the nervous system chooses movement patterns from a potential redundant set of DFs for a particular motor task (known as the redundancy problem), was first raised by Bernstein (1967). To deal with the problem of redundancy, it has been proposed that the nervous system constrains the number of DFs to work in groups known as synergies. Movement synergies may be engaged in a time-ordered sequence and controlled as a unit to meet a specific demand in motor output, such as stabilization of a movement trajectory or prevention of falling during trunk bending (Bernstein, 1967; Jeannerod, 1988; Latash et al., 2002).

Coordination between the arm and trunk has been studied extensively in healthy adults. For example, Kaminski and colleagues (1995) asked healthy young adults to reach to five targets, two which were within arm's reach (i.e., near targets), and three beyond (i.e., far targets). They found that the trunk participated mainly in reaches to far targets that could not be attained by arm motion alone. When the trunk did contribute to the transportation of the hand to the target, its motion started simultaneously with the arm movement and continued until target contact. The involvement of trunk flexion had no effect on the path of the hand or the smoothness of its velocity profile. This has also been shown by Ma and Feldman (1995) who asked participants to make fast uncorrected planar movements of the right arm from a near to a far target placed in the ipsilateral workspace at a 45° angle to the sagittal midline of the trunk. These reaching movements were combined with forward or backward sagittal motion of the trunk. Direction, positional error, curvature, and velocity profile of the hand trajectory remained invariant despite different trunk movements. Feldman and colleagues suggested that the invariance of the hand trajectories across conditions was due to two synergies: an arm transport synergy that coordinates the arm joints to bring the hand to the target and a compensatory arm–trunk synergy that decreases the influence of the trunk motion on hand position by additional changes at the arm joints (Ma & Feldman, 1995; Pigeon & Feldman, 1998). The compensatory synergy is flexible such that when target is placed beyond arm's reach (Mark et al., 1997), the degree of compensation (i.e., modifications in the arm joints to decrease the influence of the trunk movement on hand movement) is attenuated to permit the trunk to increase movement extent (Rossi, Mitnitski, & Feldman, 2002). Adamovich et al. (2001) refers to these angular modifications in trunk-assisted reaching as "compensatory arm–trunk coordination." According to Adamovich et al. (2001), sensory feedback (i.e., proprioceptive, cutaneous, and/or vestibular) that arises from the trunk motion may underlie the compensatory modifications in arm joint angles used to maintain the same hand trajectory regardless of changes in the number of degrees of freedom involved in the pointing task.

The role of sensory feedback in compensatory arm-trunk modifications has been examined in patients with altered sensation (i.e., deafferented patients) (Tunik et al., 2003) and patients with unilateral vestibular lesions (Raptis, Dannenbaum, Paquet, & Feldman 2007). Tunik et al. (2003) found that patients, who lacked cutaneous and proprioceptive sensitivity, but had relatively intact vestibular function maintained their ability to adapt movements using compensatory arm-trunk coordination for reaching tasks in the absence of vision. Thus, it was suggested that vestibular signals evoked by head motion following trunk flexion may play a major role in the initiation, maintenance, and modification of compensatory arm-trunk coordination, as opposed to proprioceptive input. This proposal was later confirmed by Raptis et al. (2007) who found that patients with vestibulospinal pathology, caused by unilateral vestibular lesions, had deficits in adapting arm joint motion for reaching when trunk motion was imposed. In their study, participants were asked to lean forward with the trunk, in the absence of vision, while maintaining the same hand position or while moving the hand to a target. While healthy participants were able to maintain the required hand position or trajectory to targets by modifying elbow and shoulder joint rotation after trunk movement onset, patients with unilateral vestibular deficits did not compensate for 30-100% of the trunk displacement, leading to alterations in the final hand position or arm trajectory.

In a similar study, Sibindi et al. (2013) quantified the extent of arm-trunk compensation in patients with unilateral vestibular deficits using two different reaching tasks: (1) a Stationary Hand Task (SHT), in which participants maintained their hand position while flexing their trunk, and (2) a Reaching Hand Task (RHT), in which participants reached to a target while simultaneously flexing their trunk. Movements were made in the absence of vision. In the SHT, Sibindi et al. (2013) characterized the efficiency of compensatory arm-trunk coordination with a gain (g) score that ranged from a value of 1, when the effect of trunk motion on the hand position was fully compensated for (the hand remained in a stable position), to a value of 0 when no compensation occurred, and the trunk motion was transmitted to the hand (Raptis et al., 2007; Pigeon & Feldman, 1998). The gain score was calculated based on reach endpoints from trials in which the trunk was free to move and those in which it was unexpectedly blocked. On average, gain scores in the patients ($g = 0.67 \pm 0.19$) were significantly lower than those in healthy controls ($g = 0.85 \pm 0.07$). In other words, the hand position of vestibular patients deviated more from the target during trials with trunk movement compared to healthy controls, indicating an increased influence of trunk motion on hand position. In the RHT, vestibular patients tended to overreach the target in trials in which the trunk was free, again indicating a decreased ability to compensate for the contribution of trunk motion on hand movement extent.

While deficits in arm-trunk coordination have been demonstrated in deafferented and vestibular patients, it is unclear to what extent motor equivalence is affected by aging. Aging is accompanied by a well-documented progressive decline in motor performance (Wallace et al., 1980; Janicke & Wrobel, 1984), which includes movement coordination difficulties (Seidler et al., 2002), increased movement variability (Contreras-Vidal et al., 1998; Darling et al., 1989), and movement slowing (Diggles-Buckles, 1993). These difficulties negatively impact the ability of older adults to perform daily activities independently and have been related to an array of changes in the central nervous system, as well as peripheral structures, such as sensory receptors, muscles, peripheral nerves, and joints (Welford, 1977; Salthanouse, 1985; Stelmach & Worringham, 1985). Moreover, with age there is degeneration within the vestibular system, including a decrease in the number of vestibular hair cells (Rosenhall & Rubin, 1975; Gleeson & Felix, 1987), a decline in the size and number of neurons that make up the vestibular nucleus (Lopez, Honrubia, & Baloh, 1997), and a reduction in the number of vestibular nerve fibers (Park, Tang, Lopez, & Ishiyama, 2001). Given these difficulties, we anticipated that older individuals would have difficulties in compensating for trunk motion in the SHT and RHT.

The aim of this study was to assess compensatory arm-trunk coordination during trunk-assisted reaching in healthy older adults over the age of 60, using the SHT and the RHT. Within our experimental design we considered the influence of movement speed and hand used. Specifically, participants performed the task at two speeds, a comfortable speed (similar to Sibindi et al., 2013) and a fast speed (i.e., as fast as possible). Since aging is characterized by slowness in motor performance, performance at two speeds allowed us to compare performance across older and young adults when performing the tasks at a similar speed (e.g., the fast speed for older adults and the comfortable speed for young adults). As well, participants completed all movements with their dominant and non-dominant arms, since reaching and rapid aiming movements are typically more accurate when completed with the dominant compared to the non-dominant arm (Roy & Elliott, 1989; Carson et al., 1993). We hypothesized that, compared to healthy young adults, older individuals would: 1) in the SHT, show an increase of the influence of trunk motion on hand position; i.e., decrease in the ability to compensate for trunk movement with appropriate angular modifications at the elbow and shoulder joints, and 2) in the RHT, exhibit greater endpoint deviation; i.e., greater deviation of the index finger position when the trunk was involved in the reaches (free-trunk trials) compared to reaches without the trunk (blocked-trunk trials). Moreover, based on previous literature, we hypothesized that both groups would perform the tasks better with their dominant hand (Roy & Elliott, 1989; Carson et al., 1993) and when moving at their preferred speed (Seidler-Dobrin & Stelmach, 1998; Messier, Adamovich, Berkinblit, Tunik, & Poizner, 2003) (i.e., better compensation for trunk movement in the SHT and less arm deviation in the RHT).

2.3. Methods

2.3.1. Participants

Two groups of participants were recruited: 18 healthy young adults (mean age = 24.3 ± 2.9 years), and 18 gender-matched healthy older adults (mean age = 72.1 ± 2.4 years). All participants had no musculoskeletal, neurological, or cognitive deficits that would interfere with the performance of the experimental tasks (mean Dizziness Handicap Inventory mean score = 1.7/100 (Jacobson & Newman, 1990), joint position sense test mean score = 8/8 (Hall & McCloskey, 1983), mean Ottawa Sitting Scale mean score = 38.6/40 (Thornton & Sveistrup, 2010), Monteral Cognitive Assessment mean score (only older adults) = 27.7/30 (Nasreddine et al., 2005). Mean performance on these assessments are provided in Table 2.1 for the Older participants. Older participants' scores fell within normal ranges reported in the literature for both cognitive (see Nasreddine et al., 2005; Kessels et al., 2022), and proprioceptive assessments (see Stillman, 2000; Gilman, 2002) in healthy individuals aged between 18 and 60 years old. Thus, we considered our older participants to be high functioning individuals. As well, all participants were right-handed as indicated by their responses to the 10-item Edinburgh Handedness Inventory (mean score = +82.7 ± 17.9, where score > +40 indicate strongly right-handed; Oldfield, 1971). All participants provided informed consent prior to the start of the experiment in accordance with the ethical guidelines set by the University of Ottawa's Research Ethics Board.

Table 2.1 Mean performance of older adults on the sensory, motor, and cognitive assessments

Participant minimum (min) and maximum (max) scores are provided in brackets for each assessment. Scores are provided for the older adult Group.

Assessment	Older Adults
Dizziness Handicap Inventory	1.7/100 (min = 0, max = 6)
Joint Position Sense	8/8 for each hand (min = 8, max = 8)
Ottawa Sitting Scale	38.6/40 (min = 37, max = 39)
Montreal Cognitive Assessment	27.7/30 (min = 27, max = 30)

2.3.2. Apparatus

The VICON motion capture system (VICON motion systems, UK; 3D resolution 2.5 mm), including 7 cameras and 8 reflective markers, was used to record movement kinematics. Five markers were placed on the upper limb being tested [index fingertip (endpoint), radial styloid (wrist), lateral epicondyle of humerus (elbow), ipsilateral acromion (ipsi shoulder), and contralateral acromion (contra shoulder)], and additional markers were placed in the middle of the sternum (trunk), forehead, and on the target. Data were recorded at a sampling rate of 60 Hz for 5 s.

2.3.3. Experimental Set-Up

Participants were seated on a stool (i.e., chair with no back support and no arm rests), with their feet on the ground, shoulder width apart, and facing the motion tracking system (Portable Cartesian Stand of VICON; Figure 2.1A). Participants wore a harness, fastened posteriorly at the level of the scapulae, and held by a second experimenter. A fixed target was positioned at approximately 60% of the participant's arm length (from the medial axillary border of the shoulder to the tip of the index finger) and was represented by a "yoyo" attached to a belt hanging from the ceiling and positioned at nose level. Participants performed one calibration task and two motor tasks (SHT and RHT), as described below and illustrated in Figure 2.1.

2.3.3.1. Calibration

The aim of the calibration procedure was to quantify the maximal hand/index finger displacement possible when the participant leaned forward at the trunk, with their arm and trunk fixed relative to each another. Each participant completed 10 calibration trials per arm. Participants were seated with their testing arm held at nose level and flexed at the elbow (80° on average) so that their index finger was positioned under the fixed target. Participants were instructed to lean forward, i.e., to maximally flex their trunk. The arm was attached to a foam form strapped to the trunk that was used to make sure that the arm and trunk were fixed relative to one another (i.e., arm and trunk moved forward as one unit, Figure 2.1B).

2.3.3.2. Stationary Hand Task

For the SHT, participants were seated with their tested arm flexed at the elbow at nose level directly underneath the target without touching it. Participants were instructed that upon hearing a verbal "go" signal, they should close their eyes and lean forward with their trunk in a single uncorrected movement (15-20 cm shoulder displacement in the sagittal plane from an upright posture; Free-trunk trials). The final position was held for 2 seconds before participants returned their trunk back to the starting position (Figure 2.1C). After completing the movement, participants opened their eyes. Participants were instructed to complete the trunk flexion while maintaining a fixed arm position in space. Four sets of 10 trials (40 trials) were completed for each hand and at two movement speeds (see Introduction) for a total of 160 trials. A 2-minute rest was taken after each set of 10 trials. The first 40 trials for each arm were done as fast as possible, and the subsequent 40 were done at a preferred, comfortable speed.

During the SHT, the trunk movement was unexpectedly blocked on a subset of trials (40%) by an examiner who held the handle attached to the back of the tightly fitted harness strapped to the participant's chest (Blocked-trunk trials). When blocked, the trunk movement was arrested for the entire trial. In the blocked-trunk trials, participants were still able to maintain their initial hand position. The percentage of the blocked-trunk trials was chosen based on previous research suggesting that 40% is sufficient to minimize anticipation of the upcoming trunk condition (Adamovich et al., 2001; Raptis et al., 2007).

2.3.3.3. Reaching Hand Task

For the RHT, participants were seated with the tested arm positioned on an arm rest placed next to the trunk at hip level to stabilize the initial position. Participants were instructed to move their tested arm to the target, while simultaneously flexing the trunk forward (as for SHT). At a verbal "go" signal, participants closed their eyes and reached to the target while simultaneously flexing and leaning forward with the trunk (see Figure 2.1D). When participants believed that their hand had reached the target, they were instructed to hold the final hand position for 2 s, and then they were verbally prompted to return to the start position and open their eyes. Participants completed the task at two speeds with both arms, once moving as quickly as possible and once moving at their preferred, comfortable speed. For each arm and speed, participants completed 4 sets of 10 trials (40 trials) with a 2-minute rest period between each set of trials, for a total of 160 trials. In 40% of trials, trunk movement was unexpectedly blocked, while the participant was required to reach the same target position as in free-trunk trials.

Each participant performed the SHT and RHT with the same arm before testing the opposite arm. The order of the testing arm (right or left) was counterbalanced across participants. Within each task, the type of trial (free- versus blocked-trunk) was also randomized.

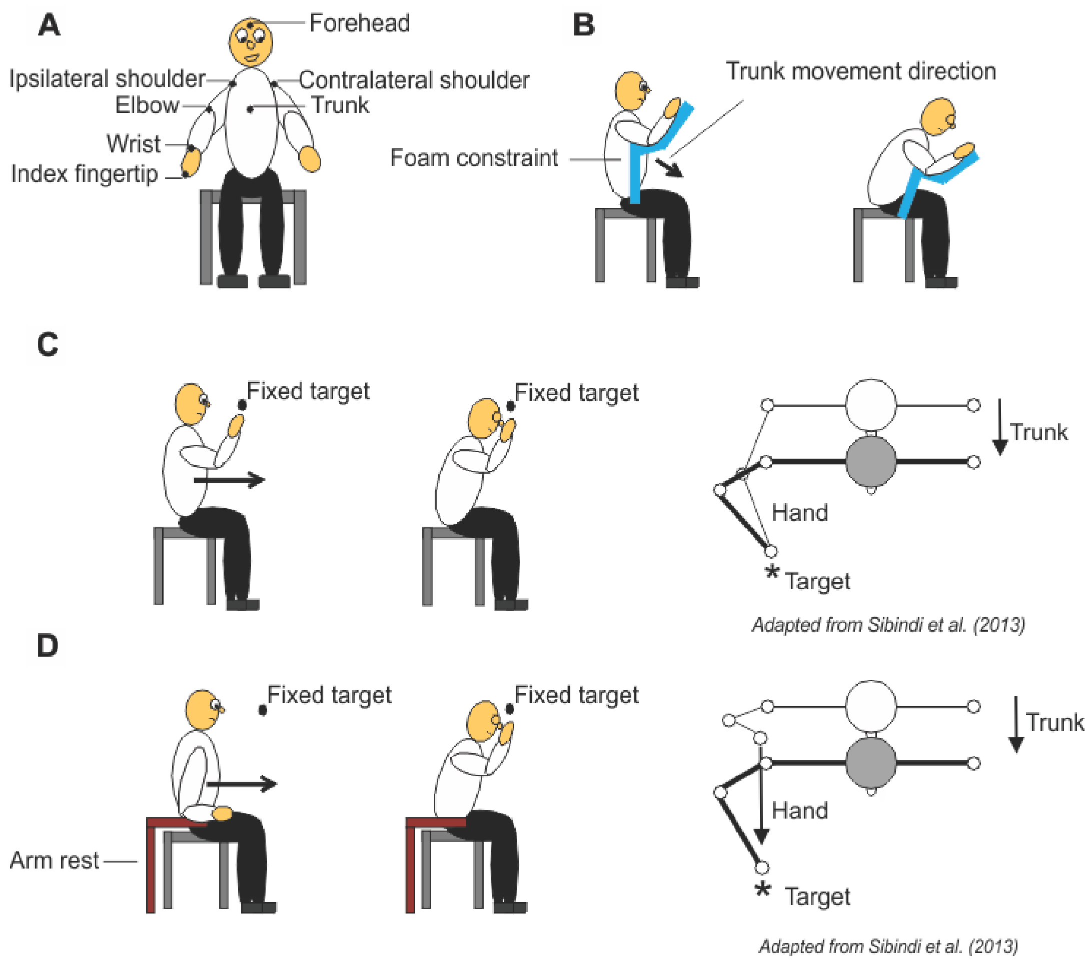

Figure 2.1 Experimental set-up and procedures

A. Marker positions: Reflective markers were placed on the upper limb being tested [index fingertip (endpoint), radial styloid (wrist), lateral epicondyle of the humerus (elbow), ipsilateral acromion (ipsi shoulder), and contralateral acromion (contra shoulder)], and additional markers were placed on the middle of the sternum (trunk), forehead, and on the target (not shown in the figure)]. B. Calibration: Participants were seated with their testing arm held at nose level and flexed at the elbow so that their index finger was positioned under the fixed target. Participants were instructed to lean forward, i.e., to flex their trunk as far as possible. A foam constraint was used to make sure that the arm and trunk were fixed relative to one another. C. Stationary Hand Task: Participants were seated with their testing arm flexed at the elbow at nose level directly underneath the target without touching it. In this task, participants were asked to maintain their arm position under the target location and flex their trunk forward, bringing their nose to the target. D. Reaching Hand Task: Participants were seated with the testing arm positioned on an arm rest which was placed next to the trunk at hip joint level to ensure a multi-joint movement. In this task, participants were asked to move their testing arm to the target, while simultaneously flexing the trunk forward.

2.4. Data Analysis

Data from each task were analyzed using custom-written software in MATLAB version R2013a and SPSS version 24. The start and end of the trunk movement were determined as the times at which the tangential velocity of the sternum marker first surpassed and remained above or fell and remained below 10% of the trunk peak velocity, respectively.

2.4.1. Calibration Task

Trunk (sternum marker) and arm displacement (i.e., index finger marker) in the sagittal plane were determined according to the anterior-posterior (A/P) distance covered (i.e., position at the end of the movement relative to the position at the start of the movement in the sagittal plane) and expressed in cm. The deviation in the finger position that was determined from the calibration trials (hm) represents the maximal horizontal deviation in the index finger position that would be expected if the trunk motion were fully transmitted to the hand (i.e., this mimics what would occur if the arm joint angles did not compensate for the trunk motion at all).

2.4.2. Stationary Hand Task

To determine arm-trunk coordination, a gain score (g) was calculated in the sagittal (y) plane (Raptis et al., 2007; Sibindi et al., 2013). Specifically, the gain score was calculated for each participant for each hand and speed using the following equation: $g = 1–(h/hm)$; where h was the average horizontal deviation of the hand position in free- compared to blocked-trunk trials and hm was determined from the calibration trials. Given that the amount of trunk displacement could be different between Calibration and free-trunk trials, hand displacement was normalized according to this difference. A score of $g = 1$ would occur when elbow flexion and shoulder horizontal flexion fully compensated for trunk motion resulting in no hand movement from the initial position ($h \sim 0$). Conversely, a score of $g = 0$ indicates that no compensation occurs (h =

hm), and the hand moves with the trunk. It should be noted that in the gain score calculation, the influence of trunk motion on final hand position was considered instead of movement accuracy with respect to the target, as according to Pigeon et al. (2000), participants typically make systematic errors that, without knowledge of results (as was the case in our study), are reproduced in repeated trials. These errors were not the focus of our study and thus, to avoid the confounding effect of vision-dependent systematic errors on gain scores, coefficient h was determined by calculating the deviation in the final positions of the index finger and sternal markers in blocked-trunk trials from the respective positions in free-trunk trials. In addition to movement time and gain score, trunk displacement and hand deviation (h from the gain score equation) were computed and expressed in cm. Trunk displacement was defined as the anterior-posterior (A/P) distance moved by the trunk in the sagittal plane during free-trunk trials, while hand deviation refers to the A/P difference of the final hand position in the free- compared to blocked-trunk trials.

2.4.3. Reaching Hand Task

For the RHT, the start and end of movement for free- and blocked-trunk trials were defined as the times at which the tangential velocity of the finger marker first surpassed and remained above or fell and remained below 10% of finger peak velocity, respectively. Movement time was calculated as the difference between these two time points. An error measure indicating the difference (d) in final hand position in the free- versus blocked-trunk trials was used to determine compensatory arm-trunk coordination during the RHT (i.e., hand deviation). This difference was calculated in 2D from the sagittal (horizontal and vertical) coordinates of the finger marker in the free- and blocked-trunk trials and was normalized by each participant’s arm length to allow comparison between groups. Specifically, this error measure was expressed in relation to the ratio (r) of the arm length of the participant to the group mean arm length. Thus, for each participant, the normalized difference (dn) was computed as dn = r·d. A small difference value indicated that participants were able to compensate for the effect of trunk movement on hand position. In addition, the 2D positions of the hand relative to the fixed target position in both free- and blocked-trunk trials were computed and expressed in cm.

2.4.4. Statistical Analysis

Mean trunk and hand (i.e., index finger) displacements in the calibration task were analyzed in a 2 Group (old vs. young) x 2 Hand (dominant/right vs. non-dominant/left) mixed analysis of variance (ANOVA) with repeated measures (RM) on the last factor. We had initially hypothesized that older participants would move more slowly at their preferred speed compared to older adults. As outlined below, this was not the case. Thus, for each variable that was analyzed in the SHT and RHT, mean values and variability (standard deviations) for each kinematic variable were compared across participants using a 2 Group x 2 Hand x 2 Speed (preferred vs. fast) mixed ANOVA with RM on the last two factors. Mean movement time (MT) and variability in the RHT were analyzed in a 2 Group x 2 Hand x 2 Speed x 2 Trial Type (free- vs. blocked-trunk trials). For all analyses, differences with a probability of < 0.05 were considered significant and Bonferroni post-hoc analyses were performed to determine the locus of the differences.

2.5. Results

2.5.1. Calibration Task

During calibration trials, trunk displacement did not differ between groups or hands. The average trunk displacement was 17.9 cm for older adults and 17.3 cm for young adults with the right arm, and 17.0 cm and 16.2 cm respectively for the left arm. Similarly, the average hand/finger displacement caused by trunk movement was similar between groups and hands. Movement of the trunk led to an average hand/finger displacement of 14.0 cm and 13.1 cm when the right and left hands were used respectively.

2.5.2. Stationary Hand Task

2.5.2.1. Trunk Movement Time (MT)

Overall, when participants performed the task at their preferred, comfortable speed, both groups completed the task in approximately 1.6 seconds, using either arm (Table 2.1). When participants were instructed to perform the task as fast as possible, older participants executed the movement faster than in the preferred speed condition only when using their left arm (Table 2.1). In contrast, young participants were able to complete the task faster using both arms (Table 2.1). In accordance with these observations, ANOVA revealed a significant Group x Hand x Speed interaction [$F(1,34) = 20.85$, $p < 0.001$]. Post hoc analysis showed that trunk movement time differed significantly between speed conditions for the same arm in the young group but not in the older group. In addition, between groups, older adults made significantly slower trunk movements when moving as fast as possible while maintaining their right hand position under the fixed target ($p = 0.043$).

While variability in MT did not differ significantly between groups [$F(1,34) = 2.61$, $p = 0.12$], there was a significant Group x Hand x Speed interaction [$F(1,34) = 4.90$, $p = 0.03$] (Table 2.1). In particular, post-hoc analysis revealed that in the older adults, MT was significantly more variable when the task was performed with the right hand compared to the left hand in the fast speed condition ($p < 0.001$).

2.5.2.2. Trunk Displacement

The harness was effective in blocking trunk movement, such that trunk flexion during blocked-trunk trials was minimal for both groups with both hands. The average amount of trunk flexion during blocked-trunk trials for both groups was 1.1 cm when the right hand was at the target and 1.0 cm when the left hand was at the target across speed conditions. In free-trunk trials, trunk displacement was similar to the 17.1 cm in the calibration trials. Specifically, collapsed across speed conditions, average trunk displacement was 16.8 cm, with a corresponding variability of 5.2 cm. These values did not vary between groups, hands or speed.

2.5.2.3. Hand Deviation

Example endpoint positions of the hand relative to the target in the horizontal plane are shown in Figures 2.2A and 2.2C for a typical young and older participant. The hand in free-trunk trials deviated from the target by 1.7 cm more on average than in blocked-trunk trials when the task was performed using the right hand and 1.2 cm more on average when the task was performed with the left hand, collapsed across participants and speed conditions. ANOVA revealed no main effects of Group or Hand (Table 2.1). However, there was a significant Hand x Speed interaction [$F(1,34) = 4.17$, $p = 0.04$], such that participants had a larger hand deviation when they performed the task using their right hand compared to their left hand, but this was only significant in the fast speed condition ($p = 0.01$) (Table 2.1).

As seen in Figure 2.2A, older adults were more variable in their ability to maintain their hand position in the free-trunk trials using either hand and in both speed conditions compared to young adults [effect of group: $F(1,34) = 7.72$, $p < 0.001$] (Table 2.1). Analyses also revealed a significant Hand x Speed interaction [$F(1,34) = 5.31$, $p = 0.02$)] when the trunk was blocked. Post-hoc analyses indicated that the variability in right hand deviation increased significantly when the movements were executed as fast as possible compared to when the movements were completed at the preferred speed for both groups (Table 2.1).

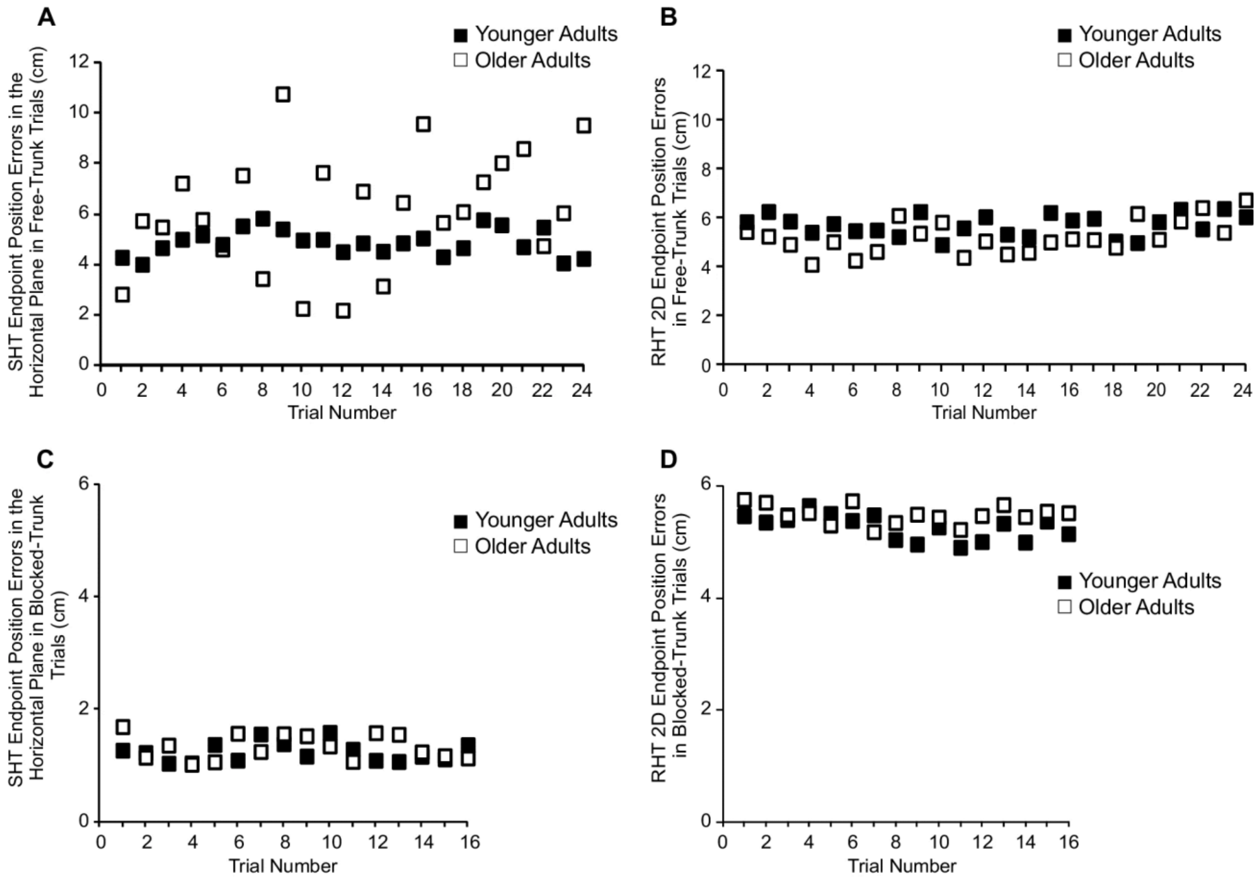

Figure 2.2 Endpoint position errors in 2D in the SHT and the RHT

Horizontal endpoint position errors relative to the target for one young adult (black squares) and one older adult (white squares) in the SHT (A & C) when moving the right hand at a comfortable speed. 2-Dimensional endpoint position errors relative to the target for one young adult (black squares) and one older adult (white squares) in the RHT (B & D) when moving the right hand at a comfortable speed. The endpoint errors for the older adult are more variable than the young adult in the SHT when trunk was involved in the movement, as seen by the scatter in endpoint positions across trials in A.

2.5.2.4. Gain

Participants in both groups were able to compensate for the influence of trunk motion on their hand position regardless of hand used and movement speed (Figure 2.3A). Although gain scores were slightly lower in older adults compared to young participants, across both hands and both movement speeds, there were no differences between groups, hands, or speeds. In the older participants, the mean gain score was 0.75 across both hands and speed conditions. Similarly, for the young participants, the mean gain score was 0.81 across both hands and speed conditions.

Although both groups were able to perform the SHT with a high level of compensation, as reflected in the high gain scores, older adults were significantly more variable in their performance compared to young participants, using either hand and at both speed conditions [main effect of group: *F*(1,34) = 6.89, *p* = 0.01] (Figure 2.3B).

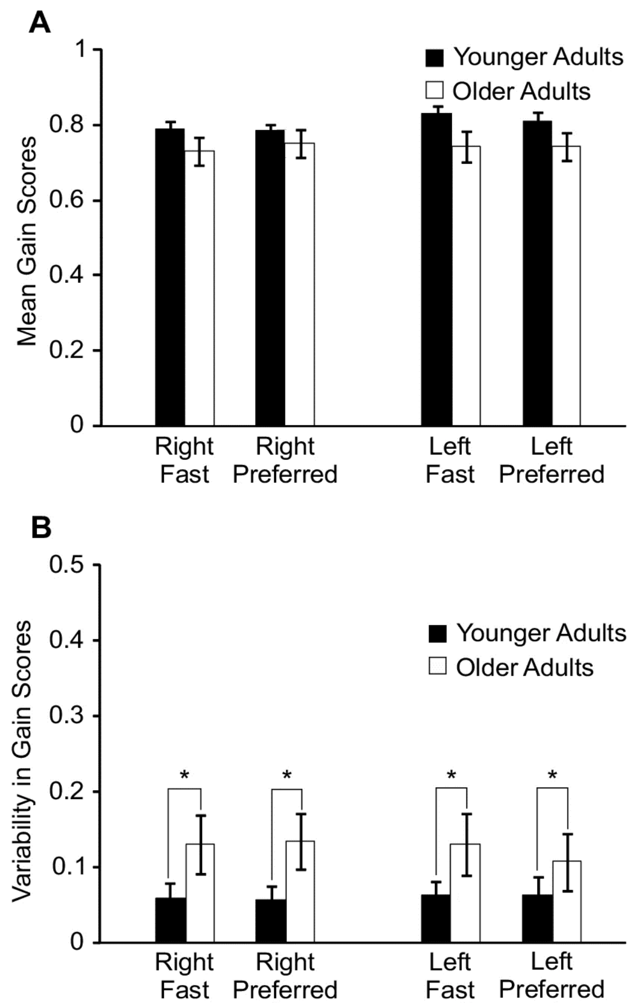

Figure 2.3 Gain scores (mean and variability) in the SHT

A. Mean gain scores in the SHT. Young and older participants performed the task in a similar manner with high gain scores (≈ 0.7), regardless of the hand being used and the speed of the movement completed. B. Variability in gain scores in the SHT. Performance of older adults was significantly more variable compared to young participants using both hands, and at both movement speeds. *Error bars* reflect standard errors of the mean.

Table 2.2 Kinematic measures for the SHT

Mean (standard deviation) and mean variability (standard deviation) for each kinematic variable for each hand (right vs. left) at each movement speed (preferred vs. fast). * Shows main effect of group (p < 0.05).

Arm / Speed	***Right / Preferred***		***Left / Preferred***		***Right / Fast***		***Left / Fast***	
Kinematic measures	**Mean**	**Variability**	**Mean**	**Variability**	**Mean**	**Variability**	**Mean**	**Variability**
Movement time (s)								
Young adults	1.65 (0.49)	0.35 (0.15)	1.51 (0.54)	0.29 (0.15)	1.18* (0.47)	0.27 (0.12)	1.29 (0.54)	0.33 (0.13)
Older adults	1.66 (0.66)	0.42 (0.23)	1.58 (0.51)	0.35 (0.24)	1.64* (0.88)	0.55 (0.47)	1.41 (0.58)	0.34 (0.19)
Trunk displacement (cm)								
Young adults	16.62 (8.62)	3.53 (1.75)	14.56 (10.59)	5.43 (2.14)	15.53 (9.52)	5.48 (1.31)	15.79 (11.21)	4.92 (2.20)
Older adults	17.59 (3.75)	4.91 (3.42)	14.39 (6.67)	5.88 (3.48)	17.11 (4.13)	6.5 4(2.28)	16.94 (4.27)	5.01 (2.25)
Hand deviation (cm)								
Young adults	1.53 (0.78)	Free:0.78* (0.24) Blocked:0.49 (0.19)	1.34 (0.78)	Free:0.89* (0.38) Blocked:0.65 (0.28)	1.81 (1.00)	Free:1.06* (0.31) Blocked:0.69 (0.22)	1.12 (0.94)	Free:1.02* (0.45) Blocked:0.66 (0.19)
Older adults	1.71 (1.11)	Free: 1.88* (1.82) Blocked: 0.57 (0.22)	1.24 (0.95)	Free:1.28* (0.92) Blocked:0.67 (0.52)	1.96 (0.95)	Free:1.68* (0.82) Blocked:0.76 (0.46)	1.23 (1.01)	Free:1.41* (0.79) Blocked:0.69 (0.63)

2.5.3. Reaching Hand Task (RHT)

2.5.3.1. Movement Time (MT)

In the preferred speed condition, both groups completed the task in approximately 1.2 seconds using either hand in both types of trials (i.e., in free- and blocked-trunk trials) (Table 2.2). Similar to the SHT, in the fast speed condition, young participants were able to execute the movement faster with both hands in both types of trials, while older adults did not move faster using either hand or in either type of trial (Table 2.2). Analysis revealed a significant Group x Hand x Speed x Trial Type interaction [$F(1,34) = 7.00$, $p = 0.01$]. Post-hoc analysis showed that in the fast speed condition, older adults were significantly slower in their performance compared to young participants, using either hand, in both types of trials ($p = 0.01$ for both hands in both types of trials). In the preferred speed condition, although older adults showed a trend of moving slower than young participants, the difference was not significant between groups with either hand or in either type of trial (all $p > 0.08$).

With respect to MT variability in free- and blocked-trunk trials, there were significant main effects of Group [$F(1,34) = 11.39$, $p < 0.001$], Trial Type [$F(1,34) = 5.18$, $p = 0.02$], and a Hand x Trial Type interaction [$F(1,34) = 5.33$, $p = 0.03$]. When moving at a fast speed, older adults were significantly more variable than the young adults in both types of trials, using either hand. In contrast, when moving at their preferred speed, older adults were more variable than the young adults only when the left hand was used for both types of trials ($p < 0.001$). (Table 2.2).

2.5.3.2. Trunk Displacement

Similar to the SHT, trunk flexion was minimal during the blocked-trunk trials (on average 1.35 cm across hands and speed conditions). Moreover, there were no effects of Group, Hand, Speed, or any interaction with respect to the mean or the variability of trunk displacement. Collapsed across speeds, older adults had an average trunk displacement of 18.8 cm when reaching with the right hand and 17.6 cm when reaching with the left hand (Table 2.2). This was similar to the average trunk displacement in young adults, which was 18.2 cm and 17.0 cm when reaching with the right and left hands respectively (Table 2.2). In terms of variability, there was no significance difference between groups. When reaching with the right hand, variability in trunk displacement was 4.8 cm for older adults and 3.9 cm for young adults, while when reaching with the left hand, it was 4.8 cm for older adults and 4.7 cm for young ones, collapsed across speed conditions (Table 2.2).

2.5.3.3. Hand Deviation

Example 2D distance errors relative to the target are shown in Figure 2.2B and 2.2D for a typical young and older participant. Overall, participants reached 7.9 cm and 6.6 cm further from the target (i.e., overshot the target) in free- and blocked-trunk trials, respectively, with no differences in reaching errors between trial types for group, hand or speed (Figure 2.4A). From Figure 2.4B it appears that older adults had greater variability in final hand position in the free-trunk trials compared to young adults, however, the difference between groups was not significant (only a trend) [main effect of Group: $F(1,34) = 0.37$, $p = 0.07$] (Figure 2.4B). As well, there was no difference in variability of final endpoint positions between groups in the blocked-trunk trials.

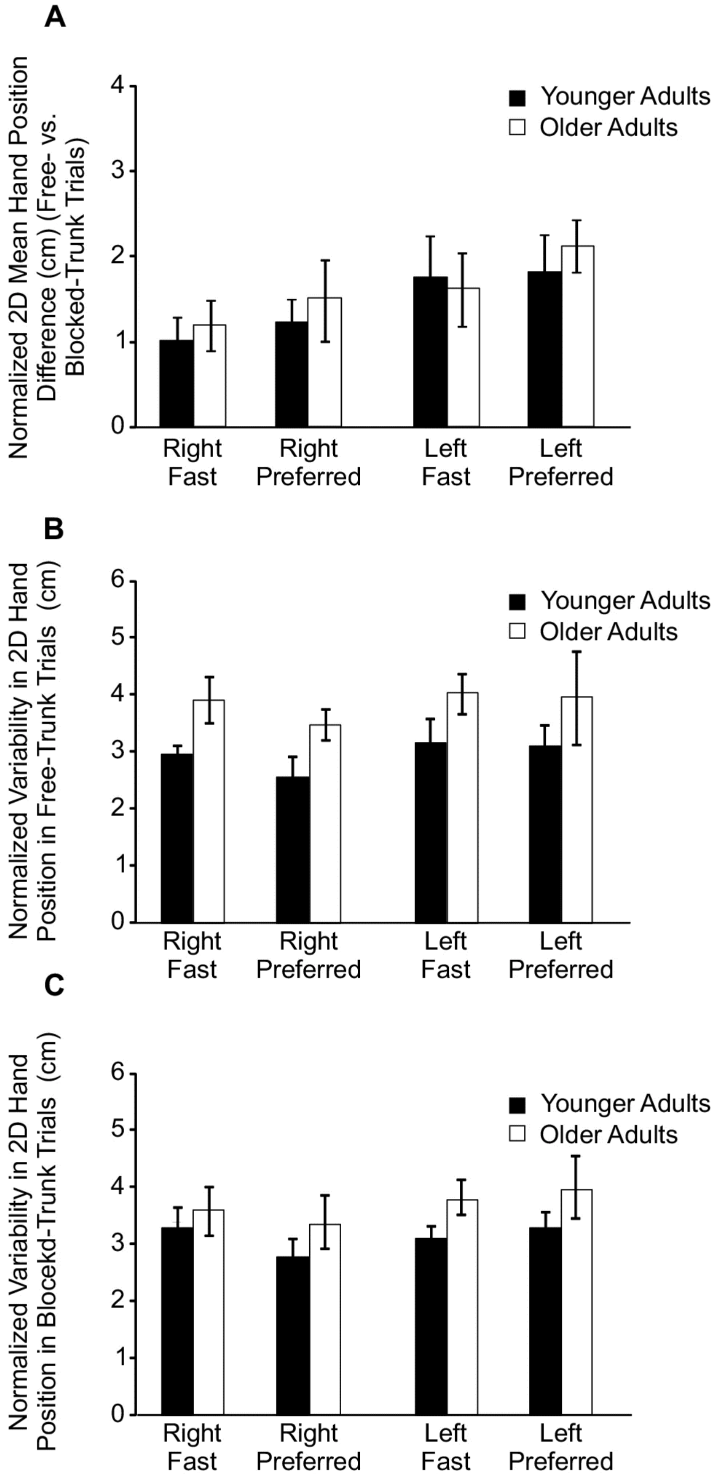

Figure 2.4 Normalized hand position differences (mean and variability) in the RHT

A. Normalized mean hand position differences in 2D in the RHT (Hand deviation). On average participants reached 1.3 cm further in the free-trunk trials compared to blocked-trunk trials. B. Variability in normalized 2D final hand position during the free-trunk trials in the RHT. C. Variability in normalized 2D final hand position during the blocked-trunk trials in the RHT. In both B and C, older adults showed a trend of greater variability compared to young adults but there was no significant effect of Group. Error bars reflect standard errors of the mean.

Table 2.3 Kinematic Measures in the RHT

Mean (standard deviation) and mean variability (standard deviation) for each kinematic variable is reported for each hand (right vs. left) used at each movement speed (preferred vs. fast). * Shows main effect of group (p < 0.05).

Hand / Speed	***Right / Preferred***		***Left / Preferred***		***Right / Fast***		***Left / Fast***	
Kinematic measures	**Mean**	**Variability**	**Mean**	**Variability**	**Mean**	**Variability**	**Mean**	**Variability**
Movement time (s)								
Young adults	Free: 1.17 (0.11) Blocked: 1.04 (0.17)	Free: 0.12 (0.04) Blocked: 0.11 (0.05)	Free: 1.14 (0.18) Blocked: 1.09 (0.33)	Free: 0.15 (0.97) Blocked: 0.15 (0.14)	Free: 0.89* (0.17) Blocked: 0.85* (0.20)	Free: 0.09 (0.04) Blocked: 0.15 (0.09)	Free: 0.88*(0.11) Blocked: 0.85* (0.17)	Free: 0.12 (0.05) Blocked: 0.12 (0.03)
Older adults	Free: 1.21 (0.37) Blocked: 1.24 (0.46)	Free: 0.15 (0.07) Blocked: 0.22 (0.19)	Free: 1.27 (0.32) Blocked: 1.18 (0.30)	Free: 0.18 (0.10) Blocked: 0.19 (0.15)	Free: 1.18* (0.48) Blocked: 1.18* (0.48)	Free: 0.18 (0.06) Blocked: 0.24 (0.13)	Free: 1.11* (0.33) Blocked: 1.14* (0.40)	Free: 0.18 (0.11) Blocked: 0.21 (0.13)
Trunk displacement (cm)								
Young adults	18.61 (11.44)	3.79 (2.31)	17.72 (12.24)	4.42 (2.39)	17.73 (11.57)	3.94 (1.77)	16.30 (11.32)	5.03 (1.57)
Older adults	19.14 (3.72)	4.17 (2.21)	18.19 (4.59)	4.85 (2.92)	18.37 (2.71)	5.51 (2.94)	17.02 (4.71)	4.77 (2.34)

2.6. Discussion

We examined age-related differences in arm-trunk coordination during two motor tasks; the Stationary Hand Task and the Reaching Hand Task. In the SHT, both groups were able to compensate for trunk motion in the free-trunk trials by appropriate changes in elbow and shoulder joint rotations as demonstrated by high gain scores (mean score range between 0.75-0.81) and minimal hand deviations (~1.4 cm compared to the blocked-trunk trials) regardless of the hand used and movement speed. In the RHT, young and older adults made similar small overshoot errors (~ 1.3 cm) in free- compared to blocked-trunk trials, for both hands and movement speeds. This small difference suggests that participants were able to compensate for the effect of trunk movement on hand position. On the other hand, performance of older adults was significantly more variable compared to the young adults as shown by the larger variability in gain scores in the SHT, greater variability in final hand positions when the trunk was involved in the SHT, and higher MT variability in the RHT.

2.6.1. Stationary Hand Task

The goal for this task was to keep the hand stationary under the fixed target position while flexing the trunk forward. Participants in both groups were able to reduce the influence of trunk motion on the hand position as demonstrated by high gain scores, reflecting that the hand remained relatively stationary. These findings resemble those previously reported for young and middle-aged healthy participants (Adamovich et al., 2001; Raptis et al., 2007; Sibindi et al., 2013). Previous literature has suggested that when the trunk is intentionally involved in reaching to targets placed within arm's reach, the influence of the trunk movement on the hand position is compensated for by appropriate rotations of the elbow and shoulder joints (Ma & Feldman, 1995; Pigeon et al., 2000; Adamovich et al., 2001). In neurologically intact participants, this compensation has been suggested to be driven by afferent signals (proprioceptive and/or vestibular) elicited by the trunk movement and transmitted to the arm muscles (Adamovich et al., 2001; Tunik et al., 2003; Raptis et al., 2007). Specifically, trunk motion is accompanied by vestibular signals from the associated head movement. These signals can be sent to the spinal cord by different descending pathways such as the vestibulospinal and reticulospinal tracts (Lobel et al., 1998), influencing motoneurons of arm muscles and resulting in compensatory changes in the arm joint angles during movement. Moreover, trunk flexion evokes proprioceptive signals from muscles in the hip, trunk, and neck in addition to proprioceptive signals from the joints and skin. These signals can be sent to arm motoneurons by short- and long-loop pathways (propriospinal and transcortical tracts) resulting in compensatory arm movements (Adamovich et al., 2001, Bresciani et al., 2002b, 2005; Mars et al., 2003; Guillaud et al., 2006). Since all our participants were healthy with no musculoskeletal or neurological impairments, these sensory feedback signals would be expected to be available during the performance of the motor task, potentially leading to similarities in the degree of compensation regardless of age.

2.6.2. Reaching Hand Task

Hand deviations were small in both groups of participants in the RHT despite the task complexity. Specifically, participants in both groups were able to neutralize the effect of trunk movement on hand displacement. These results are also consistent with the findings of Archambault et al. (1999) and Adamovich et al. (2001), who reported similar compensation in healthy young participants, as well as Raptis et al. (2007) and Sibindi et al. (2013), who showed good compensation for trunk movement in healthy middle-aged participants. It has been suggested that while the brain issues central commands for transporting the hand to the target and flexing the trunk, compensatory arm movements are not issued in the same way (i.e., modifications in arm joint angles to diminish the influence of the trunk flexion on the hand). Instead, compensation emerges from vestibular and proprioceptive signals evoked by the trunk movement, leading to a reorganization of the arm movement synergy. Control systems have also been suggested to modulate the degree of compensation by “gating” the afferent signals evoked by the trunk movement to provide the appropriate contribution of the trunk to hand transport based on the task requirements (e.g., whether the target is within or beyond the reach of the arm) (Adamovich et al., 2001).

2.6.3. The difference in movement speed between groups

Young and older adults had similar preferred speeds when completing both the SHT and RHT. Young adults were able to increase the speed of their movements when instructed to move faster. Older adults were also able to increase their movement speed, but only when using their left hand. Previous research has suggested that movement slowing with aging may be strategic in older adults such that they may select a strategy in which greater emphasis is placed on response accuracy leading to a decrement in speed of performance (Seidler & Stelmach, 1998).

In contrast to our hypothesis, the performance of older adults with respect to mean outcome measures and variability was similar across instructed movement speeds. One reason for this similarity across speed conditions, may be due to their inability to increase their movement speed in either task with the right hand. Although young adults were able to increase their movement speed significantly in both tasks and with both hands, the increase in movement speed did not impact their movement kinematics (i.e., gain in SHT and hand deviation in RHT). In a previous study, Messier et al. (2003) had older adult participants make reaching movements to four remembered visual targets at slow, natural, and fast speeds. Their results showed that participants made larger spatial errors at both slow and fast speeds compared to their natural speed. However, most movement kinematic features were invariant across speed conditions. It is possible that their subjects were able to sustain fairly accurate and straight hand trajectories for multi-joint reaching movements at different speeds regardless of changes in inter-segmental dynamics or interaction torques (Morasso, 1981; Hollerbach & Flash, 1982; Adamovich et al., 1994; Gordon et al., 1994b).

2.6.4. Handedness

We found that the hand used did not influence movement kinematics in either the SHT or RHT (specifically, gain and hand deviation scores). Similar findings have been shown in other studies. For example, when Al-Senawi and Cooke (1985) instructed participants to move a lever in the horizontal plane to different distances (i.e., 5°, 10°, 20°, 30°, and 40°) with each arm at a self-selected speed, there was no difference in spatial error between the arms and the velocity profiles were nearly identical. In another study, Sainburg and Kalakanis (2000) asked participants to move their hand to targets that required 20° of elbow extension and either 5°, 10°, or 15° of shoulder extension without visual feedback using both the dominant and non-dominant arms. Although each arm used a different strategy to reach the target (i.e., the dominant arm used elbow and shoulder torques synergistically to move the upper arm but the same torques countered one another in the non-dominant arm), accuracy was similar for both limbs. Such findings support the notion of motor equivalence (Head, 1920; Bartlett, 1932; Bernstein, 1967; Schmidt, 1975).

2.6.5. Inter-joint coordination

Our findings in both motor tasks did not support our hypotheses. Since aging results in a decline in sensorimotor control and functioning, we expected that older participants would show an increase of the influence of trunk motion on hand position, i.e., a decrease in the gain score in the SHT, and exhibit greater hand deviation, i.e., greater deviation of the finger position in the free- compared to blocked-trunk trials in the RHT. Few studies have evaluated the effects of aging on coordination. Moreover, most previous studies have focused on inter-limb rather than intra-limb coordination, with inconclusive findings. For example, Stelmach et al. (1988) found greater reaction time differences between the two hands for older adults compared to young adults during bimanual aiming movements. On the other hand, Rothstein et al. (1989) showed no age effects on inter-limb differences in movement initiation and termination times. In a study by Seidler and colleagues (2002), intra-limb coordination in older adults was examined during the performance of multi-joint arm pointing movements to four different targets. One target could be reached using elbow extension only and the remaining three required a coordination between elbow extension and shoulder horizontal flexion. Older adults co-activated antagonist muscles to a greater extent than young adults for single-joint actions, which compensated for heightened muscle force variability leading to smoother movements. On the other hand, older adults did not apply this compensatory mechanism to movements that were more complex, i.e., double-joint movements. Instead, they decreased co-activation levels when transitioning from single- to double-joint actions, while young adults increased their elbow joint co-activation. Decreasing co-activation was accompanied by movements that became less smooth and less accurate as shoulder joint contribution increased. Based on these results, Seidler et al. (2002) concluded that increasing co-activation may be difficult for older adults to implement in double-joint actions due to increases in complexity of movement planning and associated energy costs. Therefore, older adults appeared to use co-activation in a fundamentally different manner from the young adults. In our experiment, similar to young adults, older adults showed good compensation for trunk motion in the SHT and attained similar hand deviation errors in the RHT. However, performance of older adults was significantly more variable in the SHT and trended to greater variability in the RHT compared to young participants. We did not investigate the activation in upper-limb muscles while performing the tasks. Further investigation regarding the activation in upper-limb agonist and antagonist muscles is needed in order to determine what compensatory strategy older adults used that resulted in similar performance to the young participants but accompanied with a significant increment in variability.

2.6.6. Variability in performance (SHT and RHT)

Performance of older adults was more variable compared to young participants in both the SHT and RHT (see Table 2.1 and Table 2.2). Variability in motor output can be defined as the unintentional variations in the output of voluntary contractions (Christou, 2010). It can be found within a trial (e.g., movement trajectory) or from trial to trial (e.g., endpoint variability) (Christou, 2010). It is well documented that older adults exhibit greater motor output variability compared to young adults. Literature suggests that both forms of variability (within trial and between trials) are associated with greater end-point error in force, displacement, and time in older adults (Christou et al., 2007; Christou, 2011), which influence their ability to move smoothly and accurately (Christou, 2005). Moreover, increased variability may decrease the ability to learn new tasks and adapt to changing environments, thus compromising their independence (Christou, 2009). The increment in variability in movements of older adults has been linked to altered activation of the involved muscles due to structural and neural changes associated with aging in higher centers (e.g., death of cortical neurons) (Eisen et al., 1996) and the spinal cord (e.g., motor unit reorganization) (Enoka et al., 2003). According to Darling et al. (1988), who compared muscle EMG patterns and trajectory variability between movements made by older participants with those of young ones during an aiming task, the increase in variability of movements with age can be caused by factors affecting the production of joint torques necessary for acceleration and deceleration of the limb. These factors include: 1) changes in the motor neuron population and firing rate variability, and 2) abnormal control of the phasic and tonic antagonist muscle activity. Moreover, the inconsistency in the performance of older adults in their ability to maintain endpoint performance (i.e., maintain a stable hand position) in reaching tasks requiring additional DFs (i.e., trunk movement) implies decreases in movement adaptability (i.e., capacity of motor equivalence) (Raptis et al., 2007; Sibindi et al., 2013; Tunik et al., 2004).

2.7. Conclusion

To summarize, healthy older adults were able to maintain a stable hand position when reaching movements involved the trunk. The preservation of hand position was achieved by active compensatory changes in the arm joint angles nullifying the influence of the trunk motion on hand position. The integration of additional degrees of freedom (trunk) into movement is assumed to be driven by afferent signals (proprioceptive and/or vestibular) evoked by the trunk motion and transmitted to the arm muscles. Despite the fact that older adults were able to coordinate arm and trunk movements efficiently during the reaching actions, they were not as consistent as young adults. This increase in variability across movements could be linked to structural and neural changes at higher centers (i.e., brain and spinal cord) associated with aging and may suggest a reduction in the capacity of the nervous system to achieve motor equivalence (i.e., reduced movement adaptability).

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3. Chapter 3 Age-related changes in upper limb coordination in a complex reaching task

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3.1. Abstract

When reaching to targets within arm's reach, intentional trunk motion must be neutralized by compensatory motion of the upper limb (UL). Advanced age has been associated with deterioration in the coordination of multi-joint UL movements. In the current study we looked to determine if older adults also have difficulties modifying their UL movements (i.e., coordination between the shoulder and elbow joints), during a complex reaching task when trunk motion is manipulated. Two groups of healthy participants were recruited: 18 young (mean age = 24.28 ± 2.89 years old) and 18 older (mean age = 72.11 ± 2.39 years old) adults. Participants reached to a target with their eyes closed, while simultaneously moving the trunk forward. In 40% of trials, the trunk motion was unexpectedly blocked. Participants performed the task with both their dominant and non-dominant arms, and at a preferred and fast speed. All participants were able to coordinate motion at the elbow and shoulder joints in a similar manner and modify this coordination in accordance with motion at the trunk, regardless of the hand used or speed of movement. Specifically, in reaches that involved forward trunk motion (free-trunk trials), all participants demonstrated increased elbow flexion (i.e., less elbow extension) compared to blocked-trunk trials. In contrast, when trunk motion was blocked (blocked-trunk trials), all reaching movements were accompanied by increased shoulder horizontal adduction. While coordination of UL joints was similar across older and young adults, the extent of changes at the elbow and shoulder was smaller and less consistent in older adults compared to young participants, especially when trunk motion was involved. These results suggest that older adults can coordinate their UL movements based on task requirements, but that their performance is not as consistent as young adults.

3.2. Introduction

Motor equivalence refers to the phenomenon of multiple ways to perform the same motor task using different degrees of freedom (DFs) (Lashley, 1951; Bernstein, 1967; Latash et al., 2007). For example, reaching movements can be performed using only the arm DFs or can include additional DFs of the scapula and trunk. Specific adaptive strategies have been described to maintain the stability of the hand trajectory when reaching. For reaching movements to targets placed within arm's reach, the hand trajectory remains invariant in terms of direction, curvature, velocity, and error whether reaches are made with or without trunk movement (i.e., in the case when one bends forward while reaching for a cup). The ability to maintain endpoint position or trajectory invariance despite the addition of the trunk movement occurs through adaptive motor equivalent modifications of elbow and shoulder movement. These modifications combine two spatial movement synergies: an arm-transport synergy that coordinates the arm joints to bring the hand to the target and a compensatory arm–trunk synergy that decreases the influence of the trunk motion on the hand position by additional arm-joint changes (Ma & Feldman, 1995; Archambault et al., 1999; Pigeon & Feldman, 1998). Such compensatory synergies have been described for other movement tasks such as eye-head coordination provided by the vestibulo-ocular reflex, with the purpose of nullifying the gaze shift elicited by head rotations (Crawford & Vilis, 1991).

Analysis of reaching synergies provides information on underlying motor control and movement adaptability mechanisms and how they may be affected by aging. Aging is accompanied by declines in skilled motor performance, including coordination across the elbow and shoulder joints (Welford, 1984; Seidler, Alberts, & Stelmach, 2002). Specifically, upper limb (UL) movements involving multiple joints are 15-30% slower in older adults over 75 years of age compared to young adults and their movements are less smooth (Diggles-Buckles, 1993). Furthermore, adults over 65 years demonstrate declines in movement spontaneity (Luft et al., 1999), greater time to initiate (reaction time: RT) and execute (movement time: MT) movement (Yan et al., 1998), greater spatial and temporal variability (Contreras-Vidal et al., 1998), and more inaccurate movements when executing multi-joint movements (Poston et al., 2013; Seidler et al., 2002) compared to young adults. Older adults also have difficulty adapting movements to changing environmental and task requirements (Vaillancourt & Newell, 2002; Newell, Vaillancourt, & Sosnoff, 2006). Such functional changes may be related to degenerative neuromuscular changes, including a reduction in the number of corticospinal fibers (Eisen, Entezari-Taher, & Stewart, 1996), declines in intracortical inhibition (Peinemann, Lehner, Conrad, & Siebner, 2001), decreased number of spinal motoneurons (Tomlinson & Irving, 1998), and neuronal degradation in other higher nervous centers, such as the cerebellum and basal ganglia (Sjobeck, Dahlen, & Englund, 1999; Raz, Williamson, Gunning-Dixon, Head, & Acker, 2000).

In order to understand the ability of older adults to modify shoulder and elbow coordination in response to changing task demands, we performed a detailed comparison of UL kinematics during reaches in the presence and absence of trunk motion (i.e., free- vs. blocked-trunk trials) between young and older adults. Specifically, young and older adults performed the Reaching Hand Task (RHT) of Raptis et al. (2007). Given that aging is characterized by slowness in motor performance, reaches were performed at two speeds, participants' comfortable speed (similar to Sibindi et al. (2013)) and a fast speed (i.e., as fast as possible). Additionally, participants performed each task with their dominant arm and non-dominant arm in order to examine the effect of handedness.

In the current study, successful completion of the task necessitated rapid adaptive changes in UL inter-joint coordination in response to the presence or absence of trunk motion. Given that aging is accompanied by deterioration in adaptive motor behaviour (Kapur, Zatsiorsky, & Latash, 2010; Verrel, Lövdén, & Lindenberger, 2012) and a decline in coordination of multi-joint movements (Poston et al., 2013; Seidler et al., 2002), we expected older participants to demonstrate: 1) decreased UL coordination between the elbow and shoulder joints during performance of the RHT (e.g., delayed onset and magnitude of compensatory modifications), 2) decreased movement consistency (e.g., varied onset and magnitude of compensatory modifications among older participants), and 3) impaired ability to modify UL inter-joint coordination to account for changes in the availability of trunk motion (e.g., decreased motor equivalence).

3.3. Methods

The procedures and data presented below were part of a larger study examining UL coordination in older adults, for which movement accuracy related to the RHT was previously reported (Khanafer et al., 2019).

3.3.1. Participants

Two groups of participants were recruited: 18 healthy young adults (mean age = 24.3 ± 2.9 years), and 18 sex-matched healthy older adults (mean age = 72.1 ± 2.4 years). All participants were free of musculoskeletal, neurological, or cognitive deficits that could interfere with the performance of the experimental tasks (Dizziness Handicap Inventory mean score (both groups) = 1.7/100 ± 0.9 (Jacobson & Newman, 1990), joint position sense test mean score (both groups) = 8/8 (Hall & McCloskey, 1983), Ottawa Sitting Scale mean score (both groups) = 38.6/40 ± 1.2 (Thornton & Sveistrup, 2010), Montreal Cognitive Assessment mean score (older adults only) =

27.7/30 ± 0.7 (Nasreddine et al., 2005). Mean performance on these assessments are provided in Table 2.1 for the Older participants. Older participants' scores fell within normal ranges reported in the literature for both cognitive (see Nasreddine et al., 2005; Kessels et al., 2022), and proprioceptive assessments (see Stillman, 2000; Gilman, 2002) in healthy individuals aged between 18 and 60 years old. Thus, we considered our older participants to be high functioning individuals. As well, all participants were right-handed as indicated by their responses to the 10-item Edinburgh Handedness Inventory (mean score = +82.7 ± 17.9, where scores > +40 indicate strongly right-handed) (Oldfield, 1971). All participants provided informed consent prior to the start of the experiment in accordance with the ethical guidelines of the Research Ethics Board of the University of Ottawa.

Table 3.1 Mean performance of older adults on the sensory, motor, and cognitive assessments

Participant minimum (min) and maximum (max) scores are provided in brackets for each assessment. Scores are provided for the older adult Group.

Assessment	Older Adults
Dizziness Handicap Inventory	1.7/100 (min = 0, max = 6)
Joint Position Sense	8/8 for each hand (min = 8, max = 8)
Ottawa Sitting Scale	38.6/40 (min = 37, max = 39)
Montreal Cognitive Assessment	27.7/30 (min = 27, max = 30)

3.3.2. Apparatus

A VICON motion capture system (VICON motion systems, UK; 3D resolution 2.5 mm), including 7 cameras and 8 reflective markers, was used to record movement kinematics. Five markers were placed on the UL being tested [index fingertip (endpoint), radial styloid (wrist), lateral epicondyle of the humerus (elbow), ipsilateral acromion (ipsi shoulder), and contralateral acromion (contra shoulder)], and additional markers were placed in the middle of the sternum (trunk), forehead, and on the target. Data were recorded at a sampling rate of 60 Hz for 5 s.

3.3.3. Experimental Set-Up

Participants were seated on a stool (i.e., chair with no back support or arm rests), with their feet on the ground, shoulder width apart, and facing the motion tracking system (Portable Cartesian Stand of VICON; Figure 3.1A). Participants wore a harness, fastened posteriorly at the level of the scapula and held by a second experimenter. A fixed target was positioned at approximately 60% of the participant's arm length (from the medial axillary border of the shoulder to the tip of their index finger) and was represented by a "yoyo" attached to a belt hanging from the ceiling and positioned at nose level. Participants performed the RHT as described below and illustrated in Figure 3.1.

3.3.3.1. Reaching Hand Task

Participants were seated with the testing arm positioned on an arm rest placed next to the trunk at hip level initially. At a verbal "go" signal, participants closed their eyes and reached to the target with their testing arm while simultaneously leaning forward with their trunk (free-trunk trial in which participants flexed at their hips) (see Figure 3.1B). When participants believed that their hand had reached the target, they were instructed to hold the final hand position until they were verbally prompted (approximately 2 s) to return their hand to the start position and open their eyes. Participants completed the task with each arm at two speeds, once moving as quickly as possible and once moving at their preferred, comfortable speed. For each arm and speed, participants completed 4 sets of 10 trials (40 trials per arm and per speed) with a 2-minute rest between each set of 10 trials, for a total of 160 trials.

In 40% of trials, trunk motion was unexpectedly blocked prior to the onset of movement by an examiner who held the handle attached to the back of the tightly fitted harness strapped to the participant's upper trunk (blocked-trunk trials). When blocked, the trunk motion was arrested for the entire trial. On these blocked-trunk trials, participants were still required to try to lean forward while reaching the same end target position as in free-trunk trials. The percentage of the blocked-trunk trials was chosen based on previous research suggesting that 40% is sufficient to minimize anticipation of the upcoming trunk condition (Adamovich et al., 2001; Raptis et al., 2007).

The order of the testing arm (right or left) was counterbalanced across participants. Participants completed the task with the same arm, at two speed conditions, before the second arm was tested. With each arm, participants completed the task first at their preferred speed then as fast as possible. Within each task, the type of trial (free- versus blocked-trunk) was also randomized.

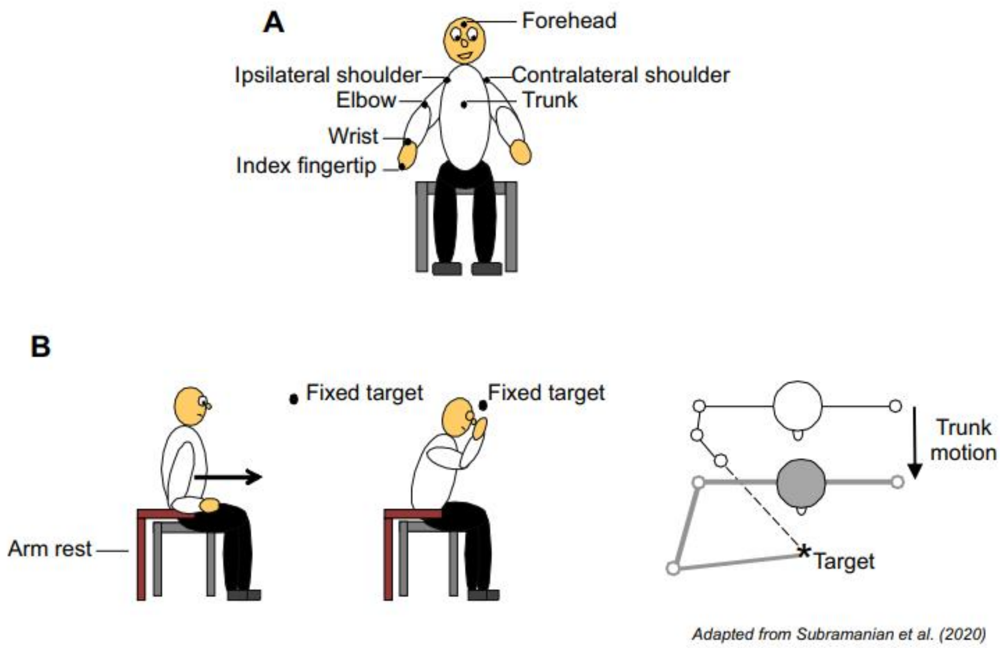

Figure 3.1 Experimental set-up and procedures

A. Marker positions: Reflective markers were placed on the UL being tested [index fingertip (endpoint), radial styloid (wrist), lateral epicondyle of the humerus (elbow), ipsilateral acromion (ipsi shoulder), and contralateral acromion (contra shoulder)]. Additional markers were placed on the middle of the sternum (trunk), forehead, and on the target (not shown in the figure)]. B. Reaching Hand Task: Participants were seated with the testing arm positioned on an arm rest which was placed next to the trunk at hip joint level to ensure a multi-joint movement. In this task, participants were to move their testing arm to the target, while simultaneously flexing forward with their trunk. The right-side sketch in B shows the start position as the lighter segments and the end position as the darker segments.

3.4. Data Analysis

3.4.1. Performance Variables

Data from each trial were analyzed using custom-written software in MATLAB version R2013a. Elbow and shoulder angles were calculated based on the dot product of vectors defined by the coordinates of appropriate markers. The elbow angle (i.e., flexion-extension) was computed based on the product of two vectors, one joining the markers on the wrist and lateral epicondyle and the other joining the markers on the lateral epicondyle and acromion (i.e., shoulder), where a fully extended arm equals 180°. The shoulder angle (i.e., horizontal abduction-adduction) was measured as the horizontal projection of the angle between vectors, one defined by the right and left shoulder markers and the other parallel to the humerus between the right or left shoulder and elbow markers, where the arm in line with the two shoulders equals 180° (Adamovich et al., 2001; Subramanian et al., 2020).

Movement onset and offset were calculated for the hand (i.e., index finger) and trunk, as well as the elbow and shoulder from tangential velocity traces, where onset and offset were defined as the times at which tangential velocity first surpassed and remained above or fell and remained below 10% of the peak velocity (PV) for the body segment/angle of interest. PV of the hand, trunk, elbow and shoulder were defined as the highest velocity value achieved for the body segment/angles of interest during the movement. Movement time (MT) of the trial was determined based on hand motion. We computed the difference in time between movement onset and offset of the trunk relative to the hand. As well, the difference in time between movement onset and offset of the elbow and shoulder relative to the trunk were used to determine whether participants were able to elicit the compensatory modifications at an appropriate time.

3.4.1.1. Arm Compensatory Modifications

We further computed changes at individual joints, to determine age-related differences in coordination in reaches with and without trunk motion. In order to compensate for trunk motion in free-trunk trials or to preserve the arm movement in blocked-trunk trials, modifications in arm joint angles were required. To determine the magnitude of changes at the shoulder and elbow, vectors joining the appropriate markers were used to compute shoulder horizontal abduction-adduction and elbow flexion-extension angles using vector algebra. Additionally, trunk forward motion in the anterior–posterior (A/P) direction (i.e., trunk displacement) was computed and expressed in cm. The magnitude of change at the shoulder, elbow (both in degrees), and trunk (in cm) were calculated by finding the difference in joint/segment position at the end of the motion versus the start of the motion.

3.4.1.2. Inter-joint Coordination (IJC)

Compensatory arm movements were evaluated based on the coordinated change between shoulder horizontal abduction-adduction and elbow flexion-extension, rather than on changes in a single joint (Adamovich et al., 2000, 2001). Specifically, elbow-shoulder inter-joint coordination was evaluated by calculating the slope and the coefficient of determination (r^2) of the linear regression equation between shoulder and elbow joint motion for each reaching movement. Positive slope values indicated that the shoulder moved to a more horizontally adducted position and the elbow moved to a less extended (i.e., more flexed) position. The magnitude of the positive slope value indicates the contribution of both joints. A slope equal to 1 indicates that both joints contributed equally to the task, whereas slope values greater or less than 1 indicate that the movement primarily involved one joint.

3.4.1.3. Statistical Analyses

Mean and variability (standard deviation) of the magnitude of trunk flexion and trunk peak velocity in free-trunk trials were analyzed in a two Group (old vs. young) x 2 Arm (dominant/right vs. non-dominant/ left) x 2 Speed (preferred vs. fast) mixed analysis of variance (ANOVA) with repeated measures (RM) on the last two factors. For all other variables analyzed, mean values and variability were compared across participants using a 2 Group x 2 Trial Type (free- vs. blocked- trunk trials) x 2 Arm x 2 Speed (preferred vs. fast) mixed ANOVA with RM on the last three factors. For all analyses, differences with a probability of < 0.05 were considered significant and Bonferroni post-hoc analyses were performed to determine the loci of the differences.

3.5. Results

Given the lack of significant differences between groups with respect to variability across the majority of the dependent variables examined, only significant findings related to variability are reported in the text. All results related to mean performance and mean performance variability are reported in Tables 2.1 and 2.2 respectively.

3.5.1. Movement Time, Movement Onsets and Offsets

In Khanafer et al. (2019), we reported that both groups completed the task in approximately 1.2 s (SD = 0.1 s) in the preferred speed condition, using either arm and in both types of trials (i.e., in free- and blocked-trunk trials; see Table 2.1). Young participants were able to execute the movement significantly faster when instructed (mean MT = 0.87 s (SD = 0.2 s)), while older adults were not able to do so regardless of the arm used or the type of trial (mean MT = 1.2 s (SD = 0.4 s)) [$F(1,34) = 5.38$, $p = 0.03$, $\eta p^2 = 0.14$]). With respect to MT variability, older adults demonstrated greater variability than young adults, regardless of trial type or arm used [$F(1,34) = 11.39$, $p < 0.001$, $\eta p^2 = 0.12$] (see Table 2.2).

In free-trunk trials, both groups began moving their trunk approximately 100 ms (SD = 0.85 ms) prior to hand motion. Trunk motion ceased 210 ms (SD = 1.1 ms) after the hand stopped moving. To prevent trunk motion from contributing to the hand trajectory, participants needed to make appropriate compensatory modifications in the arm joint angles. For all participants, compensatory changes at both the elbow and shoulder were initiated 60 ms (SD = 1.8 ms) following trunk motion onset. As well, motion at the elbow and shoulder continued throughout the trunk motion, and up to 200 ms (SD = 0.95 ms) after the hand stopped moving. In blocked-trunk trials, UL motion at the elbow and shoulder began approximately 75 ms (SD = 1.3 ms) following trunk arrest, for both young and older participants. Motion at the elbow and shoulder continued for 150 ms (SD = 0.91 ms) after the hand stopped moving to maintain the hand's trajectory. Statistical analysis revealed no significant main effects of Group, Arm, Speed, and no interactions (all *p's* > 0.05) with respect to movement onset and offset of the trunk, elbow and shoulder.

3.5.2. Peak Velocity

With respect to trunk peak velocity, statistical analysis showed a significant effect of Group [$F(1,34) = 4.21$, $p = 0.04$, $\eta p^2 = 0.11$] and Group x Speed interaction [$F(1,34) = 7.71$, $p < 0.001$, $\eta p^2 = 0.19$]. Post hoc analysis revealed a significant difference between groups in the fast speed condition for both arms ((left arm: young adults: 0.31 m/s (SD = 0.1 m/s) vs. older adults: 0.22 m/s (SD = 0.1 m/s) ($p = 0.02$); right arm: young adults: 0.32 m/s ± 0.1 vs. older adults: 0.17 ms (SD = 0.1 m/s) ($p = 0.02$)), but not at the preferred speed with either arm ((left arm: young adults: 0.24 m/s (SD = 0.1 m/s) vs. older adults: 0.21m/s (SD = 0.1 m/s) ($p = 0.29$); right arm: young adults: 0.24 m/s (SD = 0.1 m/s) vs. older adults: 0.21 m/s (SD = 0.1 m/s) ($p = 0.29$)) (Figure 3.2A). Moreover, the difference in trunk peak velocity between speed conditions was significant in young adults for both arms but not for older adults for either arm ($p < 0.001$) (Figure 3.2A).

With respect to hand peak velocity, ANOVA revealed a significant effect of Speed [$F(1,34) = 19.19$, $p < 0.001$, $\eta p^2 = 0.36$], Group x Speed interaction [$F(1,34) = 6.68$, $p = 0.01$, $\eta p^2 = 0.16$], and Group x Arm interaction [$F(1,34) = 4.29$, $p = 0.04$, $\eta p^2 = 0.11$]. Hand peak velocity was similar between groups in the preferred speed condition across both types of trials (1.2 ± 0.31 m/s; Figure 3.2B & 3.2C). In the fast speed condition, young adults were able to increase their hand peak velocity significantly to 1.7 m/s (SD = 0.64 m/s), in both types of trials ($p < 0.001$), while older adults were not able to do so; their hand peak velocity increased only to 1.3 m/s (SD = 0.52 m/s), in both types of trials ($p = 0.23$), (Figure 3.2B & 3.2C). According to post hoc analysis, in the fast speed condition, older adults were significantly slower in their performance compared to young participants, using either arm, in both types of trials ($p = 0.01$ for both arms in both types of trials) (Figure 3.2B & 3.2C).

Elbow peak velocity and shoulder peak velocity did not vary between groups, across trial types, arms or speed conditions (all *p's* > 0.05). Specifically, collapsed across both speed conditions, mean elbow peak velocity was 133.7 degree/s (SD = 6.7 degree/s), and mean shoulder peak velocity was 104.6 degree/s (SD = 9.1 degree/s), in both free- and blocked- trunk trials.

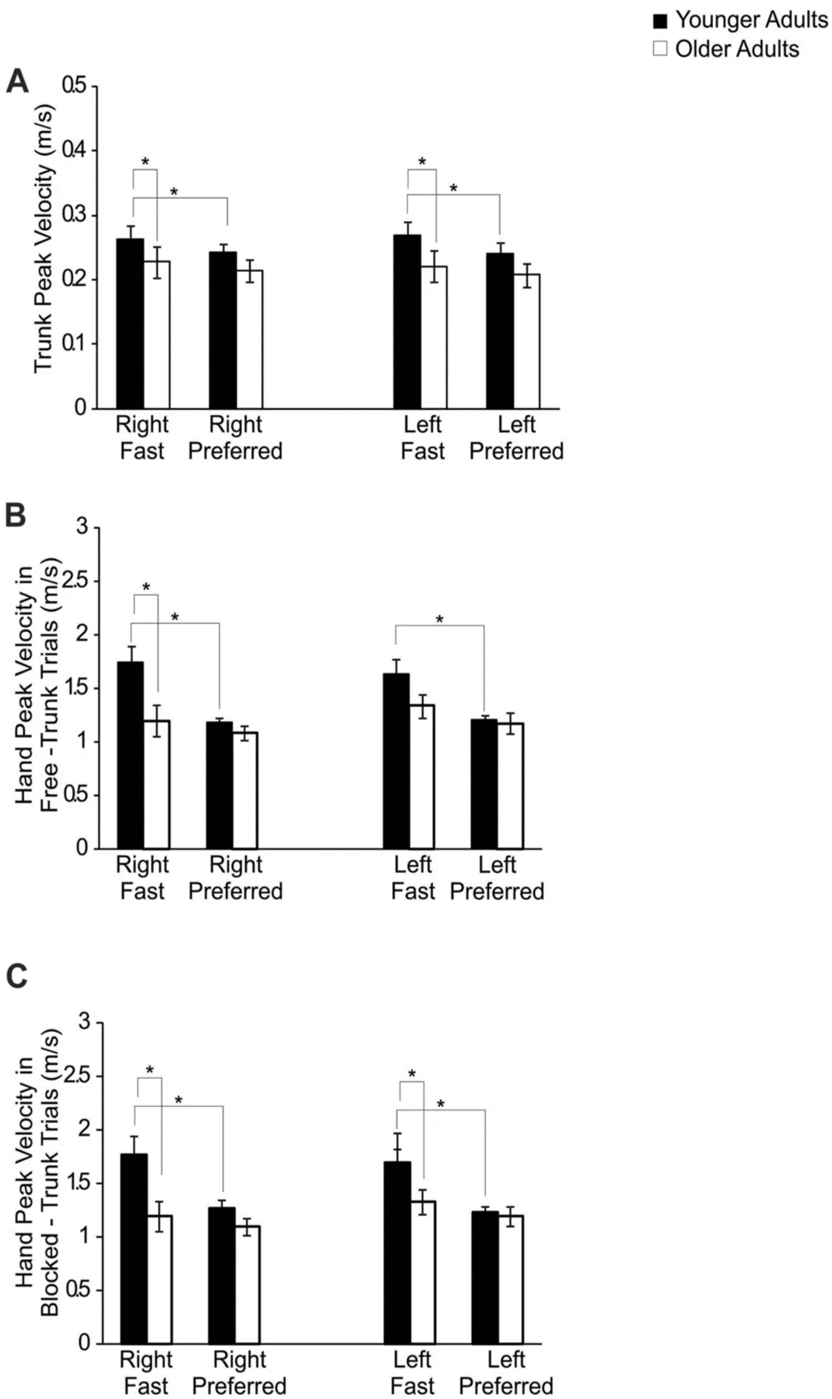

Figure 0.2 Mean trunk peak velocity and mean hand peak velocity in the RHT during free- and blocked-trunk trials

A. Older adults demonstrated a slower trunk peak velocity compared to young participants in the fast speed condition. Young participants demonstrated a significant difference in trunk peak velocity between preferred and fast speeds conditions when reaching with both arms, while older adults moved at similar speeds across the 2 types of movements. B &C. Across participants, the difference in hand peak velocity between speed conditions was only significant in young adults for both arms in free- and blocked-trunk trials. *Error bars* reflect standard errors of the mean. Asterisks indicate significant differences ($p < 0.05$).

3.5.3. Arm Compensatory Modifications

Trunk displacement during the blocked-trunk trials was limited (on average 1.35 cm across arms and speed conditions). Moreover, there was no influence of group, arm or speed on the variability of trunk flexion. In the free-trunk trials, trunk displacement was 18.2 cm (SD = 3.9 cm) for older adults and 17.6 cm (SD = 3.1 cm) for young adults across arms and speed conditions. These values were not statistically different between groups [$F(1,34) = 2.61$, $p = 0.83$, $\eta p^2 = 0.03$].

With respect to the magnitude of elbow extension, statistical analysis showed a significant effect of Group [$F(1,34) = 7.02$, $p = 0.001$, $\eta p^2 = 0.17$], Trial Type [$F(1,34) = 192.54$, $p < 0.001$, $\eta p^2 = 0.85$], and Group x Trial Type interaction [$F(1,34) = 19.05$, $p < 0.001$, $\eta p^2 = 0.36$] (Figure 3.3). The changes at the elbow joint were smaller in the older adult group compared to the young adult group by 7.6° in free-trunk trials and by 3.8° in blocked-trunk trials, however, the difference between groups was only significant during free-trunk trials ($p < 0.001$). Moreover, to minimize the influence of trunk motion on hand trajectory, participants in both groups extended their elbow significantly less during the free-trunk trials (Figure 3.3A) compared to blocked-trunk trials (Figure 3.3B), for both arms and at both speeds ($p < 0.001$). In terms of variability, statistical analysis revealed a main effect of Trial Type [$F(1,34) = 16.49$, $p < 0.001$, $\eta p^2 = 0.33$] and a Group x Trial Type interaction [$F(1,34) = 7.86$, $p < 0.001$, $\eta p^2 = 0.19$]. According to post-hoc analysis, elbow joint extension was significantly more variable in older compared to young adults, regardless of arm used or trial type.

With respect to shoulder horizontal adduction, older adults tended to have smaller changes at the shoulder joint compared to young adults (e.g., smaller by 4.4° in free-trunk trials and by 2.4° in blocked-trunk trials). These differences between groups were not significant [$F(1,34) = 0.73$, p

= 0.34]. ANOVA revealed a significant effect of Trial Type [$F(1,34) = 66.85$, $p < 0.001$, $\eta p^2 = 0.66$]. That is, participants in both groups adducted their shoulder in the horizontal plane significantly less in free-trunk trials (Figure 3.3A) compared to blocked-trunk trials (Figure 3.3B).

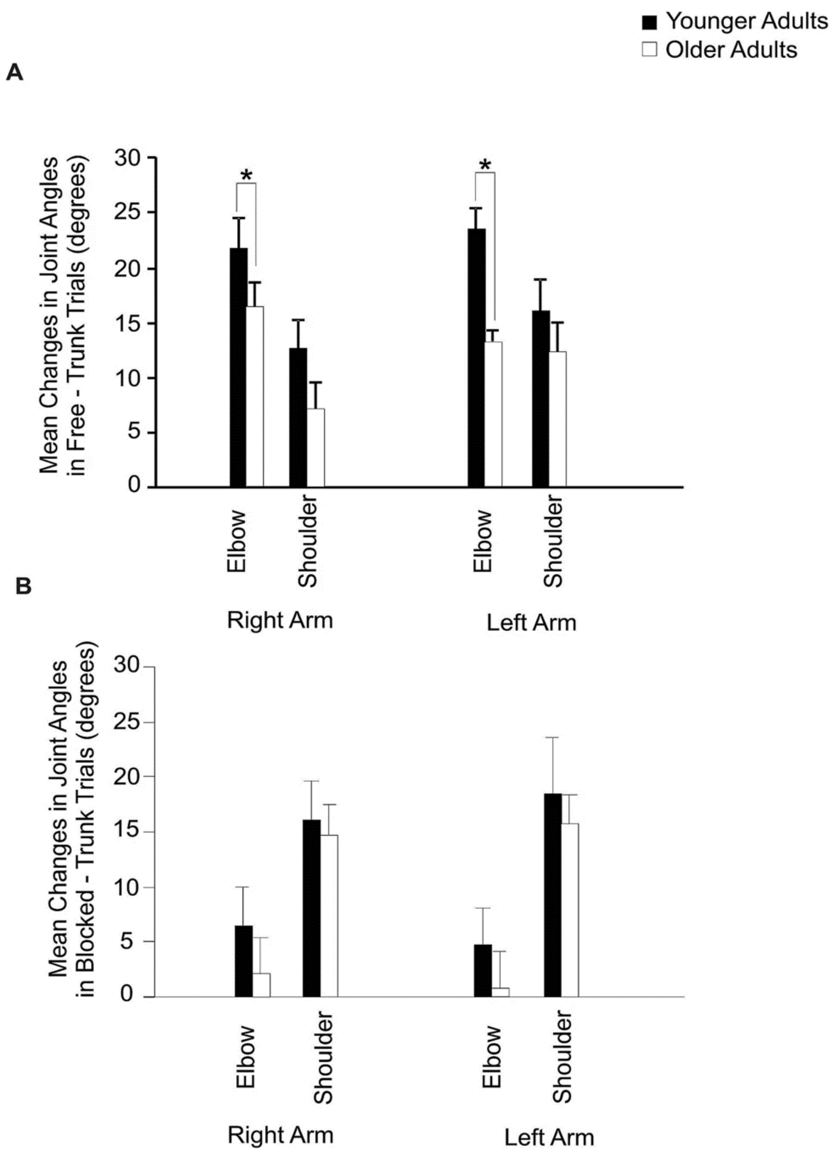

Figure 0.3 Mean changes in joint angles during free- and blocked-trunk trials

A. The modifications in elbow angle were significantly smaller in the older adult group compared to young participants in the free-trunk trials. B. There was no difference in motion at the elbow and shoulder in the blocked trunk trials. Asterisks indicate significant differences ($p < 0.05$).

3.5.4. Inter-Joint Coordination

The slope of the linear regression equations fit to motion at the elbow and shoulder joints did not differ between groups ($p > 0.05$). However, statistical analysis revealed a main effect of Trial Type [$F(1,34) = 93.71$, $p < 0.001$, $\eta p^2 = 0.62$]. In free-trunk trials, the mean slope values were 1.37 (SD = 0.13) in older adults and 1.52 (SD = 0.11) in young adults, collapsed across arms and speed conditions. These slope values indicate that participants in both groups mainly limited elbow extension (i.e., greater elbow flexion) to compensate for trunk motion (Figure 3.4A & 3.4B). On the other hand, when trunk motion was blocked (Figure 3.4C & 3.4D), the mean slope values, collapsed across arms and speeds, were 0.62 (SD = 0.13) and 0.79 (SD = 0.12) in older and young participants, respectively. These values indicate that participants in both groups adducted their shoulder in the horizontal plane to a greater extent to reach for the target with minimal hand deviation compared to free-trunk trials (Figure 3.4C & 3.4D). With respect to the goodness of fit, ANOVA revealed no significant main effect of Group or Trial Type (all *p's* > 0.05). The mean r^2 values were on average 0.69 (SD = 0.1) for older adults and 0.77 (SD = 0.1) for young participants in free-trunk trials, collapsed across arms and speed conditions. As well, the mean r^2 values were 0.62 (SD = 0.1) in older adults and 0.71 (SD = 0.1) in young adults in blocked-trunk trials, collapsed across arms and speed conditions. The high r^2 values suggest that elbow and shoulder joint motion were highly spatially coupled in both groups, regardless of trunk motion.

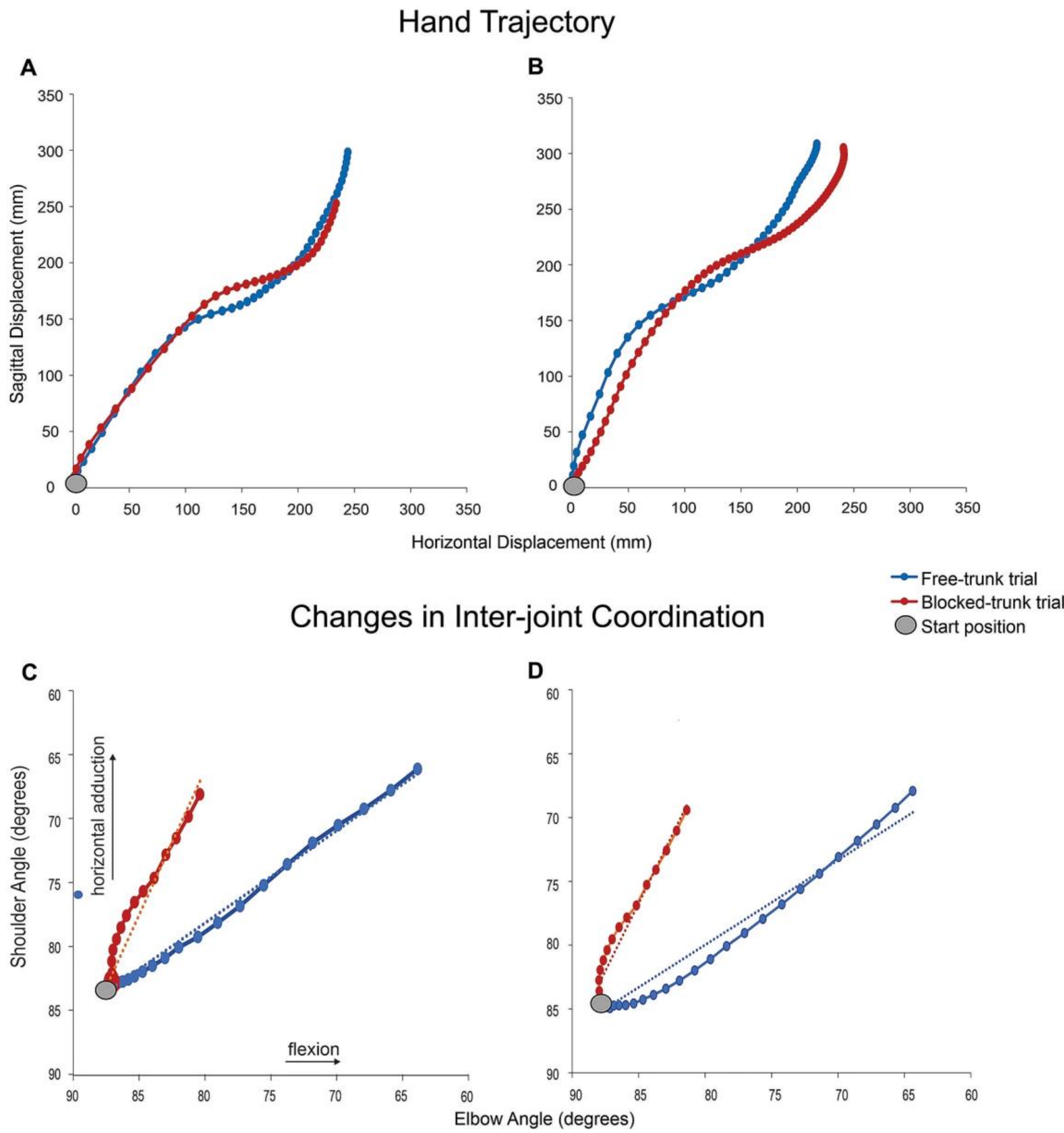

Figure 0.4 Hand trajectory and changes in inter-joint coordination in free- and blocked-trunk trials

Top panel: Example of reaching trajectory of the hand (in mm) when the trunk was free (blue line) and when it was blocked (red line) in one young adult (A) and one older adult (B) when moving the left arm at a comfortable speed. Bottom panel: changes in inter-joint coordination (in degrees) in these two types of trials in a young participant (C) and older participant (D). Both participants changed the coordination between their shoulder and elbow joints to maintain the same reaching trajectory in the two conditions (i.e., free vs. blocked trunk condition).

Table 3.2 Mean performance in the RHT

Young and Older participants' mean performance (standard deviation) is reported for each dependent variable of interest when the task was completed with the right and left arms at participants preferred and fast speed. * Indicates a main effect of group ($p < 0.05$) and $^{+}$ indicates a main effect of trial type (i.e., free- vs. blocked-trunk trials) ($p < 0.05$).

Arm / Speed	Right / Preferred		Left / Preferred		Right / Fast		Left / Fast	
Trial Type	**Free**	**Blocked**	**Free**	**Blocked**	**Free**	**Blocked**	**Free**	**Blocked**
Movement Time (s)								
Young Adults	1.17 (0.11)	1.04 (0.17)	1.14 (0.18)	1.09 (0.33)	0.89 (0.17) *	0.85 (0.20) *	0.88 (0.11) *	0.85 (0.17) *
Older Adults	1.21 (0.37)	1.24 (0.46)	1.27 (0.32)	1.18 (0.30)	1.18 (0.48) *	1.18 (0.48) *	1.11 (0.33) *	1.14 (0.40) *
Hand Peak Velocity (m/s)								
Young Adults	1.18 (0.15)	1.27 (0.35)	1.20 (0.18)	1.23 (0.23)	1.74 (0.66) *	1.77 (0.73) *	1.64 (0.55) *	1.69 (0.56) *
Older Adults	1.08 (0.27)	1.09 (0.33)	1.18 (0.93)	1.18 (0.39)	1.19 (0.62) *	1.19 (0.59) *	1.34 (0.45) *	1.33 (0.48) *
Trunk Flexion (cm)								
Young Adults	18.61 (1.44)	4.44 (1.22)	17.72 (2.24)	4.53 (1.04)	17.73 (1.57)	4.45 (1.52)	16.30 (1.32)	4.32 (1.35)
Older Adults	19.14 (3.72)	4.63 (1.66)	18.19 (4.59)	4.74 (1.57)	18.37 (2.71)	4.75 (1.72)	17.02 (4.71)	4.54 (1.83)
Elbow Flexion (°)								
Young Adults	22.05 (2.74) * $^{+}$	5.56 (14.38) $^{+}$	22.41 (1.99) * $^{+}$	4.38 (14.16) $^{+}$	21.70 (2.84) * $^{+}$	6.49 (15.11) $^{+}$	23.45 (1.88) * $^{+}$	4.86 (13.63) $^{+}$
Older Adults	16.88 (2.79) * $^{+}$	1.01 (16.04) $^{+}$	13.99 (2.59) * $^{+}$	1.83 (16.47) $^{+}$	15.35 (2.26) * $^{+}$	2.23 (13.98) $^{+}$	13.11 (1.47) * $^{+}$	0.84 (14.47) $^{+}$
Shoulder Horizontal adduction (°)								
Young Adults	13.91 (3.03)	17.27 (15.16)	14.82 (4.34)	20.14 (17.57)	12.53 (2.74)	16.14 (15.44)	15.98 (3.15)	16.43 (19.09)
Older Adults	7.43 (2.53)	14.71 (12.26)	13.12 (3.43)	17.99 (13.67)	7.01 (2.56)	14.81 (11.86)	12.17 (3.11)	12.94 (9.26)

Elbow Flexion vs. Shoulder Horizontal adduction Slope								
Young Adults	0.91 (0.46)	0.89 (0.55)	0.82 (0.25)	0.75 (0.18)	0.85 (0.54)	0.83 (0.19)	0.67 (0.12)	0.71 (0.17)
Older Adults	0.83 (0.26)	0.67 (0.48)	0.65 (0.49)	0.60 (0.40)	0.76 (0.42)	0.62 (0.36)	0.72 (0.24)	0.40 (0.41)

Table 3.3 Mean variability in the RHT

Young and Older participants' mean variability (standard deviation) is reported for each dependent variable of interest when the task was completed with the right and left arms at participants preferred and fast speed. * Indicates a main effect of group ($p < 0.05$) and + indicates a main effect of trial type (free- vs. blocked-trunk trials) ($p < 0.05$).

Arm / Speed	**Right / Preferred**		**Left / Preferred**		**Right / Fast**		**Left / Fast**	
Trial Type	**Free**	**Blocked**	**Free**	**Blocked**	**Free**	**Blocked**	**Free**	**Blocked**
Movement Time (s)								
Young Adults	0.12 (0.04)	0.11 (0.05)	0.15 (0.97) *	0.12 (0.04)	0.11 (0.05)	0.15 (0.97) *	0.12 (0.04)	0.11 (0.05)
Older Adults	0.15 (0.07)	0.22 (0.19)	0.18 (0.10) *	0.19 (0.15) *	0.18 (0.06) *	0.24 (0.13) *	0.18 (0.11) *	0.21 (0.13) *
Hand Peak Velocity (m/s)								
Young Adults	0.11 (0.06)	0.13 (0.06)	0.11 (0.04)	0.13 (0.05)	0.14 (0.07)	0.21 (0.12)	0.15 (0.05)	0.19 (0.06)
Older Adults	0.12 (0.08)	0.17 (0.09)	0.13 (0.05)	0.16 (0.08)	0.21 (0.14)	0.23 (0.16)	0.19 (0.09)	0.24 (0.13)
Trunk Flexion (cm)								
Young Adults	3.79 (2.31)	2.33 (1.10)	4.42 (2.39)	2.42 (2.25)	3.94 (1.77)	2.05 (1.70)	5.03 (1.57)	2.71 (1.53)
Older Adults	4.17 (2.21)	5.57 (2.22)	4.85 (2.92)	2.60 (2.85)	5.51 (2.94)	3.01 (2.45)	4.77 (2.34)	2.92 (1.82)
Elbow Flexion (°)								
Young Adults	3.44 (2.09) *	4.61 (2.24) *	3.97 (1.22) *	4.71 (2.06) *	4.17 (1.31) *	5.80 (2.38) *	3.86 (1.34) *	5.29 (1.86) *
Older Adults	5.12 (1.79) *	5.36 (2.86) *	5.54 (2.97) *	5.07(2.23) *	5.56 (1.65) *	7.29 (3.23) *	5.92 (2.31) *	6.26 (2.86) *
Shoulder Horizontal adduction (°)								

Young Adults	4.23 (3.12)	3.98 (1.76)	5.62 (2.74)	3.84 (1.30)	4.87 (2.08)	5.39 (2.27)	6.04 (5.59)	4.83 (1.26)
Older Adults	4.04 (1.52)	4.44 (2.03)	4.75 (2.27)	4.43 (1.65)	6.40 (4.97)	6.17 (3.38)	6.08 (4.37)	5.44 (3.99)
Elbow Flexion vs. Shoulder Horizontal adduction Slope								
Young Adults	0.40 (0.23)	0.32 (0.26)	0.45 (0.31)	0.31 (0.19)	0.46 (0.29)	0.43 (0.42)	0.62 (0.24)	0.58 (0.41)
Older Adults	0.52 (0.37)	0.42 (0.30)	0.53 (0.48)	0.47 (0.34)	0.49 (0.36)	0.58 (0.44)	0.79 (0.12)	0.71 (0.17)

3.6. Discussion

It is well documented that young participants are able to adapt their movements in response to changes in task and/or environmental demands. This adaptation has been suggested to arise due to the concept of motor equivalence (Lashley, 1951). Specifically, the same motor outcome can be achieved using different degrees of freedom. In the current study we asked if degenerative changes in the neuromuscular system due to aging may lead to deficits in motor equivalence, and hence, the ability to rapidly adapt movement to changes in task demands (i.e., trunk motion). Contrary to our hypothesis, participants in both groups were able to coordinate their movements between elbow and shoulder joints according to the trunk motion condition. When the trunk was involved in the movement, subjects used less elbow extension to compensate for the influence of the trunk forward motion on the final hand position. When the trunk motion was blocked, reaching movements were accomplished using more shoulder horizontal adduction. While a similar trend in inter-joint coordination was seen in both older and young adults, older adults showed a decrease in compensatory modification at the elbow and shoulder (i.e., decrease in the magnitude of changes in shoulder and elbow angles), and tended to have greater trunk displacement. Moreover, older adults were less consistent in their performance compared to young participants, regardless of the trunk motion condition, as shown by the larger variability in elbow extension movements.

3.6.1. Movement Time and Amplitude

Older participants were able to use the appropriate compensatory modifications at the elbow and shoulder at an appropriate time whether or not the trunk was involved in the reaching to ensure that the hand reached the target with similar accuracy as young adults. These results extend previous findings, demonstrating similarities in the timing of arm and trunk motion in healthy young adults (Adamovich et al., 2001; Rossi, Mitnitski, & Feldman, 2002), healthy middle-aged adults (Raptis et al., 2007; Sibindi et al., 2013), stroke patients (Levin, 1996; Archambault et al., 1999; Subramanian et al., 2020), vestibular patients (Raptis et al., 2007; Sibindi et al., 2013), and deafferented patients (Tunik et al., 2003).

In Khanafer et al. (2019), we reported that for the RHT, movement duration did not vary between groups in the preferred speed condition. In contrast, only young adults were able to decrease their movement time significantly when instructed to move faster (Khanafer et al., 2019). In the current study, these findings were extended by analyzing hand peak velocity. Like our previous findings, both groups had a similar hand peak velocity in the preferred speed condition, but only young participants were able to increase their hand peak velocity significantly when instructed to move faster. According to previous literature, slowness in performance associated with advanced age could be attributed to older adults selecting a movement strategy in which greater emphasis is placed on response accuracy leading to a decrement in movement speed (Goggin & Stelmach, 1990; Seidler-Dobrin & Stelmach, 1998).

Across all participants, we found that movement speed was not influenced by trunk motion. Similar to our findings, Kaminski et al. (1995) and Ma and Feldman (1995) also found that the velocity profile of the hand trajectory remained invariant despite the contribution of the trunk in the transportation of the hand to the target. Thus, it has been suggested that the invariance of the hand trajectories across conditions was due to the compensatory arm–trunk synergy. The current results extend these findings and suggest that older adults are capable of engaging a similar compensatory arm-trunk synergy, suggesting a preservation in their ability to produce motor equivalent actions within the framework of a redundant reaching task.

3.6.2. Inter-joint coordination

Previous studies examining compensatory arm-trunk synergies (e.g., Levin, 1996; Archambault et al., 1999; Adamovich et al., 2001; Michaelsen, Luta, Roby-Brami, & Levin, 2001; Raptis et al., 2007; Sibindi et al., 2013; Subramanian et al., 2020) suggest that the arm compensatory synergy is driven by proprioceptive feedback and/or vestibular feedback arising from motion at the hip joint, or associated head motion, respectively. In our study, older and young participants used compensatory arm coordination to preserve the endpoint trajectory. All of our participants were healthy, with no history of serious musculoskeletal or neurological problems, thus proprioceptive and vestibular sensory signals would be expected to be available during the performance of each motor task. However, the integrity of proprioceptive and vestibular systems has been shown to decline with advanced aging (Welford, 1977; Salthanouse, 1985; Stelmach & Worringham, 1985; Gleeson & Felix, 1987). This decline may be responsible for the differences observed between groups with respect to the magnitude of motion at the elbow and shoulder joints, when the trunk was involved in the movement.

The linear regression analysis supports the notion that the nervous system benefits from the redundancy in the number of DFs. Specifically, we found that when trunk motion was involved in the movement, participants tended to limit elbow extension to decrease the influence of trunk motion on endpoint trajectory. On the other hand, shoulder horizontal adduction was increased to reach the target when trunk motion was blocked. Similar findings have been shown in a recent study in which inter-joint coordination in the non-dominant arm of healthy older adults and both arms of individuals with chronic stroke were examined using the same RHT protocol (Subramanian et al., 2020). In healthy participants, when the trunk was involved in the movement, the task was done with relatively more elbow than shoulder movement (slope = 1.28).

Across our task, older adults tended to have more variable performance compared to young participants (Table 3.2), however, the difference between groups did not reach significance. Increase variability with advanced age could be related to a significant loss of motor units (Campbell, McComas, & Petito, 1973) and/or alternations in the morphology and properties of existing motor units (Hepple & Rice, 2016). As well, advanced age has been shown to lead to increased neural noise, which may lessen the efficiency of delivering the information in the sensorimotor system (Walker, Philbin, & Fisk, 1997), and greater cortical involvement of non-motor areas in motor actions executed by upper limbs (Voelcker-Rehage et al., 2006; Fraser et al., 2010).

3.6.3. Handedness

In accordance with our previous findings (Khanafer et al., 2019), movement kinematics were not influenced by hand dominance. Similarly, in reaches to targets placed at different aiming angles, no difference in spatial errors was found between arms and the velocity profiles of each arm were nearly identical (Al-Senawi & Cook, 1985; Poston et al., 2009). Even when visual feedback was eliminated, reaching accuracy was similar for both arms (Sainburg & Kalakanis, 2000). Moreover, when instructional conditions of reaching movements are varied (e.g., fast vs.

accurate), dominant and non-dominant arms had similar relative timing (i.e., proportion of the total time required by any phase of the movement; Roy et al., 1994). These results support the notion of similar capacity for motor equivalence in both dominant and non-dominant arms.

3.7. Conclusion

Aging is associated with a general decline in motor performance. In this study, we determined if these deficits include changes in one's ability to modify UL coordination in a complex motor task in which trunk motion was unexpectedly manipulated. We found that older adults were able to modify their UL movements and reach to the target by utilizing the appropriate compensatory modifications at arm joints based on task demands. On the other hand, older adults demonstrated declines in UL performance reflected by decreases in angular modifications at the arm joints when trunk motion was involved and less consistent performance.

3.8. References

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4. Chapter 4 The influence of age on the intermanual transfer and retention of implicit visuomotor adaptation

A version of this chapter has been published online in the Journal of Motor Behavior:

Khanafer, S., Sveistrup, & Cressman, E. K. (2022). The influence of age on intermanual transfer and retention of implicit visuomotor adaptation.

4.1. Abstract

We examined age-related changes in intermanual transfer and retention of implicit visuomotor adaptation. We further asked if providing augmented somatosensory feedback regarding movement endpoint would enhance visuomotor adaptation. Twenty young adults and twenty older adults were recruited and randomly divided into an Augmented Feedback group and a Control group. All participants reached to five visual targets with visual feedback rotated 30° counter-clockwise relative to their actual hand motion. Augmented somatosensory feedback was provided at the end of the reach via the robotic handle that participants held. Implicit adaptation was assessed in the absence of visual feedback in the right trained hand and in the left untrained hand following rotated training trials to establish implicit adaptation and intermanual transfer of adaptation respectively. Participants then returned 24 hours later to assess retention in the trained and untrained hands. Results revealed that older adults demonstrated a comparable magnitude of implicit adaptation, transfer and retention of visuomotor adaptation as observed in young adults, regardless of the presence of augmented somatosensory feedback. To conclude, when visuomotor adaptation is driven implicitly, intermanual transfer and retention do not differ significantly between young and older adults, even when the availability of augmented somatosensory feedback is manipulated.

4.2. Introduction

Visuomotor adaptation is a form of motor learning and can be assessed in a laboratory setting by having participants reach to targets in an altered visual environment. For example, visual feedback regarding hand position can be distorted by having participants reach in a virtual environment while a cursor on a screen misrepresents the position of their hand in space (Sainburg & Wang, 2002; Cressman & Henriques, 2009; Cheng & Sabes, 2007). When first introduced to the visuomotor distortion, participants typically make large reaching errors, such that the cursor does not land on the target as expected. However, over the course of training trials, reaches are adapted such that the cursor once again lands on the target (Krakauer et al., 2000; Cressman & Henriques, 2009; Maksimovic & Cressman, 2018). Moreover, when participants are then instructed to reach directly to the target in the absence of visual feedback, they tend to make reaching errors in the opposite direction of the visual distortion, such that they continue to reach as if they were still influenced by the visuomotor distortion (Krakauer et al., 1999, 2000; Baraduc & Wolpert, 2002; Cressman & Henriques, 2009, 2010). These reaching errors are referred to as “aftereffects,” and are suggested to reflect implicit (i.e., unconscious) motor adaptation arising in response to experiencing a sensory prediction error (i.e., the predicted and actual sensory feedback experienced do not match; Wolpert, Ghahramani, & Jordan, 1995a; Baraduc & Wolpert, 2002).

In addition to visuomotor adaptation observed in the trained hand, visuomotor adaptation has been shown to transfer to the untrained hand (Sainburg & Wang, 2002; Wang & Sainburg, 2003, 2006; Thompson & Henriques, 2010). Studies have further reported that visuomotor adaptation is maintained long after initial training, such that retention is observed when assessed several days following training or even up to a year later (Yamamoto et al., 2006; Nourouzpour et al., 2015;

Maksimovic & Cressman, 2018). Retention of visuomotor adaptation has been established by observing aftereffects at the start of a second testing session, i.e., recall (Krakauer et al., 1999; Baraduc & Wolpert, 2002; Yamamoto et al., 2006) and/or savings within a second testing session, i.e., faster relearning upon exposure to a previously experienced visuomotor distortion compared to initial training performance (Krakauer et al., 1999; Bock et al., 2001; Tong, Wolpert, & Flanagan, 2002; Caithness et al., 2004; Krakauer et al., 2005). Recent work has suggested that explicit processes (i.e., engagement of a cognitive strategy) contribute to intermanual transfer (Poh, Carroll, & Taylor, 2016; Werner, Struder, & Donchin, 2019; Bouchard & Cressman, 2021) and retention (Morehead, Qasin, Crossley, & Ivry, 2015; Haith, Huberdeau, & Krakauer, 2015; Bouchard & Cressman, 2021) in young adults. Specifically, Bouchard and Cressman (2021) reported that explicit adaptation observed in the trained hand was transferred completely to the untrained hand, whereas implicit adaptation did not significantly transfer between hands. Moreover, explicit adaptation was retained in both hands over testing days. In contrast, while implicit adaptation was present in the trained hand 24 hours later, the magnitude of implicit adaptation had decayed.

The trends in performance and engagement of implicit and/or explicit processes in visuomotor adaptation reported above are based on results observed in young, healthy adults. Given that the ability of the motor system to adapt to changes within the body and the environment is critical for ensuring appropriate motor function throughout the lifespan, it is imperative that we understand our ability to adapt our movements with advanced age. To date, research examining the effects of aging on visuomotor adaptation, including intermanual transfer and retention of visuomotor adaptation, has been limited and findings controversial (Buch et al., 2003; Bock, 2005; Seidler, 2007; Cressman, Salomonczyk, & Henriques, 2010; Wang et al., 2011; Leow et al., 2012, 2013;

Pan & Van Gemmert, 2013). Several studies examining visuomotor adaptation in older adults have reported that reaching errors when learning to reach with distorted visual feedback do not differ across young and older participants (e.g., Cressman et al., 2010), whereas others suggest that aging results in slower and reduced visuomotor adaptation (McNay & Willingham, 1998; Bock, 2005; Bock & Girgenrath, 2006; Heuer & Hegele, 2008, 2009, 2010a). On the other hand, older adults have consistently demonstrated aftereffects that are similar in magnitude to those observed in young participants (McNay & Willingham, 1998; Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon, Modchalingam, ‘t Hart, & Henriques, 2020). Based on these findings, it has been suggested that differences in performance across young and older adults may arise due to the ability to engage implicit and explicit processes (Buch et al., 2003; Bock, 2005; Heuer & Hegele, 2008; Anguera, Reuter-Lorenz, &mSeidler, 2010; Cressman et al., 2010; Vachon et al., 2020). Specifically, a similar magnitude of aftereffects is observed across young and older adults due to preserved implicit adaptation with aging. In contrast, less adaptation may be observed in older adults compared to young adults when first introduced to a (large) visuomotor distortion due to impairments in cognition (e.g., declines in strategic corrections and/or explicit knowledge of how to adjust one’s movements to counteract the visuomotor distortion) (Heuer & Hegele, 2014). In accordance with this proposal, Anguera et al. (2011) showed that age-related deficits during visuomotor adaptation are associated with declines in spatial working memory.

Given the proposed role of explicit processes in intermanual transfer and retention, and the declines in performance observed in older adults when explicit processes are engaged, one may assume that older adults have difficulty transferring or retaining visuomotor adaptation. To date, few studies have looked at intermanual transfer or retention of visuomotor adaptation in older adults. Wang et al. (2011) assessed intermanual transfer by having young and older adults (mean age 71 years old) complete reaches with the untrained (i.e., left) hand while seeing a cursor that was rotated 30° relative to hand motion following initial opposite (i.e., right) hand adaptation. As well, Pan and Van Gemmert (2013) had young and older adults (mean age 70 years old) perform a multidirectional pointing task with their untrained hand when visual feedback was rotated 45° relative to hand motion and a cursor gain of 1.4 was introduced following initial training of the opposite hand. Both studies found evidence of intermanual transfer regardless of age, such that participants reached with less errors when reaching with the left untrained hand after right hand training, compared to reaching naively with the left hand (i.e., having no prior training). However, neither study assessed intermanual transfer of adaptation in the absence of the distortion (i.e., transfer of aftereffects), which provides insight into the transfer of implicit adaptation. Additionally, intermanual transfer was only assessed in a single testing session, thus the ability of older adults to retain implicit visuomotor adaptation in the untrained hand remains to be determined.

With respect to the examination of retention of visuomotor adaptation (i.e., recall or savings in the trained hand), Reuter et al. (2020) had young and older adults (aged between 65–80 years old) reach while experiencing a 30° visuomotor distortion. Participants received feedback regarding task success/failure at the end of each trial. Results indicated that both young and older adults recalled about 14% of the visuomotor adaptation observed on the initial testing day and showed a similar extent of savings when re-exposed to the visual distortion two to seven days later. Reuter et al. (2020) argued that the absence of a significant behavioral deficit in their older adult sample could be due to recruiting older participants from the university community, who were presumed to be extremely high functioning on a cognitive level. Moreover, the success/failure feedback that was provided might have made the task particularly motivating, especially for older adults, and motivational feedback has been found to attenuate age-related differences in reach adaptation (Huang et al., 2018). Recruiting older adults from the community in a typical visuomotor adaptation study, where participants do not receive task success/failure feedback, is needed to provide insight into age-related differences in the retention of implicit visuomotor adaptation.

In the current research, we investigated the preservation of intermanual transfer and retention of implicit visuomotor adaptation in older adults. According to previous literature, adaptation to small cursor distortions (i.e., 30° or less) arises implicitly (Neville & Cressman, 2018; Vachon et al., 2020), while adaptation to larger rotations and/or when prior instructions are provided to counteract the visuomotor rotation tend to engage explicit processes (Buch et al., 2003; Bock, 2005; Neville & Cressman, 2018). Thus, we had young and older participants train to reach when a small 30° visuomotor distortion was introduced. Participants were not made aware of the introduction of the visuomotor distortion, nor instructed on how to counteract it. Based on previous results, we expected both young and older participants to adapt their reaches to the 30° in the training trials and demonstrate aftereffects when reaching in the absence of visual feedback (e.g., McNay & Willingham, 1998; Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon et al., 2020). We were then interested in establishing transfer of implicit visuomotor adaption from the trained right hand to untrained left hand in the absence of visual feedback, as well as retention in both hands. Given that adaptation was expected to be driven implicitly, we hypothesized that both young and older participants would demonstrate minimal transfer and retention of implicit adaptation, and that the overall extent would not differ across ages.

As a final question, we asked if providing augmented somatosensory feedback regarding movement endpoint would enhance intermanual transfer and retention of visuomotor adaptation. To date, enhancing augmented (somatosensory) feedback regarding movement outcome has been found to benefit motor learning in both young and older adults (see Sigrist et al., 2013). Moreover, motor adaptation has been shown to benefit from transient somatosensory cues (Emken et al., 2005) and amplified movement related error signals (Patton et al., 2013). Augmented somatosensory feedback was provided to half of the young and older participants at the end of their reach during training trials via the robotic handle that participants held, providing an additional external afferent signal indicating actual hand position. We expected to observe the greatest intermanual transfer and retention of visuomotor adaptation for participants in the augmented somatosensory feedback group, as motor learning has been shown to benefit from augmented somatosensory feedback (Emken et al., 2005; Sigrist et al., 2013).

4.3. Methods

4.3.1. Participants

Twenty healthy young adults (Young group ranging in age from 20 to 29 years; mean age = 24.3 ± 2.9 years old), and twenty healthy older adults (Older group ranging in age from 68 to 76 years; mean age = 72.1 ± 2.4 years old) were recruited to participate in this study from the Ottawa community via word of mouth and posters hung in community centers. Older adults had to be 65 years of age or older to participate. Sample size was determined based on previous investigations into visuomotor adaptation and older adults (see Cressman et al, 2010). Participants were further divided into sub-groups based on the feedback they would receive at the end of their reach. Specifically, half of the participants in the Young and Older groups were randomly placed in an Augmented Feedback group (Visual + Somatosensory feedback (V+S); 10 young adults and 10 older adults), and the remaining participants were placed in the Control group (Visual feedback only (V); 10 young adults and 10 older adults). Thus, the experiment consisted of 4 groups in total (Young V, Young V+S, Older V and Older V+S).

All participants were right-handed as indicated by their responses to the 10-item version of the Edinburgh handedness inventory (mean score = 82.7 ± 17.9; Oldfield, 1971) and reported being free from musculoskeletal, neurological, or cognitive deficits that would interfere with their performance on the experimental tasks. Cognitive abilities were further assessed for participants in the Older group using the: 1) Montreal Cognitive Assessment (Nasreddine et al., 2005), 2) Trail Making Test Parts A & B (Arnett & Seth, 1995), and 3) the three different sections of the Rey-Osterrieth Complex Figure (Osterrieth, 1944). Older adults also completed a joint position sense test (Hall & McCloskey, 1983) and a vibration sensation test using a 128 Hz tuning fork (Macleod, Munro, & Campbell, 2000) to assess their proprioceptive acuity. Mean performance on these cognitive and proprioceptive assessments are provided in Table 4.1 for the Older participants. Older participants' scores fell within normal ranges reported in the literature for both cognitive (see Tombaugh, 2004; Nasreddine et al., 2005; Ashendorf et. al., 2008; Roy & Molnar, 2013; Zhang et al., 2021; Kessels et al., 2022), and proprioceptive assessments (see Stillman, 2000; Gilman, 2002) in healthy individuals aged between 18 and 60 years old. Thus, we considered our older participants to be high functioning individuals. All participants provided informed consent prior to the start of the experiment in accordance with the ethical guidelines set by the University of Ottawa's Research Ethics Board.

Table 4.1 Mean performance of older adults on the cognitive and proprioceptive assessments
Participant minimum (min) and maximum (max) scores are provided in brackets for each assessment. Scores are provided for older adults in the Control and Augmented Feedback Group.

Assessment	Older Adults – Control Group	Older Adults – Augmented Feedback Group
Montreal Cognitive Assessment	27.7/30 (min = 27, max = 30)	27.6/30 (min = 26, max = 30)
Trail Making Test Part A (sec)	25.5 (min = 24, max = 27)	26.3 (min = 25, max = 28)
Trail Making Test Part B (sec)	76.1 (min = 70, max = 80)	75.7 (min = 70, max = 83)

Rey-Osterrieth Complex Figure - Copy	34.5 points (accuracy 90%) (min = 33.5, max = 36)	34.8 points (accuracy 90%)) (min = 33.5, max = 36)
Rey-Osterrieth Complex Figure – Immediate Recall	26.1 points (accuracy 70%) (min = 24, max = 28)	26 points (accuracy 70%) (min = 24, max = 27)
Rey-Osterrieth Complex Figure – Delayed Recall	24.5 points (accuracy 70%) (min = 22.5, max = 26.5)	24.6 points (accuracy70%) (min = 23.5, max = 25.5)
Joint Position Sense	8/8 for each hand (min = 8, max = 8)	8/8 for each hand (min = 8, max = 8)
Vibration Sensation	4/4 for each hand (min = 4, max = 4)	4/4 for each hand (min = 4, max = 4)

4.3.2. Experimental Set-Up

Participants were seated in a height adjustable chair so that they could comfortably see and reach to all targets. Once the chair was adjusted, it remained in the same position during the entire experimental session. Participants were asked to grasp the vertical handle of a 2-joint robot manipulandum (END-Point Lab, KINARM Technologies, Kingston, Ontario) with their dominant right hand (Figure 4.1A). Visual stimuli were projected from a monitor onto a reflective surface. The reflective surface was opaque and positioned 20.5 cm below the monitor so that images displayed on the monitor appeared to lie in the same horizontal plane as that of the robot handle, positioned 20.5 cm below the reflective surface. The room lights were dimmed, and participants' view of their right and left hands was blocked by the reflective surface and a black cloth that was draped between the experimental set-up and participants' shoulders.

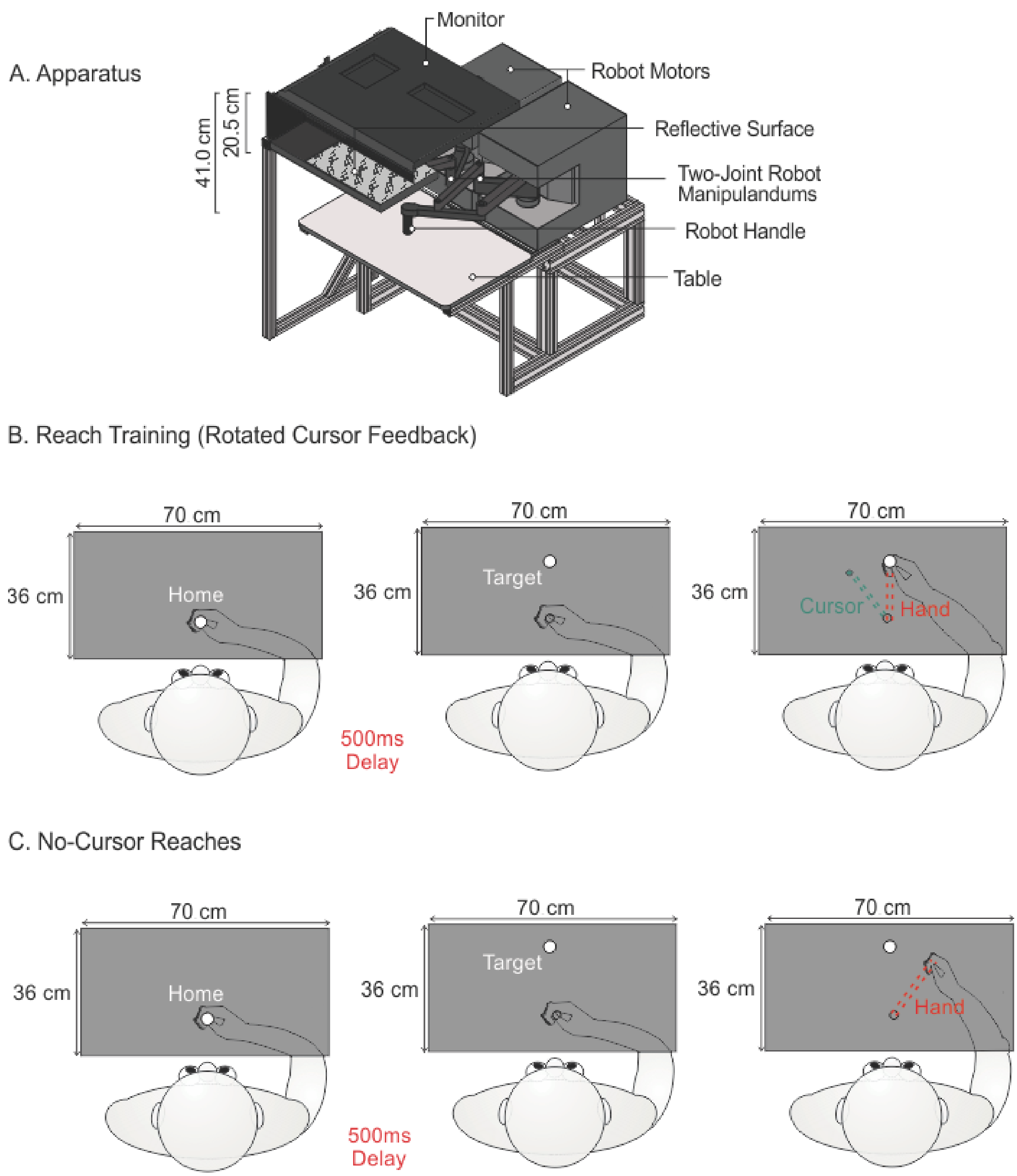

Figure 4.1 Experimental apparatus and visual stimuli

A. A side view of the experimental set-up. Participants were seated in a height adjustable chair so that they can comfortably see and reach to all targets. Participants were asked to grasp the vertical handle of a 2-joint robot manipulandum (KINARM Technologies, Kingston, Ontario) with either their right or left hand. B. Training trials with rotated cursor feedback (Rotation session). After maintaining their hand at the home position for 500 ms, a single target (white circle, 1 cm diameter) appeared cueing the participant to start their reach. During rotated training, the cursor (green circle, 1 cm diameter) representing the participant's hand was rotated 30° counter-clockwise relative to the trajectory of the unseen hand. C. No-cursor reaches. Participants reached to visual targets in the absence of visual feedback.

4.3.3. Procedures

In general, participants reached to 5 targets, with each target represented by a white circle (1 cm in diameter), located 12 cm from a central home position (white circle, 1 cm in diameter). The home position was located approximately 20 cm in front of a participant's chest and aligned with their midline. The targets were then located straight ahead of the home position (at 0°), as well as 30° and 60° to the right and left of the 0° target. To start a trial, the robot moved the participant's hand to the home position, and 1 of the 5 targets was displayed on the screen in a pseudo-random order, such that each target was displayed once before any target was repeated.

The experiment consisted of 10 testing blocks completed in a fixed order over three sessions. The first two sessions were completed on Day 1 and the third session completed on Day 2, 24 hours later. A breakdown of the blocks completed in each session is shown in Figure 4.2. On Day 1, participants completed a Baseline session (top row Figure 4.2) and an Adaptation session (middle row Figure 4.2). In both of these testing sessions, participants completed 125 training trials (i.e., B2) in which they reached with cursor feedback that was aligned with their hand position (Baseline Session) or rotated 30° counter-clockwise (CCW) relative to their hand trajectory (Adaptation Session). The training trials were preceded (i.e., B1) and followed (i.e., B3) by reaches performed with no-cursor feedback. The no-cursor reaches consisted of 10 trials performed first with the right hand, followed by 10 trials performed with the left hand. The Baseline session ended with participants completing 50 reaches with their left hand with aligned cursor feedback (i.e., B4). On Day 2 (i.e., Retention session, bottom row Figure 4.2), participants completed 10 no-cursor reaches with their right hand first and then their left hand to assess recall (i.e., B1).

Participants then completed 50 rotated training trials with the right hand (i.e., B2), followed by 50 rotated training trials with the left hand (i.e., B3).

Following completion of the third testing session, participants were probed on their awareness of the visuomotor distortion and changes in their reaches. While some of the participants indicated that they thought the reaching environment had changed, none of the participants were able to accurately describe the visuomotor rotation or indicate they had adapted their reaches by moving to the right of the target.

4.3.3.1. Training Trials (aligned and rotated cursor feedback)

During the training trials (Figure 4.1B), participants were instructed to grasp the robot handle with a comfortable but firm grip. The handle was positioned at the illuminated home position and their hand position was represented as a cursor on the screen (i.e., a green circle, 1 cm in diameter). After maintaining their hand at the home position for 500 ms, the home position disappeared, and a single reach target appeared cueing the participant to start their reach. Participants were instructed to move as quickly and accurately as possible to the target while grasping the robot handle. Once the middle of the cursor was within 0.5 cm of the center of the target, the reach was considered complete. At that time, participants in the V+S group received augmented somatosensory feedback. In particular, the robot handle vibrated with a frequency of 5 Hz and amplitude of 2 cm for 1500 ms. Also, they received congruent visual feedback as the green cursor vibrated with the vibrating handle. Conversely, participants in the V group only saw the cursor vibrate for 1500 ms, while the robot handle was held stationary.

Following 1500 ms, the target and cursor disappeared, and the trial was considered complete. Upon completion, the robot handle was locked to a grooved path. This grooved path allowed participants to guide their hand back to the home position via a direct linear route in the absence of visual feedback. If participants attempted to move outside of the grooved path, a resistance force [proportional to the depth of penetration with a stiffness of 2 N/mm and a viscous damping of 5 N/(mm/s)] was generated perpendicular to the grooved wall (Henriques & Soechting, 2003).

4.3.3.2. No-Cursor Reaches

As in the training trials, participants were cued to start their reach with the appearance of a single target. In these trials, no visual feedback (i.e., no-cursor) representing the hand was presented (Figure 4.1C). As well, no feedback regarding reach endpoint was provided. Participants were instructed to move their hand as quickly and accurately as possible to the target while grasping the robot handle. Once movement velocity fell below 0.01 m/s and stayed below 0.01 m/s for 50 ms, the hand was stopped, and the trial was considered complete.

Baseline: Session 1 (Day 1)

No-Cursor Reaches (right hand and left hand) 10 trials each hand B1	Aligned Reach Training (right hand) 125 trials B2	No-Cursor Reaches (right hand and left hand) 10 trials each hand B3	Aligned Reach Training (left hand) 50 trials B4

Adaptation: Session 2 (Day 1)

No-Cursor Reaches (right hand and left hand) 10 trials each hand B1	Rotated Reach Training (right hand) 125 trials B2	No-Cursor Reaches (right hand and left hand) 10 trials each hand B3

Retention: Session 3 (Day 2)

No-Cursor Reaches (right hand and left hand) 10 trials each hand B1	Rotated Reach Training (right hand) 50 trials B2	Rotated Reach Training (left hand) 50 trials B3

Figure 4.2 Overview of the trials completed in each of the three testing sessions

On Day 1, participants completed the Baseline Session (Session 1: top row) and Adaptation Session (Session 2: middle row). In each of these sessions, participants trained to reach with cursor feedback that was aligned with their hand (Session 1, B2) or rotated 30° counter-clockwise relative to their hand motion (Session 2, B2). Before (B1) and after (B3) the training trials, participants reached with their right and left hands when no-cursor feedback was provided. As well, at the end of the Baseline Session, participants completed training trials with their left hand when cursor feedback was aligned with hand motion (B4). On Day 2, participants completed the Retention Session (Session 3: bottom row). To assess recall, participants reached with their right and left hands when no-cursor feedback was provided (B1). As well, participants reached with rotated cursor feedback with their right (B2) and left (B3) hands.

4.4. Data Analysis

Reaching performance on all trials was analyzed using custom written programs in MATLAB. First, the start and end of each movement were selected based on a velocity criterion, such that movement onset and offset were defined as the times at which movement velocity first surpassed and remained above or fell and remained below 0.01 m/s for 50 ms respectively. The angular position of the hand at peak velocity (PV) relative to a reference vector joining the home position and the target was then determined for each trial. We refer to this position as an angular error (AE), as if the hand was to reach directly to the target the PVAE would be 0°. PVAE is reported as a negative value when the error fell to the left (CCW) of the target and a positive value when the error fell to the right (clockwise (CW)) of the target.

4.5. Statistical Analyses

We compared both the mean and variance in PVAE within the three sessions across groups of participants based on age and augmented feedback as indicated below to determine whether participants (1) adapted their reaches and if this adaptation was (2) transferred across hands and (3) retained in both hands. For all analyses, data were collapsed across target positions. All statistical analyses were completed with SPSS version 27, and differences with a probability of < 0.05 were considered significant. Given the lack of significant differences between sessions and groups with respect to PVAE variability, findings related to variability are not reported below.

4.5.1. Visuomotor adaptation

To determine if participants adapted to the 30˚ cursor rotation when reaching with their right hand and if this adaptation differed depending on age or augmented feedback, we compared PVAE during initial right hand training trials (i.e., average PVAE on training trials 2 – 6) in a 2 Age (Young vs. Older) x 2 Endpoint Feedback (V vs. V+S) x 2 Session (Baseline vs.

Adaptation) mixed analysis of variance (ANOVA) with repeated measures (RM) on the last factor. We also examined PVAE during final right hand training by averaging PVAE over the last 30 training trials and comparing across groups using a 2 Age x 2 Endpoint Feedback x 2 Session mixed ANOVA with RM on the last factor. The number of trials included in initial versus final training was much less (i.e., 5 vs. 30 trials), as visuomotor adaptation has been shown to plateau in as little as 10 trials (e.g., Zbib et al., 2016; Maksimovic & Cressman, 2018), and we wanted to ensure that we captured potential group differences in visuomotor adaptation. A greater number of trials was used to represent final training, after visuomotor adaptation had plateaued, in attempt to minimize variation in reaching errors.

To establish implicit adaptation in the right hand, PVAE during the right hand no-cursor trials were compared in a 2 Age x 2 Endpoint Feedback x 2 Session (B1 Adaptation vs. B3 Adaptation) mixed ANOVA with RM on the last factor. Participants' performance in B3 of the Baseline Session did not differ significantly from B1 of the Adaptation Session for any group (all *p's* > 0.05), thus performance on B1 in the Adaptation Session was used to capture baseline performance before rotated reach training.

4.5.2. Intermanual Transfer of Visuomotor adaptation

To determine if participants demonstrated evidence of intermanual transfer of visuomotor adaptation, we compared initial training PVAE (trials 2 - 6) between the right and left hands in a 2 Age x 2 Endpoint Feedback x 2 Hand (Right vs. Left) mixed ANOVA with RM on the last factor. PVAE for each hand were normalized by subtracting initial training errors in the Baseline Session (i.e., B2 for the right hand and B4 for the left hand) from training errors when first introduced to the visuomotor distortion with the right hand (i.e., B2 Adaptation Session) and left hand (i.e., B3 Retention Session). The magnitude of final adaptation (i.e., last 30 trials) in the right and left hands was also compared in a 2 Age x 2 Endpoint Feedback x 2 Hand ANOVA with RM on the last factor. Similar to initial training, final training PVAE were normalized by subtracting final training errors in the Baseline Session. Finally, we compared PVAE in the left hand no-cursor trials in a 2 Age x 2 Endpoint Feedback x 2 Session (B1 Adaptation vs. B3 Adaptation) mixed ANOVA with RM on the last factor.

4.5.3. Retention of Visuomotor Adaptation

We looked for evidence of recall (i.e., aftereffects) in the right and left hands on Day 2. For both the right and left hands, we compared PVAE in the no-cursor trials in a 2 Age x 2 Endpoint Feedback x 2 Session (B1 Adaptation vs. B1 Retention) mixed ANOVA with RM on the last factor. Given that participants showed evidence of recall (see Results), retention in the form of savings in the right hand was not examined. We did compare the extent of final adaptation (i.e., last 30 trials) in the right hand during training trials between the Adaptation and Retention Sessions in a 2 Age x 2 Endpoint Feedback x 2 Session (Adaptation vs. Retention) mixed ANOVA with RM on the last factor.

4.6. Results

4.6.1. Visuomotor Adaptation: Training and Aftereffects in the Right (Trained) Hand

Figure 4.3A displays mean PVAE of the right hand over training trials for the Young and Older groups in the Baseline and Adaptation Sessions. For trials completed with the aligned cursor (Baseline Session), we notice that participants reached with minimal errors. In particular, they tended to aim slightly to the left of the target such that mean PVAE across the last 30 training trials with aligned cursor feedback was -2.4° (SD = 2.3°). When the rotated cursor feedback was introduced in the Adaptation Session, we see that participants adapted their movements over the course of the training trials such that their hand moved more and more to the right of the target.

Initial training PVAE when reaching with rotated cursor feedback differed from errors observed when reaching with aligned cursor feedback [Session: $F(1,36) = 179.682$, $p < 0.001$]. However, these PVAE observed across Sessions did not differ between groups based on Age [Session x Age: $F(1,36) = 0.295$, $p = 0.590$] or Endpoint Feedback [Session x Endpoint Feedback: $F(1,36) = 0.023$, $p = 0.881$]. Furthermore, ANOVA did not reveal any group effects of Age or Endpoint Feedback (both $p > 0.05$).

Across groups, we observed an average rightwards shift in PVAE in the last 30 rotated training trials of 24.5° (SD = 3.2°) relative to the Baseline Session (Figure 4.3B, solid bars). In accordance with this observation, statistical analysis revealed a main effect of Session [$F(1,36) = 2239.832$, $p < 0.001$]. ANOVA showed a main effect of Age [$F(1,36) = 6.861$, $p = 0.013$]. However, while older participants reached with slightly lower PVAE overall (9.1°) compared to young participants (10.5°), all groups adapted their reaches to a similar extent as ANOVA revealed no significant interactions between the factor of Session and Age or Endpoint Feedback (all p's > 0.05).

Results for the no-cursor reaches with the right hand are displayed in Figure 4.4A for all groups. On average, participants reached 15.8° (SD = 6.2°) more rightwards after training with rotated cursor feedback in the Adaptation Session compared to PVAE observed prior to training. Statistical analysis revealed a significant main effect of Session [$F(1,36) = 242.443$, $p < 0.001$], and no significant interactions or main effects involving the factors of Age or Endpoint Feedback (all p's > 0.05). Taken together, all groups adapted their reaches with their right hand on Day 1, demonstrating no significant differences in the magnitude of initial or final adaptation, nor the extent of implicit adaptation as established by aftereffects.

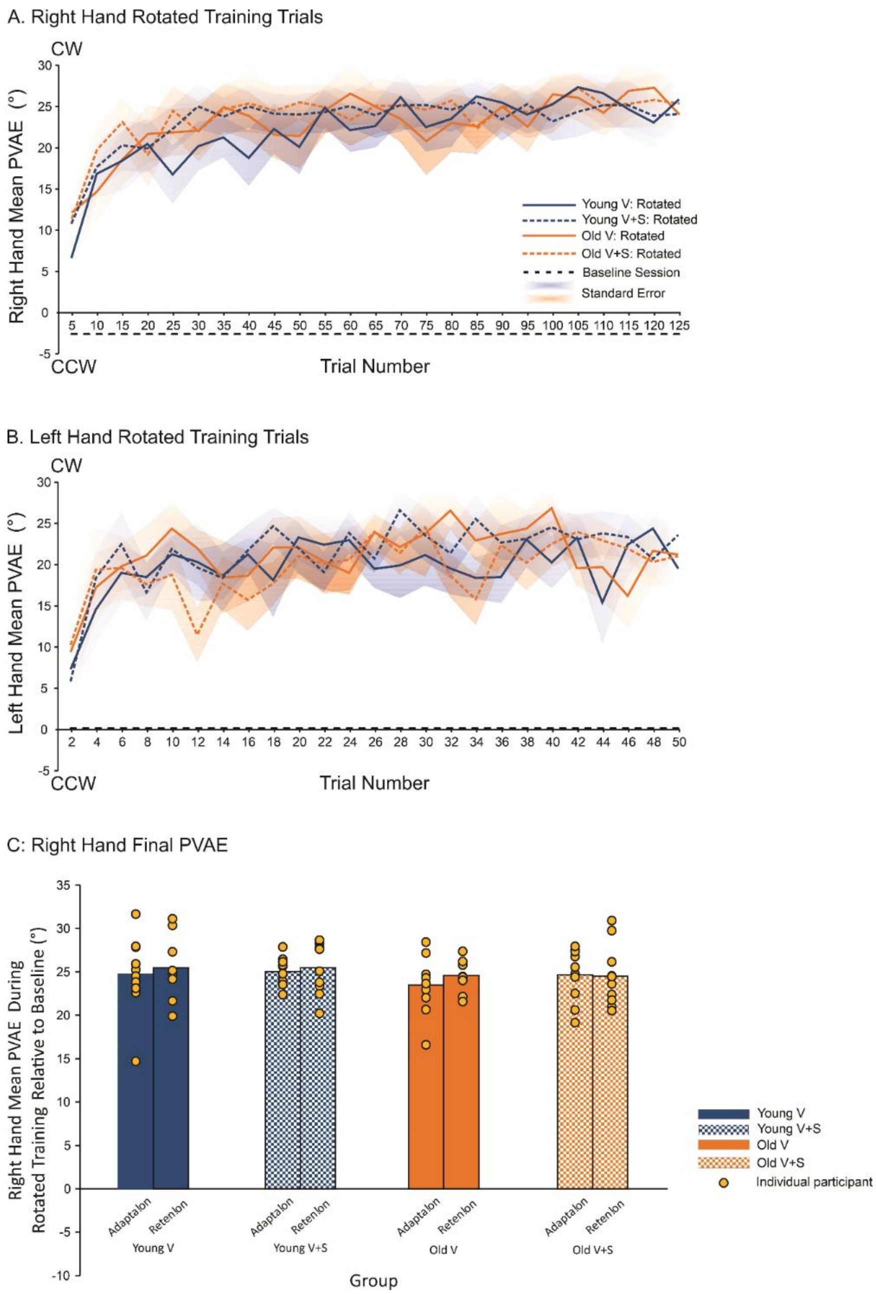

Figure 4.3 Mean PVAE across rotated training trials with the right hand in the Adaptation Session and left hand in the Retention Session

Mean PVAE across rotated training trials with the right hand in the Adaptation Session (A) and left hand in the Retention Session (B) are shown for Young (blue) and Older (orange) participants. Solid lines represent performance by participants in the V Feedback group, while dashed lines represent performance by participants in the V+S Feedback group. Shaded areas represent standard error of the mean. The dashed black lines represent average PVAE during the training trials in the Baseline Session with aligned cursor feedback across all groups and across all trials. (C) Mean PVAE of the right hand during the last 30 rotated training trials in the Adaptation Session (B2) and Retention Session (B2) relative to the last 30 training trials in the Baseline Session (B2). The blue bars represent average performance by the Young participants, while the orange bars represent performance by the Older participants. Filled bars represent performance by the V feedback groups, while the striped bars represent performance by the V+S feedback groups. Individual data for each participant are displayed in yellow.

4.6.2. Intermanual Transfer of Visuomotor Adaptation

With respect to PVAE in the left hand compared to the right hand, we found that the left hand reached with greater errors when first introduced to the rotation compared to the right hand (see Figure 4.3B vs. 4.3A). Analysis revealed a main effect of Hand [$F(1,36) = 65.575$, $p < 0.001$], but no main effects or interactions involving Age or Endpoint Feedback (all *p's* > 0.05). Initial PVAE in the left hand changed by 23.6° (SD = 5.2°) compared to 12.7° (SD = 5.8°) in the right hand when first introduced to the visuomotor rotation compared to baseline reaches, suggesting intermanual transfer of visuomotor adaptation. With respect to the final extent of visuomotor adaptation achieved (see Figure 4.3C), ANOVA did not reveal any differences between Hands [$F(1,36) = 0.203$, $p = 0.655$]. On average, the extent of final adaptation across all groups and both hands were 24.3° (SD = 3.3°).

To establish if intermanual transfer was driven implicitly, we look to the no-cursor trials. Aftereffects for the left hand are shown in Figure 4.4B. Participants reached significantly more rightwards following rotated training with the right hand compared to prior to rotated reach training [Session: $F(1,36) = 17.402$, $p < 0.001$]. Specifically, mean PVAE shifted 3.6° (SD = 5.2°) rightwards following rotated training across all groups (Figure 4.4B). This indicates that 23% of aftereffects measured in the trained right hand transferred to the untrained left hand. The extent of intermanual transfer did not differ across groups based on Age or Endpoint Feedback (all *p's* > *0.05*).

4.6.3. Retention of Visuomotor Adaptation

On Day 2, we found that participants showed evidence of recall of implicit visuomotor adaptation in their right hand [Session: $F(1,36) = 34.458$, $p < 0.001$] (Figure 4.4A). That is, participants continued to aim more rightwards even 24 hours after initial training, such that the mean PVAE was shifted 3.9° (SD = 7.1°) rightwards relative to PVAE prior to rotated training on Day 1. As can be seen in Figure 4.4A, the aftereffects observed in the Retention Session were much smaller than aftereffects observed in the Adaptation Session (25%). The extent of aftereffects recalled did not differ significantly across groups based on Age or Endpoint Feedback (all *p's* > 0.05).

Since participants demonstrated significant recall of aftereffects in the right hand on Day 2, we were unable to look at savings. However, we did compare the overall extent of visuomotor adaptation in the training trials with the visuomotor rotation on Day 1 versus Day 2 in the right hand. We found that participants reached with an average PVAE of 22.3° (SD = 2.9°) at the end of reach training in the Adaptation and Retention Sessions (see Figure 4.3C). ANOVA did not reveal a significant main effect of Session, or significant interactions involving Age or Endpoint Feedback (all *p's* > 0.05), suggesting that the final extent of adaptation did not vary across groups over time. ANOVA did reveal a significant main effect of Age [Session: $F(1,36) = 7.566$, $p = 0.009$], such that older adults 23.2° (SD = 2.4°) reached with slightly lower PVAE compared to young adults 21.4° (SD = 3.1°).

Retention of aftereffects in the left hand was also assessed. Although participants showed evidence of intermanual transfer from the right hand to left hand immediately following rotated training (B3 Adaptation Session), they failed to demonstrate significant recall of implicit visuomotor adaptation in the left untrained hand 24 hours later. On Day 2, PVAE on the no-cursor reaches with the left hand returned to baseline levels of performance (see Figure 4.4B; Session: [$F(1,36) = 2.817$, $p = 0.102$]. Finally, the lack of recall of aftereffects in the left hand did not differ statistically across Age or Endpoint Feedback (all *p's* > 0.05).

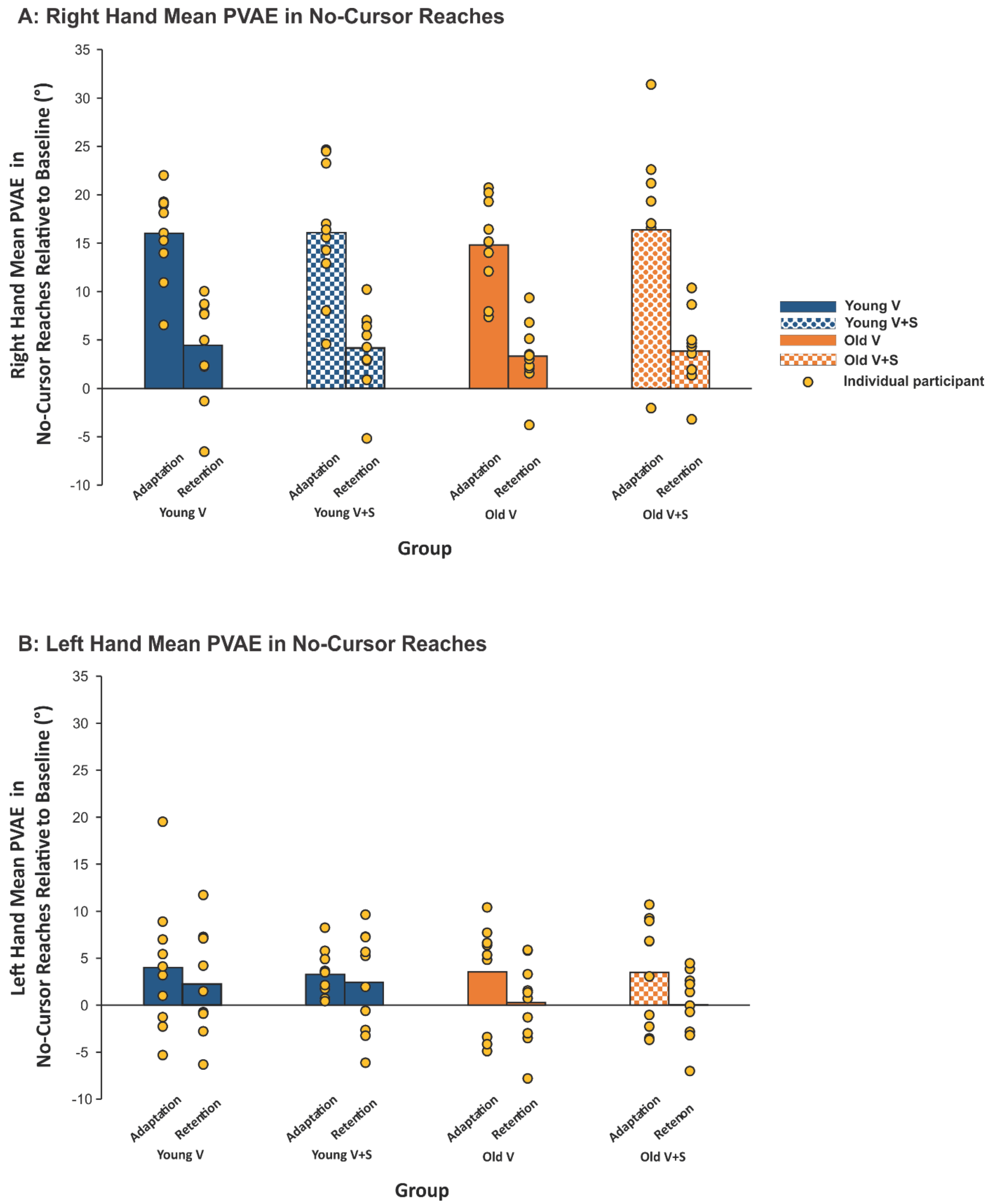

Figure 4.4 Mean PVAE during the no-cursor reaches

(A) Aftereffects in the Adaptation Session (B3) and Retention Session (B1) in the right hand for Young (blue) and Older (orange) participants. (B) Aftereffects in the Adaptation Session (B3) and Retention Session (B1) in the left hand for Young (blue) and Older (orange) participants. Mean PVAE are expressed relative to PVAE on the no-cursor reaches during the Adaptation Session prior to rotated training (i.e., B1). Filled bars represent performance by the V feedback groups, while the striped bars represent performance by the V+S feedback groups. Individual data for each participant are displayed in yellow.

4.7. Discussion

In this study we investigated the ability of older adults to transfer and retain visuomotor adaptation in comparison to young adults when adaptation was driven implicitly. We further looked to determine if adaptation was enhanced by providing augmented somatosensory feedback at the end of movement. In agreement with previous literature on implicit adaptation, we found that older adults were able to adapt their reaches, and the extent of implicit adaptation as demonstrated by aftereffects did not differ from young adults (McNay & Willingham, 1998; Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon et al., 2020). Moreover, we found that older participants transferred and retained implicit visuomotor adaptation to the same extent as young adults. However, and contrary to our expectations, neither young nor older participants benefited form augmented somatosensory endpoint feedback, which implies that visual feedback drives implicit visuomotor adaptation. Taken together, our results suggest that when implicit processes underlie visuomotor adaptation, older adults transfer and retain visuomotor adaptation as seen in young participants, regardless of the presence of augmented somatosensory feedback.

4.7.1. Visuomotor Adaptation

Both young and older adults adapted their reaches when introduced to a 30° visual rotation, such that the extent of adaptation at the start and end of the rotated training block did not differ between groups. As well, both young and older adults demonstrated aftereffects in the trained hand in the no-cursor reaches immediately following right hand training. The magnitude of aftereffects did not differ between groups. These findings agree with previous studies that have compared visuomotor adaptation to small rotations (like the 30° used in our study) in young and older adults (Cressman et al., 2010; Vachon et al., 2020). According to previous literature, adaptation to small visuomotor distortions arises implicitly due to updating of an internal model in response to a sensory prediction error (Wolpert et al., 1995; Baraduc & Wolpert, 2002). However, when large rotations are introduced (such as 60° or 90°; Buch et al., 2003; Bock, 2005), or prior instructions provided (Heuer & Hegele, 2008), it has been established that older adults do not adapt at the same rate nor to the same extent as young adults. It has been suggested that larger rotations and/or prior instructions tend to evoke more explicit adaptation than smaller rotations do, such that participants engage in cognitive strategies and age-related cognitive decline may explain age related differences (Buch et al., 2003; Bock, 2005). For example, when young and older adults were matched by explicit knowledge (i.e., mental rotation scores between young and older participants matched), the age-related variation in visuomotor adaptation disappeared (Heuer & Hegele, 2008; Hegele & Heuer, 2010). Moreover, when a large visuomotor rotation was introduced incrementally in small steps, such that participants remained unaware of the distortion, age-related differences were not observed (Buch et al., 2003).

Age-related changes in explicit adaptation have been suggested to be related to structural changes in the frontal lobes (Heuer & Hegele, 2008) and functional changes like increased neural noise and neural de-differentiation, such that different mental operations come to rely more and more on common neural substrates (Rand, Wang, Müsseler, & Heuer, 2013). These changes may lead to reduced sensitivity to the difference between the direction of hand movement and cursor motion. In other words, aging may decrease one’s ability to discriminate differences between visually perceived cursor directions and proprioceptively perceived hand directions, resulting in poorer knowledge of the visuomotor distortion and hence reduced explicit adaptation (Rand et al., 2013). Taken together with the current findings, we show that older adults do not differ from young adults when adapting their reaching movements implicitly in response to distortions that are not likely to solicit cognitive strategies (such as large rotations). Having established implicit visuomotor adaptation across young and older adults, we next looked to examine intermanual transfer and retention of implicit visuomotor adaptation with age.

4.7.2. Intermanual Transfer

Intermanual transfer arises when practice of a novel motor task with one arm results in an improvement in subsequent performance with the other arm (Wang & Sainburg, 2006; Hinder, Carroll, & Summers, 2013; Poh et al., 2016). In general, previous literature demonstrates that the extent of intermanual transfer may vary depending on a number of factors, such as the hand initially trained (right hand first vs. left hand first) (Sainburg & Wang, 2002; Thompson & Henriques, 2010; Mostafa, Salomonczyk, Cressman, & Henriques, 2014), the location of the targets in the workspace (Wang & Sainburg, 2006), and the visibility of cursor feedback during reaches with the untrained limb (Sainburg & Wang, 2002; Anguera, Russell, Noll, & Seidler, 2007; Taylor, Wojaczynski, & Ivry, 2011).

Recently, intermanual transfer of visuomotor adaptation has been suggested to be driven explicitly in young adults (Haith et al., 2015; Morehead et al., 2015; Poh et al., 2016; Werner et al., 2019; Bouchard & Cressman, 2021). In older adults, studies regarding transfer of visuomotor adaptation are limited, and the transfer of implicit visuomotor adaptation (i.e., in the form of aftereffects) has not been examined. In the current study we looked at transfer of aftereffects from the trained hand to untrained hand, as well as training performance with the left hand when introduced to the visuomotor distortion 24 hours later. We show that all groups, regardless of age and endpoint feedback, exhibited aftereffects in the left hand following rotated training with the right hand, thus demonstrating transfer of implicit visuomotor adaptation. Furthermore, on Day 2 when participants reached with their left hand with the small 30° rotation for the first time, we noticed that the left hand showed greater adaptation earlier on in training compared to when the right hand initially reached with the same rotation. Given that our participants (1) did not receive prior instructions regarding the distortion, (2) did not report awareness of the visuomotor distortion, and (3) demonstrated aftereffects in the left hand, we assume the role of explicit processes in facilitating transfer of motor learning across the hands in this study is minimal. Thus, we conclude that implicit adaptation in the form of aftereffects can be transferred from the right trained hand to the left untrained hand in both young and older individuals when adapting to small visuomotor distortions in the absence of instructions regarding how to counteract the rotation.

While intermanual transfer of visuomotor adaptation was present in both young and older adults, we note that this transfer was minimal (approximately 23% of the implicit adaptation observed in the right hand). Thus, it seems like the untrained hand did not have access to the same information needed to counter the visuomotor distortion as the trained hand. According to Taylor et al. (2011), there are a number of reasons why there may be a loss of error information when examining the untrained versus trained hand, including noise arising in interhemispheric communication or asymmetries related to hand dominance. When an error arises when reaching with the right hand, the right hand is in the appropriate state to incorporate that error information. In other words, the right hand is task relevant since it produced the movement that led to the error. In contrast, the untrained left hand is not in a state that is appropriately suited to incorporate this information. Therefore, an error signal, even if transmitted equally to controllers for both hands, may be less effective when applied to a controller that is not fully engaged.

4.7.3. Retention

Recent literature suggests that explicit processes also contribute to the retention of visuomotor adaptation in young adults (Morehead et al., 2015; Haith et al., 2015; Bouchard & Cressman, 2021). For example, Bouchard and Cressman (2021) found that explicit adaptation was retained in both hands over testing days after participants adapted to a 40° rotation, whereas implicit adaptation decayed. In our study, we had participants adapt their movements to a small 30° rotation to better understand whether implicit processes alone are sufficient to drive retention in the form of recall in young and older adults. We found evidence of recall, such that both young and older adults continued to exhibit aftereffects in the right trained hand 24 hours later, regardless of age and endpoint feedback.

It is necessary to note that the magnitude of aftereffects was significantly less on Day 2 compared to Day 1, with only 25% of initial aftereffects retained. The decay in implicit adaptation following a delay period has been reported previously in studies with young and older participants. For example, Maksimovic and Cressman (2018) reported a significant decay in implicit adaptation in young adults when assessed via aftereffects after a 24 hour delay period following initial training with a 30° CW visuomotor distortion (aftereffects decreased from 24° to 7°). Similarly, Reuter et al. (2020) showed that both young and older adults only retained about 14% of visuomotor adaptation observed in a first day of testing when assessed between two and seven days after initial training with a 30° rotated cursor. The decay in implicit learning may reflect differences in the contributions of a fast labile component and a slow temporally stable component of learning as put forth by Smith and colleagues (Hadjiosif & Smith, 2013a, b; Miyamoto et al., 2014). In particular, decreased aftereffects following a delay reflect a decay of the fast labile component, which has been shown to start to decay in as little as 16.5 s (Hadjiosif & Smith, 2013a).

Significant recall was only present in the trained right hand, as there was no evidence of aftereffects when reaching with the untrained left hand in the Retention Session. The lack of recall observed in the untrained hand after a 24 hour delay is likely due to the limited intermanual transfer of implicit visuomotor adaptation to the left hand, as discussed above. Future research is required to determine the contributions of explicit and implicit processes to the retention of visuomotor adaptation in the trained and untrained hands across age when such factors as methods of assessment (i.e., trials with cursor present versus absent), rotation size, and use of a cognitive strategy are manipulated. For now, we conclude that implicit adaptation can be retained in the trained hand across age, at least when participants adapt to a small cursor rotation that they are not aware of.

4.7.4. Augmented Somatosensory Endpoint Feedback

Augmentation of sensory feedback has been widely used to enhance one's performance on tasks related to activities of daily living (Sigrist et al., 2013). The present study aimed to assess the impact of augmented somatosensory feedback regarding reach endpoint during adaptation to a novel visuomotor rotation. Contrary to our expectations, participants did not benefit from the augmented somatosensory feedback, as demonstrated by comparable performance between the V+S and V groups. Our results agree with Castronovo et al. (2019), who recently showed that, in the presence of visual feedback, enhancing proprioceptive input through electrical noise stimulation that was not perceived at a conscious level had no substantial impact on visuomotor adaptation in young and older adults. The lack of benefit of enhanced somatosensory feedback may arise due to how the brain integrates visual and proprioceptive information during visuomotor adaptation.

According to Ernst and Banks (2002), the brain integrates multiple sources of sensory input related to an object of body part in an optimal manner. Specifically, when the brain encounters visual and proprioceptive estimates regarding the location of the hand in space, the brain combines these multiple sensory inputs such that the more reliable sensory inputs (i.e., sources providing more precise information) are assigned a greater weight (i.e., provide more weight). In visuomotor adaptation, it has been suggested that updating an internal model is driven primarily by visual feedback (Krakauer et al., 1999; Krakauer, 2009). In fact, somatosensory input has been shown to be suppressed during initial visuomotor adaptation (Bernier, Burle, Vidal, Hasbroucq, & Blouin, 2009) and adaptation to a visuomotor rotation does not benefit from haptic guidance during practice (Heuer and Rapp, 2011; 2012). Thus, it is perhaps not surprising that augmenting somatosensory feedback did not benefit the extent of implicit visuomotor adaptation in the current study. In addition to the lack of benefits, it is also important to note that the augmented somatosensory feedback did not hinder implicit visuomotor adaptation, suggesting that the augmented somatosensory feedback did not add additional noise into the system (or at least not noise that impeded updating the internal model).

4.8. Conclusion

In the present study we demonstrated that implicit visuomotor adaptation is sufficient to evoke intermanual transfer and retention of visuomotor adaptation in young and older participants. In addition, we found that, in the presence of visual feedback, augmented somatosensory feedback regarding movement endpoint did not enhance implicit adaptation in either age group. Such results suggest that visuomotor adaptation is transferred and retained to comparable amounts between young and older participants when adaptation is driven implicitly, even in the presence of augmented somatosensory feedback.

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5. Chapter 5 Age-related differences in reaching performance during implicit visuomotor adaptation

A version of this chapter will be submitted for publication:

Khanafer, S., Sveistrup, & Cressman, E. K. (2022). Age-related differences in reaching performance during implicit visuomotor adaptation

5.1. Abstract

In the current study we examined age-related differences in the engagement of offline and online control processes during implicit visuomotor adaptation. Ten healthy young adults and 10 healthy older adults trained to reach to five visual targets while visual feedback of their unseen hand position was rotated 30° counter-clockwise relative to their actual hand position. Participants then reached in the absence of visual feedback (i.e., no-cursor reaches). A detailed analysis of reaching performance across both trial types was conducted, comparing reaction time (RT), movement time (MT), resultant peak velocity (PV), proportional time after peak velocity (pTAPV), and path curvature (PC) between the two age groups. Results revealed that both age groups performed their movements in a similar manner when the cursor rotation was introduced, such that all participants took longer time to initiate (i.e., increased RT) and complete their movements (i.e., MT increased), reached with a lower PV and spent more time homing in on the target (i.e., pTAPV increased) compared to reaches with aligned cursor feedback. In addition, older adults had more curved paths (i.e., PC increased) with rotated cursor feedback compared to their reaches with aligned cursor feedback. Changes in reaching performance, including increased MT and PC, and decreased PV, continued following adaptation in the no-cursor reaching trials for both young and older adults. Taken together, results suggest that, when adaptation is driven implicitly, young and older adults increase engagement of online control processes.

5.2. Introduction

The ability to acquire and adapt motor skills remains essential across the lifespan. For instance, older adults may have the desire or need to learn a new skill (e.g., playing golf), or to adapt previous movements to changing environmental or physical demands (e.g., wearing prescription glasses) (Carnahan, Vandervoort, & Swanson, 1996). The ability to adapt to novel environments is well-documented across the lifespan. For example, it has been shown that young and older adults compensate for misaligned visual feedback when reaching in an altered visual environment, where a cursor misrepresents the position of one's hand on a screen (Buch et al., 2003; Cressman, Salomonczyk, & Henriques, 2010; Wang et al., 2011; Pan & Van Gemmert, 2013). Specifically, if the cursor motion is rotated by 30° counter-clockwise (CCW, i.e., left) relative to hand motion, participants begin to aim to the right of the target, ensuring the cursor lands on the target as expected. Moreover, reaches continue to be altered even when the rotated feedback is removed (i.e., individuals exhibit aftereffects) (Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon, Modchalingam,'t Hart, & Henriques, 2020).

Older adults adapt their reaches to a similar extent as younger participants when reaching with a small visuomotor distortion (e.g., 30˚ cursor rotation), such that they demonstrate comparable reaching errors when learning to reach with distorted visual feedback, as well as aftereffects that are similar in magnitude to young adults (Seidler, 2006; Heuer & Hegele, 2008; Cressman et al., 2010; Vachon et al., 2020). These aftereffects are suggested to reflect implicit (i.e., unconscious) motor adaptation arising in response to experiencing a sensory prediction error (i.e., the predicted and actual sensory feedback experienced do not match; Wolpert, Ghahramani, & Jordan, 1995a; Baraduc & Wolpert, 2002). Given that older and young adults demonstrate comparable aftereffects, suggests that implicit adaptation is preserved in older adults (Buch et al., 2003;

Bock, 2005; Heuer & Hegele, 2008; Anguera, Reuter-Lorenz, & Seidler, 2010; Cressman et al., 2010; Vachon et al., 2020).

Recently, in our lab, we demonstrated this preservation of implicit adaptation in older adults. We had young and older participants train to reach with a small 30° visuomotor distortion. Participants were not made aware of the introduction of the visuomotor distortion, nor instructed on how to counteract it. We found that older adults adapted their reaches to a similar extent and exhibited comparable aftereffects as young adults, in agreement with previous literature examining implicit visuomotor adaptation (McNay & Willingham, 1998; Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon et al., 2020).

In the current study we look to determine how reaches are controlled when implicit adaptation arises in young and older adults. Limited work has examined the engagement of offline (i.e., movement planning) and online (i.e., movement execution) control processes during visuomotor adaptation in young adults. Moreover, most of these studies examined processes underlying visuomotor adaption to large cursor rotations (i.e., 45° or greater; see Saijo & Gomi, 2010; Fernandez-Ruiz et al., 2011; Leow et al., 2017; Wijeyaratnam, Chua, & Cressman, 2019; Wijeyaratnam, Chua, & Cressman, 2022). When adapting to these large cursor rotations, young participants reach with increased reaction time (RT) compared to when reaching with typical (i.e., aligned) cursor feedback (Fernandez-Ruiz et al., 2011; Leow et al., 2017; Saijo and Gomi, 2010; Wijeyaratnam et al., 2019). As well, Saijo and Gomi (2010) have shown that participants take longer to execute their movements and spend more time in the movement before peak velocity (PV) is achieved. Recently, Wijeyaratnam et al. (2019) also found that participants were less consistent in the time it took to initiate their movements and time to achieve peak velocity. These increases in RT and RT variability, as well as time before PV and time before PV variability, are suggested to reflect engagement of offline control processes. Specifically, participants process errors from previous trials and take them into account when planning an upcoming movement (Elliott & Allard, 1985; Khan et al., 2002, 2003, Elliott, Hansen, Mendoza, & Tremblay, 2004; Hansen et al., 2006; Saijo & Gomi, 2010; Fernandez-Ruiz et al., 2011; Leow et al., 2017; Wijeyaratnam et al., 2019; Wijeyaratnam et al., 2022). This proposal is in agreement with previous findings demonstrating that participants are typically aware of changes in their reaches, and engage both explicit (i.e., conscious strategy) and implicit processes when adapting to large cursor rotations (Buch et al., 2003; Bock, 2005; Neville & Cressman, 2018).

In contrast to offline control processes, online control processes are engaged during movement execution in order to decrease reaching errors (Jeannerod, 1986; Meyer et al., 1988; Woodworth, 1899; Elliott et al., 1991; Elliott et al., 2001). Engagement of online control processes is reflected by a longer deceleration phase during the reach, providing participants with a longer time to use feedback and correct their movements (Elliott, Chua, Pollock, & Lyons, 1995; Khan & Franks, 2000).

To our knowledge there has been no investigation into how older adults control their movements during visuomotor adaptation. As such, the current study looked to establish the engagement of offline and online control processes during implicit visuomotor adaption to a small cursor rotation in both young and older adults, when visuomotor adaptation is preserved across age. Young and older participants adapted their reaches to a small 30° visuomotor distortion. A detailed analysis of reaching performance was conducted by comparing reaction time (RT), movement time (MT), resultant peak velocity (PV), proportional time after peak velocity (pTAPV), and path curvature (PC), between the two age groups, during and after visuomotor adaptation. Given that adaptation was presumed to be driven implicitly, we expected young and older adults to adapt their movements to a similar extent and in a similar manner. Specifically, we expected a larger contribution of online control processes when reaching with a rotated cursor compared to when reaching with aligned cursor feedback. A greater engagement of online control processes would be evident through increased MT, decreased PV, increased pTAPV and increased PC when reaching with rotated cursor feedback compared to aligned cursor feedback. Such findings would suggest that the flexibility to adjust the contributions of offline and online movement control processes are maintained across life span.

5.3. Methods

The procedures and data presented below are part of a larger study examining age-related differences in implicit visuomotor adaptation, for which reaching error data were previously reported (see Chapter 4 in the dissertation).

Participants

Ten healthy young adults (Young Group: mean age = 22.6 ± 4.1 years old), and 10 healthy older adults (Older Group: mean age = 70.5 ± 3.1 years old) participated in this study. All participants were right-handed as indicated by their responses to the 10-item version of the Edinburgh handedness inventory (mean score = 84.5 ± 16.4; Oldfield, 1971) and reported being free from musculoskeletal, neurological, or cognitive deficits that would interfere with their performance on the experimental tasks. Cognitive abilities were further assessed in older adult participants using the: 1) Montreal Cognitive Assessment (MOCA) (mean score = 27.7/30) (Nasreddine et al., 2005), 2) Trail Making Test Parts A and B (TMT) (mean score = 25.5 seconds on Part A and 76.1 seconds on Part B) (Arnett & Seth, 1995), and 3) Rey-Osterrieth Complex Figure (ROCF), consisting of three different sections: Copy, Immediate Recall, and Delayed Recall (Copy section mean score = 34.5 points, indicating 90% accuracy, Immediate Recall section mean score = 26.1 points, indicating 70% accuracy, Delayed Recall section mean score = 24.5 points, indicating 70% accuracy) (Osterrieth, 1944). Mean performance on these cognitive and proprioceptive assessments are provided in Table 5.1 for the Older participants. Older participants' scores fell within normal ranges reported in the literature for both cognitive (see Tombaugh, 2004; Nasreddine et al., 2005; Ashendorf et. al., 2008; Roy & Molnar, 2013; Zhang et al., 2021; Kessels et al., 2022), and proprioceptive assessments (see Stillman, 2000; Gilman, 2002) in healthy individuals aged between 18 and 60 years old. Thus, we considered our older participants to be high functioning individuals. All participants provided informed consent prior to the start of the experiment in accordance with the ethical guidelines set by the University of Ottawa's Research Ethics Board.

Table 5.1 Mean performance of older adults on the cognitive and proprioceptive assessments
Participant minimum (min) and maximum (max) scores are provided in brackets for each assessment. Scores are provided for older adults in the Control and Augmented Feedback Group.

Assessment	**Older Adults – Control Group**
Montreal Cognitive Assessment	27.7/30 (min = 27, max = 30)
Trail Making Test Part A (sec)	25.5 (min = 24, max = 27)
Trail Making Test Part B (sec)	76.1 (min = 70, max = 80)
Rey-Osterrieth Complex Figure - Copy	34.5 points (accuracy 90%) (min = 33.5, max = 36)
Rey-Osterrieth Complex Figure – Immediate Recall	26.1 points (accuracy 70%) (min = 24, max = 28)
Rey-Osterrieth Complex Figure – Delayed Recall	24.5 points (accuracy 70%) (min = 22.5, max = 26.5)
Joint Position Sense	8/8 for each hand (min = 8, max = 8)
Vibration Sensation	4/4 for each hand (min = 4, max = 4)

5.3.1. Experimental Set-Up

Participants sat on a standard height-adjustable chair at a self-desired height and distance from the experimental apparatus (Figure 5.1A), such that they could comfortably see and reach to all targets. Participants then grasped the vertical handle of a 2-joint robot manipulandum (END-Point lab system, KINARM Technologies, Kingston, Ontario) with their right hand, such that their elbow was flexed approximately 90° and their forearm in a neutral position. Visual stimuli were projected from a monitor onto a reflective surface. The reflective surface was opaque and positioned 20.5 cm below the monitor so that images displayed on the monitor appeared to lie in the same horizontal plane as that of the robot handle, positioned 20.5 cm below the reflective surface. The room lights were dimmed, and a participant’s view of their right hand was blocked by the reflective surface and a black cloth that was attached to the edge of the reflective surface and tied around their neck and shoulders.

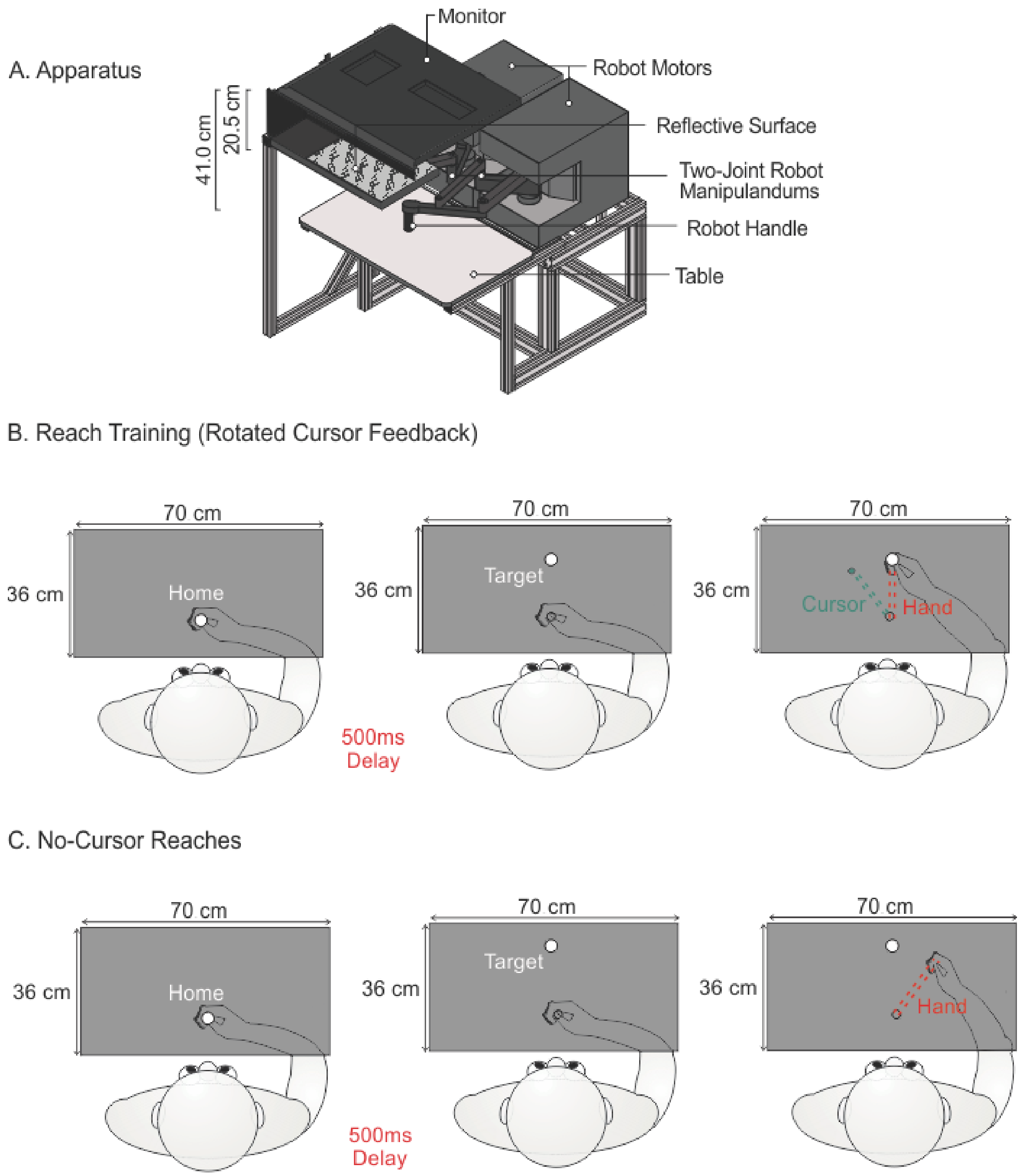

Figure 5.1 Experimental apparatus and visual stimuli

A. A side view of the experimental set-up. Participants were seated in a height adjustable chair so that they could comfortably see and reach to all targets. Participants were asked to grasp the vertical handle of a 2-joint robot manipulandum (KINARM Technologies, Kingston, Ontario) with their right hand. B. Training trials with rotated cursor feedback (Rotation session). After maintaining their hand at the home position for 500 ms, a single target (white circle, 1 cm diameter) appeared cueing the participant to start their reach. During rotated training, the cursor motion (green circle, 1 cm diameter) representing the participant's hand was rotated 30° counter-clockwise relative to the trajectory of the unseen hand. C. No-cursor reaches. Participants reached to visual targets in the absence of visual feedback.

5.3.2. Procedures

To start a trial, the robot moved the participant's right hand to a central home position (white circle, 1 cm in diameter), which was located approximately 20 cm in front of a participant's chest and aligned with their midline. Participants were required to reach with the robot handle from the home position to a visual target (white circle, 1 cm in diameter) presented 12 cm away from the home position. There were 5 target locations, such that targets were located straight ahead of the home position (at 0°), as well as 30° and 60° to the right and left of the 0° target. The sequence of target presentations was pseudo-random, such that each target appeared once before any target was repeated.

The experiment consisted of two sessions completed on the same day, with half an hour break between sessions. As demonstrated in Figure 5.2, in Session 1, The Baseline session, participants completed an aligned reach training block [i.e., Block 2 (B2)] in which they performed 125 reach training trials with cursor feedback that was aligned with their hand position. In Session 2, The Adaptation session, participants completed a rotated reach training block [i.e., Block 2 (B2)] in which they performed 125 reach training trials while seeing a cursor that was rotated 30° counter-clockwise (CCW) relative to their hand trajectory. The reach training trials (aligned or rotated) were preceded [i.e., Block 1 (B1)] and followed [i.e., Block 3 (B3)] by 10 right-hand reaches, performed with no-cursor feedback (Figure 5.2).

5.3.3. Reach Training Trials (aligned and rotated cursor feedback)

During the reach training trials, participants were instructed to grasp the robot handle with a comfortable but firm grip. The handle was positioned at the illuminated home position and their hand position was represented as a cursor on the screen (green circle, 1 cm in diameter). Hand position was maintained at the home position for 500 ms, after which a single target appeared cueing the participant to start their reaching movement. Participants were instructed to move as quickly and accurately as possible to the target while holding the robot handle. Once the cursor landed on the target, (i.e., once the center of the green cursor was within 0.5 cm of the target's center), the reach was deemed complete. The participant's hand was held at the final position for 500, followed by the target and cursor disappearing. Upon completion, the robot handle was locked to a grooved path. This grooved path allowed participants to guide their hand back to the home position via a direct linear route in the absence of visual feedback. If participants attempted to move outside of the grooved path, a resistance force [proportional to the depth of penetration with a stiffness of 2 N/mm and a viscous damping of 5 N/(mm/s)] was generated perpendicular to the grooved wall (Henriques & Soechting, 2003).

5.3.4. No-Cursor Reaches

Similar to reach training trials, participants were instructed to grasp the robot handle with a comfortable but firm grip. The handle was positioned at the illuminated home position for 500 ms. After this time, the home position disappeared, and a single target appeared cueing the participant to start their reach. In these trials, no visual feedback (i.e., no-cursor) representing the hand was provided. Participants were asked to move their hand as quickly and accurately as possible to the target while grasping the robot handle. The trial was considered complete once velocity of the robot handle decreased below 0.01m/s. The final position was then maintained for 500 ms. Upon trial completion, the target was removed, and the participant's hand was guided back to the home position by the linear grooved path as explained above.

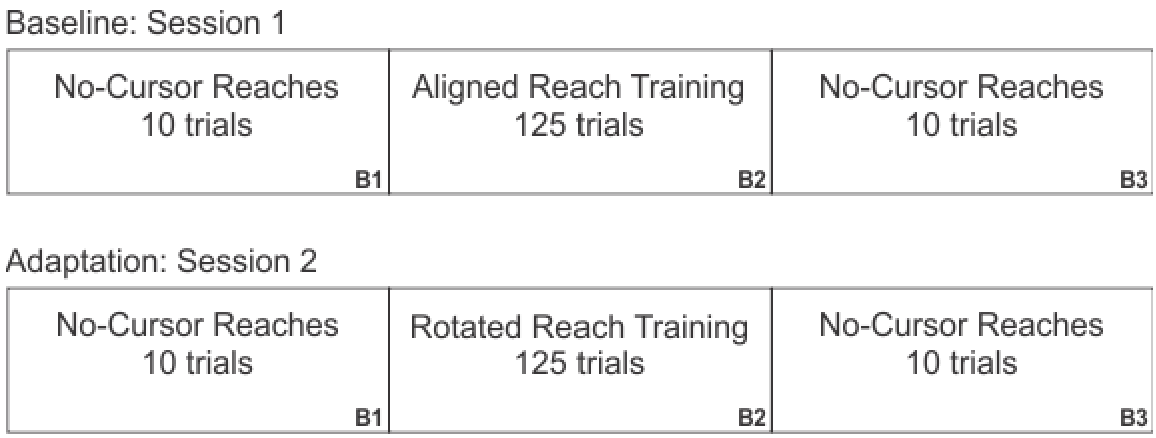

Figure 5.2 Overview of the trials completed in the testing sessions

Participants completed the Baseline Session (Session 1: top row) and Adaptation Session (Session 2: bottom row). In each of these sessions, participants trained to reach with cursor feedback that was aligned with their hand (Session 1, B2) or rotated 30° counter-clockwise relative to their hand motion (Session 2, B2). Before (B1) and after (B3) the training trials, participants reached when no-cursor feedback was provided.

5.4. Data Analysis

Reaching performance on all trials was analyzed using custom written programs in MATLAB. First, the start and end of each movement were selected based on a velocity criterion, such that movement onset and offset were defined as the times at which movement velocity first surpassed and remained above or fell and remained below 0.01 m/s for 50 ms respectively. In our previous work (refer to chapter 4 in the dissertation), we have shown that reaching errors at peak velocity did not differ between age groups. These data are not reported in the current paper. In this paper we report on movement performance related to RT, MT, PV, pTAPV, and PC. RT was defined as the time required to initiate a movement following target presentation and MT was defined as the time from movement initiation until movement termination. PV of the hand was defined as the largest velocity value achieved in the resultant direction during the movement, while pTAPV was defined as the time after PV was achieved expressed as a percentage of overall MT. PC was defined as the greatest perpendicular distance between the hand's trajectory and the reference vector connecting the home position to the target.

5.4.1. Reach Training Trials (aligned and rotated cursor feedback)

Reaching performance in Block 2 (B2) was compared between the Baseline and Adaptation sessions. We were particularly interested in reaching performance during early and late trials during the Baseline and Adaptation reach training blocks, as early trials include the period during which learning has been shown to progress most rapidly, while late trials provide an indication of performance achieved (see Huang et al., 2011; Kitago et al., 2013). Performance measures were collapsed across all targets for each participant and averaged over the first 20 trials (i.e., early training trials) or the last 20 trials (i.e., late training trials). Comparison between groups for each performance variable was conducted using a 2 Group (Young vs. Older) x 2 Session (baseline vs. adaptation) x 2 Time (early vs. late) mixed analysis of variance (ANOVA) with repeated measures (RM) on the last two factors. All statistical analyses were completed with SPSS version 27. Differences with a probability of $p < 0.05$ were considered significant.

5.4.2. No-Cursor Reaches

Performance on no-cursor reaches (Block 3 (B3)) was compared between the Baseline and Adaptation sessions. Performance measures were collapsed across all targets for each participant and averaged over the 10 trials within each Block. Comparison between groups was conducted using a 2 Group (Young vs. Older) x 2 Session mixed ANOVA with RM on the last factor.

5.5. Results

5.5.1. Reach Training Trials (aligned vs. rotated cursor feedback)

Figure 5.3 displays reaching performance measures for Young and Older participants over training trials for reaches completed with aligned and rotated cursor feedback. With respect to

RT, statistical analysis revealed significant main effects of Group [$F(1,18) = 35.7$, $p < 0.001$], Session [$F(1,18) = 15.4$, $p < 0.001$], and Time [$F(1,18) = 43.4$, $p < 0.001$]. There were also significant Session x Time [$F(1,18) = 7.2$, $p = 0.02$] and Group x Session x Time [$F(1,18) = 5.6$, $p = 0.03$] interactions. As seen in Figures 5.3A and 5.3B, the Older Group took significantly longer to initiate their movements compared to the Young Group when reaching with aligned and rotated cursor feedback. The difference between Groups was significant in early and late training for both reaching environments (all *p*'s < 0.05). Furthermore, both groups showed a significant increase in RT when reaching with rotated cursor feedback compared to aligned cursor feedback. However, the difference between the two environments was only significant early in training ($p < 0.001$), not late in training ($p > 0.05$) in either group (Figure 5.3A). Finally, both groups, demonstrated a greater RT early in training compared to late training, regardless of the reaching environment (Figure 5.3B ($p < 0.001$)).

In terms of MT, ANOVA revealed no significant main effect of Group [$F(1,18) = 1.5$, $p = 0.24$] or interactions involving Group (all *p*'s > 0.05). However, ANOVA did reveal significant main effects of Session [$F(1,18) = 31.9$, $p < 0.001$], and Time [$F(1,18) = 31.9$, $p < 0.001$] (Figure 5.3B). Participants in both Groups took a significantly longer time to complete their movements when reaching with rotated cursor feedback compared to reaching with aligned cursor feedback (mean MT with aligned cursor feedback = 1057.6 ms (SD = 102.5 ms) vs. mean MT with rotated cursor feedback = 1232.9 ms (SD = 152.6 ms), collapsed across Group and Time). Moreover, for both Groups, MT decreased significantly over time as participants took less time to complete their reaches late in training compared to early training, regardless of training with aligned or rotated feedback (mean MT early in training = 1226.2 ms (SD = 150.2 ms) vs. mean MT late in training = 1064.4 ms (SD = 04.9 ms), collapsed across Group and Session) (Figure 5.3D).

Analysis of PV established a significant difference between Groups [$F(1,18) = 16.1$, $p < 0.001$] and a significant main effect of Session [$F(1,18) = 4.7$, $p = 0.045$], but no main effect of Time [$F(1,18) = 0.6$, $p = 0.5$], or any significant interactions (all p's > 0.05). As demonstrated in Figure 5.3C, Older participants reached with a lower PV compared to Young participants, regardless of reaching with aligned or rotated cursor feedback (Yong: mean = 0.33 m/s (SD = 0.06 m/s) vs. Older: mean PV = 0.22 m/s (SD = 0.03 m/s), collapsed across Session and Time). Moreover, in both Groups, participants' reaches with the rotated cursor feedback were associated with lower PV compared to reaches with aligned cursor feedback (Figure 5.3F).

Furthermore, analysis of pTAPV revealed a significant main effect of Group [$F(1,18) = 7.9$, $p = 0.01$], Session [$F(1,18) = 7.1$, $p = 0.02$], and Time [$F(1,18) = 27.5$, $p < 0.001$] (Figure 5.3D), but no significant interactions (p's > 0.05). Older participants had a longer pTAPV compared to Young participants, regardless of reaching with aligned or rotated cursor feedback. Moreover, ANOVA revealed that when reaching with rotated cursor feedback, participants had significantly longer pTAPV compared to reaches with aligned cursor feedback (mean pTAPV with aligned cursor feedback = 59.9% (SD = 3.5%) vs. mean pTAPV with rotated cursor feedback = 68.9% (SD = 4.7%), collapsed across Group and Time). Participants also spent a longer pTAPV early in training compared to late in training, regardless of Group and Session (Figure 5.3H).

For PC, ANOVA revealed significant main effects of Group [$F(1,18) = 4.6$, $p = 0.04$], Session [$F(1,18) = 6.5$, $p = 0.02$], and Time [$F(1,18) = 49.1$, $p < 0.01$]. The Group x Session interaction [$F(1,18) = 6.7$, $p = 0.02$] was also significant (Figure 5.3E). Analysis revealed that when reaching with rotated cursor feedback, Older participants reached with significantly greater curvature than Young participants (Young: mean PC = 0.13 cm (SD = 0.01 cm) vs. Older: mean PC = 0.14 cm (SD = 0.01 cm), collapsed across Time). Moreover, Older participants' reaches with rotated cursor feedback were significantly more curved than their reaches with aligned cursor feedback ($p < 0.001$), while curvature did not change for Young participants' between reaching environments ($p = 0.9$). In addition, reaches were significantly more curved early in training compared to late training, regardless of Group or Session (mean PC early in training = 0.14 cm (SD = 0.01 cm) vs. mean PC late in training = 0.12 cm (SD = 0.01 cm), collapsed across Group and Session (Figure 5.3J).

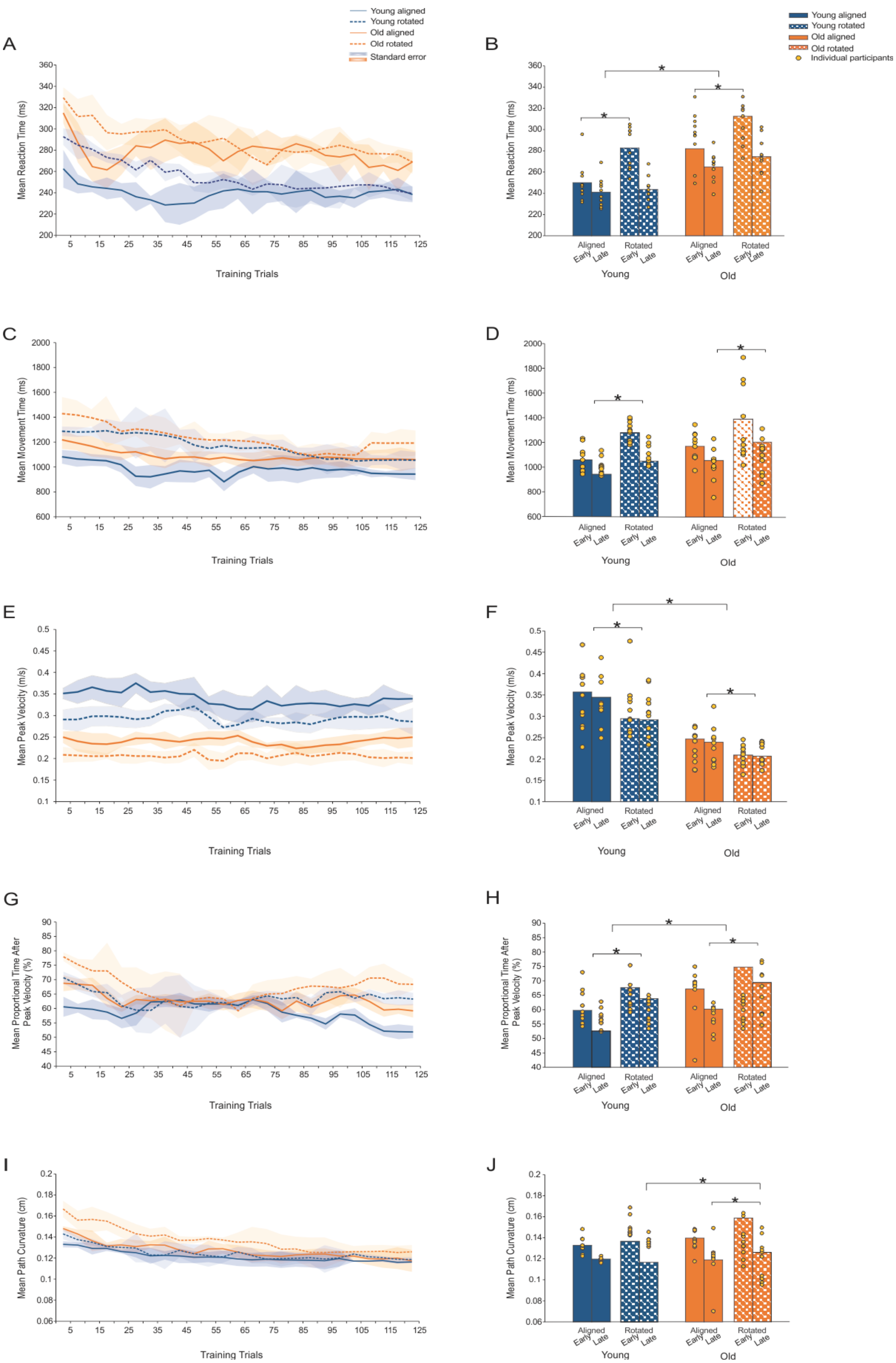

Figure 5.3 Mean performance for each Group during reach training with aligned and rotated cursor feedback

A-B: reaction time (ms). **C-D:** movement time (ms). **E-F:** peak velocity (m/s). **G-H:** proportional time after peak velocity (%). **I-J:** path curvature (cm). Left Column: Line graphs display group mean performance during training with aligned and rotated cursor feedback over trials. *Solid lines* represent reaches with aligned cursor feedback, while *dashed lines* represent reaches with rotated cursor feedback. *Blue lines* represent mean performance for participants in the Young Group and *Orange lines* represent mean performance for participants in the Older Group. Shaded regions surrounding the lines represent standard error of the mean. Right Column: Bar graphs display mean reach performance across early and late training with aligned (solid bars) and rotated (dashed bars) cursor feedback. Individual data for each participant are displayed in yellow. Asterisks (*) indicate significant differences ($p < 0.05$).

5.5.2. No-Cursor Reaches

Analysis of RT revealed no significant main effect of Group [$F(1,18) = 2.8$, $p = 0.11$] or Session [$F(1,18) = 0.33$, $p = 0.57$], and the interaction was not significant [$F(1,18) = 0.00$, $p = 0.99$], suggesting that RT did not differ statistically following training with aligned versus rotated cursor feedback (Figure 5.4A). On average, RT was 302.7 ms (SD = 45.8 ms) following reach training with aligned cursor feedback, and 307.8 ms (SD = 51.8 ms) following reach training with rotated cursor feedback.

Similarly, ANOVA revealed no significant difference between Groups [$F(1,18) = 3.1$, $p = 0.09$] and a non-significant Group x Session interaction [$F(1,18) = 0.6$, $p = 0.5$] with respect to MT. However, analysis revealed a significant main effect of Session [$F(1,18) = 18.7$, $p < 0.001$]. For both Groups, participants took longer time to complete their reaches following training with rotated cursor feedback (Young mean MT = 986.9 ms (SD = 175.8 ms) and Older mean MT = 1056.2 (SD = 199.3 ms)) compared to training with aligned cursor feedback (Young mean MT = 814.0 ms (SD = 81.9 ms) and Older mean MT = 947.0 ms (SD = 182.9 ms)) (Figure 5.4B).

Statistical analysis revealed no significant main effect of Group [$F(1,18) = 2.5$, $p = 0.13$] or Group x Session interaction [$F(1,18) = 0.7$ $p = 0.8$], but a significant main effect of Session [$F(1,18) = 5.9$ $p = 0.03$] with respect to PV. That is, for both Groups, participants achieved a higher PV when completing their reaches following training with aligned cursor feedback (Young mean PV = 0.34 m/s (SD = 0.09 m/s) and Older mean PV = 0.27 m/s (SD = 10 m/s)) compared to reaches following rotated cursor feedback (Young mean PV = 0.28 m/s (SD = 0.07 m/s and Older mean PV = 0.24 m/s (SD = 0.10 m/s)) (Figure 5.4C).

In terms of pTAPV, ANOVA revealed no significant main effects of Group [$F(1,18) = 0.00$, $p = 0.99$], or Session [$F(1,18) = 0.67$, $p = 0.42$], and no significant interaction [$F(1,18) = 0.00$, $p = 0.99$]. On average, participants spent the majority of their reach (i.e., 60.6% (SD = 4.7%)) after PV (Figure 5.4D).

Lastly, analysis demonstrated no significant main effect of Group [$F(1,18) = 0.72$, $p = 0.41$], or Group x Session interaction [$F(1,18) = 0.05$, $p = 0.83$] with respect to PC. On the other hand, ANOVA revealed a significant main effect of Session [$F(1,18) = 6.2$, $p = 0.02$]. As seen in Figure 5.4E, participants in both Groups reached with greater PC following training with rotated cursor feedback (Young mean PC = 0.13 cm (SD =0.05 cm) and Older mean PC = 0.14 cm (SD = 0.03 cm)) compared to following training with aligned cursor feedback (Young mean PC = 0.11 cm (SD = 0.04 cm) and Older mean PC = 0.13 cm (SD = 0.02 cm)) (Figure 5.4E).

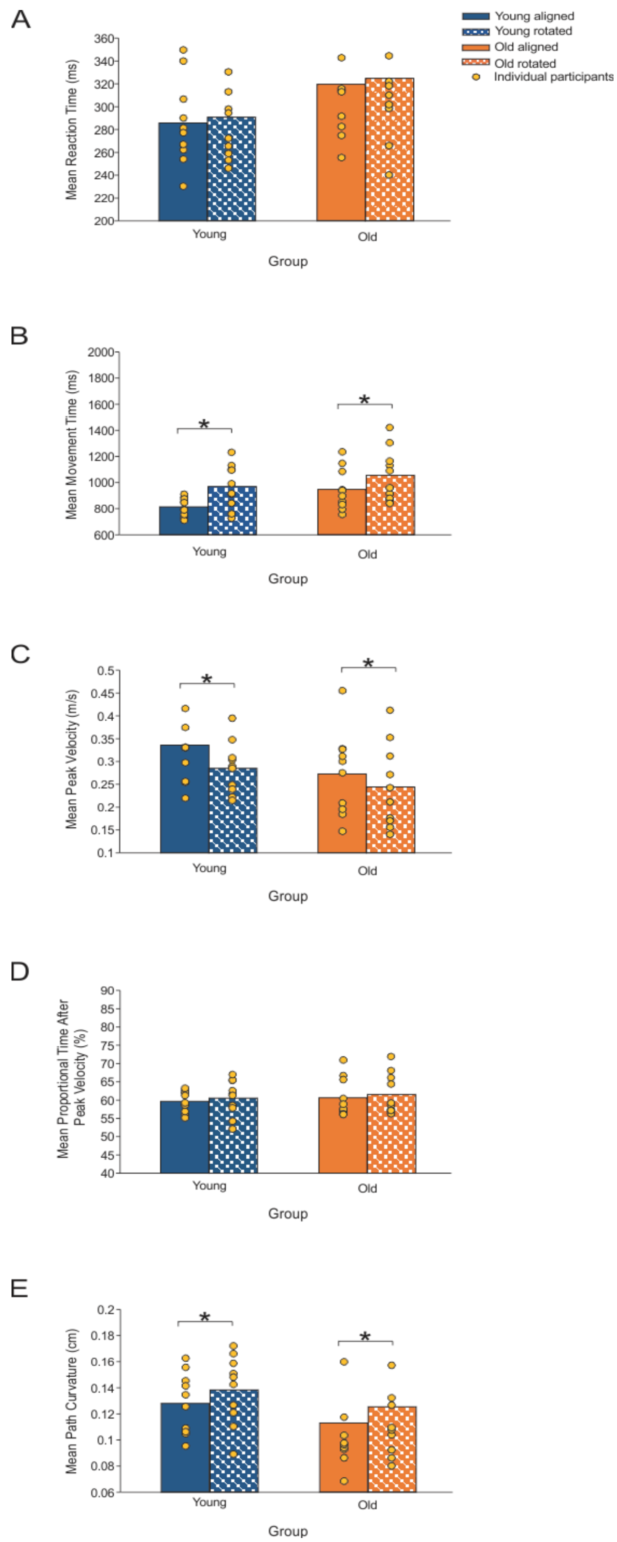

Figure 5.4 Mean reach performance measures for each Group during the no-cursor reaches following aligned (solid bars) and rotated (dashed bars) reach training

A: reaction time (ms). **B:** movement time (ms). **C:** peak velocity (m/s). **D:** proportional time after peak velocity (%). **E:** path curvature (cm). *Blue bars* represent mean performance for participants in the Young Group and *Orange bars* represent mean performance for participants in the Older Group. Individual data for each participant are displayed in yellow. Asterisks (*) indicate significant differences ($p < 0.05$).

5.6. Discussion

In this study, we sought to determine age-related differences in the engagement of offline and online control processes during implicit visuomotor adaptation. To establish underlying control processes, reaching performance with respect to RT, MT, PV, pTAPV, and PC was compared between young and older participants both when reaching with aligned and rotated (30°) cursor feedback and following reach training in the absence of cursor feedback.

5.6.1. Age-related differences in performance when reaching with aligned cursor feedback

Our results demonstrated that, when reaching with aligned cursor feedback, older adults took significantly longer time to initiate their movements (i.e., longer RT), reached with a lower PV, and had the tendency to spend more time homing in on the target (i.e., had a longer pTAPV) compared to young participants. These findings agree with previous literature that has compared reaching performance in a typical environment between young and older adults. In fact, it is well documented that aging is associated with slower movement initiation, longer movement time, and spending a greater proportion of the reach in the deceleration, or "homing in" phase compared to reach performance observed in young adults (Spirduso, 1975; Darling et al., 1989; Yan et al., 1998).

According to planning and control models of motor control (e.g., the Multiple Process Model of Elliott and colleagues (2010)), longer RT suggests a greater contribution of offline control planning processes (Heath et al., 1998; Elliott, Slatick, & Urman, 2001; Khan et al., 2003;

Hansen et al., 2006; Burkitt et al., 2013), while a longer pTAPV suggests greater engagement of online control processes (Worringham, 1991; Khan, Franks, & Goodman, 1998; Elliott, Chua, Pollock, & Lyons, 1995; Khan & Franks, 2000; Elliott et al., 2004). Therefore, our results (i.e., longer RT and longer pTAPV in increased age) imply that offline and online control processes may have been engaged to a greater extent in older participants compared to young adults to ensure that they completed the task as required (i.e., the cursor landed on the target). Specifically, our older adults spent more time processing errors from previous trials and planning their current movement (i.e., longer RT), and took more time to process visual feedback online to reduce their reaching errors (i.e., longer pTAPV) compared to young adults.

5.6.2. Age-related Differences in reaching performance when reaching with rotated cursor feedback

Traditionally, research investigating visuomotor adaptation has limited their analyses to examining reach accuracy (e.g., angular errors at peak velocity or movement endpoint; Krakauer et al., 2000; Sainburg & Wang, 2002; Yamamoto et al., 2006; Zbib et al., 2016). Lately, more attention has been given to understanding how movements may be altered with respect to underlying temporal characteristics and movement kinematics when reaching in a novel visuomotor environment (Saijo & Gomi, 2010; Fernandez-Ruiz, Wong, Armstrong, & Flanagan, 2011; Wijeyaratnam et al., 2019; Wijeyaratnam et al., 2022). Previous studies have focussed on examining changes in reaching performance when young participants adapt to large visuomotor distortions (Saijo & Gomi, 2010; Fernandez-Ruiz et al., 2011; Wijeyaratnam et al., 2019; Wijeyaratnam et al., 2022). In the current study we examined reaching performance when participants adapted their reaches to a small cursor rotation and hence adaptation was assumed to be driven implicitly (Neville & Cressman, 2018; Vachon et al., 2020).

In this study, we found that when the cursor rotation was introduced, all participants took longer to initiate and complete their movements, reached with a lower PV, and spent a greater portion of their movement after PV, compared to when reaching with aligned cursor feedback. Additionally, older participants' reaches with rotated cursor feedback were significantly more curved than their reaches with aligned cursor feedback, while curvature did not change for young participants between reaching environments. These differences in reaching performance between the two reaching environments was maintained until the end of training, except for RT, which decreased overreach training trials for both groups. The increase of RT observed when first encountering the visuomotor rotation could be interpreted as a transient change arising due to the introduction of the misaligned visual feedback. On the other hand, the changes in reaching performance related to increased MT, decreased PV and increased PC continued following rotated reach training in the no-cursor reaching trials regardless of age.

These persistent changes in reaching performance with the introduction of the cursor rotation suggest that movements across the two reaching environments were not performed in a similar manner. The continued increase in MT, pTAPV, and PC during and following adaptation suggest that participants in both age groups engaged more online control processes when completing adapted movements compared to when reaching in a typical manner (Keele & Posner, 1968; Elliott et al., 1997; Khan et al., 1998).

In general, changes in reaching performance with the introduction of the rotated cursor feedback were similar across young and older participants. Thus, participants in both age groups shifted the contribution of online and offline control processes when reaching with rotated cursor feedback. That said, older participants did reach with greater path curvature. This increased path curvature was required in order to correct movements online and have the cursor land on the target. Thus, it could be argued that older adults engaged online processes to a greater extent than young adults.

Our results differ from pervious work that has examined control processes underlying visuomotor adaption to large cursor rotations (i.e., 45° or greater, Saijo & Gomi, 2010; Fernandez-Ruiz et al., 2011; Leow et al., 2017; Wijeyaratnam et al.,2019; Wijeyaratnam et al., 2022). Large cursor rotations typically elicit both implicit and explicit processes (Buch et al., 2003; Bock, 2005; Neville & Cressman, 2018). The engagement of explicit processes has been associated with a greater contribution of offline control processes, such that participants tend to take longer to initiate their movements and achieve PV (Saijo & Gomi, 2010; Fernandez-Ruiz et al., 2011; Leow et al., 2017; Wijeyaratnam et al.,2019; Wijeyaratnam et al., 2022). In contrast, in this study, we showed that when visuomotor adaptation is driven implicitly (i.e., adaption to small cursor rotation), online control processes are engaged to a greater extent.

5.6.3. Changes in reaching performance over time during visuomotor adaptation

Interestingly, we noticed differences in how movements were controlled over time. Specifically, reaches in a novel environment changed over time, as shown by decreases in RT, MT, pTAPV, and PC as training progressed. RT decreased to baseline levels of performance, where as MT, pTAPV and PC remained raised even at the end of the 125 reach training trials. Decreases in the magnitude of these variables is indicative of participants having adapted their reaches to the visuomotor rotation, as participants were able to initiate and complete their reaches in a shorter amount of time with practice, executed less curved reaches and required less time homing in on the target. These results add support to the utilization of temporal and kinematic measures to assess the progression and success of adaptation over time (Wijeyaratnam et al., 2019; Wijeyaratnam et al., 2022).

5.7. Conclusion

In the present study we demonstrated that the engagement of online control processes is increased regardless of age when adaptation is driven implicitly. Such findings suggest that there is a flexibility to adjust the contributions of offline and online movement control processes during visuomotor adaptation and that this flexibility is maintained across lifespan.

5.8. References

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6. Chapter 6 General Discussion

The ability to coordinate and adapt goal-directed movements to changes arising within the body, and in the environment, is essential to carry out activities of daily life. Older adults may experience a variety of cognitive, sensory, and motor impairments that preclude adaptation of motor tasks, including upper-limb (UL) reaching movements. In this thesis, we examined how age-related changes impact one's ability to adapt goal-directed reaches to meet changes in task demands. The changes in task demands included sudden changes within the body or more consistent changes in the environment. Two experimental paradigms were designed to address four research questions. The first paradigm aimed to investigate age-related differences in compensatory arm-trunk coordination during trunk-assisted reaching (Research Question 1; Chapter 2) and the ability of older adults to adjust arm joint coordination with variations in trunk motion availability (Research Question 2; Chapter 3). The second paradigm aimed to investigate the preservation of intermanual transfer and retention of implicit visuomotor adaptation in older adults (Question 3; Chapter 4) and the underlying control processes engaged during visuomotor adaptation in young and older adults (Question 4; Chapter 5). Together, the findings from these series of experiments have implications for understanding underlying motor control mechanisms and how they may be affected by aging.

6.1. Paradigm 1: Reach Adaptation to Changes within the Body (Chapters 2 and 3)

Experimental investigations into movement adaptation in response to changes within the body may require participants to perform a movement involving different body segments that can be combined in different ways to accomplish the same motor goal. For example, the arm can produce reaching movements to a target placed within the arm's reach alone or in combination with active trunk bending. It has been shown that in 'typical' neurologically healthy individuals the addition of trunk motion during a reaching task does not affect the trajectory of the arm endpoint (Ma & Feldman, 1995; Pigeon & Feldman, 1998). Moreover, the potential contribution of the trunk to the motion of the arm endpoint toward a target is neutralized by appropriate compensatory rotations of the elbow and shoulder joints (i.e., ***compensatory arm-trunk synergy***) (Ma & Feldman, 1995; Pigeon & Feldman, 1998).

In general, motor synergies are defined as neural organizations of elements (i.e., joints, limbs, and/or muscle groups) by the central nerves system (CNS) to effectively control the limb movement and maximise end-effector accuracy (Bernstein, 1947; Latash, 2008). Synergic control indicates that movements are controlled collectively through activation of cortical neurons that work as a unit. Some studies argue that there is a shift from synergic to element-based control with advanced age (Gorniak, Zatsiorsky, & Latash, 2011). This is referred to as the "back-to elements" hypothesis (Kapur, Zatsiorsky, & Latash, 2010). This hypothesis suggests that the loss of neurons, including cortical neurons, in older adults (Eisen, Entezari-Taher, & Stewart, 1996; Christou 2009), results in a decline of synergic mechanisms and leads to the necessity to construct movements based on elements (Gorniak et al., 2011).

In Chapter 2, we assessed age-related differences in compensatory arm-trunk coordination using the Stationary Hand Task (SHT) and the Reaching Hand Task (RHT), in which participants had to adapt their reaches to changes in task demands (i.e., free- vs. blocked-trunk motion) to perform the movement correctly (Raptis et al., 2007; Sibindi et al., 2013). Both tasks were performed when participants had their eyes closed. Participants completed the two tasks with their dominant and non-dominant arms, and at both a fast and a preferred speed.

Contrary to our hypotheses, we found that in the SHT both age groups were able to reduce the influence of trunk motion on their hand position as demonstrated by high gain scores (mean score range between 0.75 and 0.81), regardless of the hand used and movement speed. Moreover, in the RHT, both age groups made similar, small overshooting errors (~1.3 cm) in free- compared to blocked-trunk trials, when using both hands and at both movement speeds.

The preservation of hand position in both motor tasks was achieved by active compensatory changes in the arm joint angles, nullifying the influence of trunk motion on hand position. This compensatory synergy may be driven by afferent signals, in particular, vestibular signals evoked by trunk motion (Adamovich et al., 2001; Tunik et al., 2003; Raptis et al., 2007). Vestibular signals are transmitted by vestibulospinal and vestibulotranscortical pathways to motoneurons of the shoulder and elbow muscles to produce compensatory arm movements. It has been proposed that vestibular feedback plays a leading role in guiding the compensatory arm–trunk coordination in trunk-assisted reaching in healthy young adults (Tunik et al., 2003; Raptis et al., 2007). For example, in the absence of vision, it has been found that patients, who lacked cutaneous and proprioceptive sensitivity but had relatively intact vestibular function, maintained their ability to adapt movements using compensatory arm–trunk coordination during trunk-assisted reaches (Tunik et al., 2003). On the other hand, patients with vestibulospinal pathology, had deficits in adapting arm movements when trunk motion was involved in the reach (Raptis et al., 2007).

Although we found that older participants were able to coordinate arm and trunk movements efficiently in both motor tasks, their performance was not as consistent as younger adults. In fact, older adult performance was significantly more variable compared to the younger adults as shown by larger variability in gain scores in the SHT, greater variability in final hand position when the trunk was involved in the SHT, and higher movement time (MT) variability in the RHT. This increase in variability across movements may be related to structural and neural changes in the brain and spinal cord associated with aging.

To further understand the ability of older adults to adjust shoulder and elbow coordination in response to changing task demands, we compared UL kinematics when completing the RHT in the presence and absence of trunk motion (i.e., free- vs. blocked-trunk trials) between young and older adults in Chapter 3. We found that all participants adjusted their motion at the elbow and shoulder joints in a similar manner and in accordance with the availability of trunk motion, regardless of the hand used or speed of movement. In particular, when the trunk was involved in the movement, participants used less elbow extension to compensate for the influence of the trunk forward motion on the final hand position. However, when the trunk motion was blocked, reaching movements were accomplished using more shoulder horizontal adduction. Moreover, we found that older participants were able to make the required angular modifications at the elbow and shoulder at an appropriate time regardless of whether the trunk was involved in the reach or not. For example, during free-trunk trials, in both age groups, compensatory modifications at the elbow and shoulder were initiated approximately 60 ms following trunk motion onset and continued throughout trunk motion, up to 200 ms after the hand stopped moving. In the blocked-trunk trials, in both groups, angular modifications at the elbow and shoulder began approximately 75 ms following trunk arrest and continued for 150 ms after the hand stopped moving to maintain the hand's trajectory. Although a similar trend in inter-joint coordination was seen in both young and older adults and proper timing adopted to the compensatory synergy in both age groups, the extent of changes at the elbow and shoulder was smaller and less consistent in older adults compared to young participants, especially when trunk motion was involved. These findings could be due to the array of changes in the CNS, as well as peripheral structures, such as sensory receptors, muscles, peripheral nerves, and joints (Welford, 1977; Salthouse, 1985; Stelmach & Worringham, 1985) associated with aging.

Together, based on the findings from Chapters 2 and 3 we can conclude that older adults preserved the ability to use the appropriate motor synergy based on task demands and achieve the desired motor goal. In other words, healthy older adults maintain the flexibility of modifying the coordination of the available degrees of freedom (i.e., arm joint angles) while ensuring successful achievement of the intended motor act.

After establishing the ability of older adults to adapt their reaches to meet changes within the body, we next looked to examine their ability to adapt their reaches to changes in the environment, in particular changes in the visual environment using a visuomotor adaptation paradigm.

6.2. Paradigm 2: Reach Adaptation to Changes within the Environment (Chapter 4 and Chapter 5)

One method of studying adaptation to changes within the environment is to present individuals with altered visual feedback of their hand position during a goal-directed reach via misaligned cursor feedback and observe how movements are adapted. Reaching with such altered visual feedback typically results in adaptation of one's reaches in order to reduce reaching errors so that the cursor is brought to the target (Krakauer, Pine, Ghilardi, & Ghez, 2000; Cressman & Henriques). Despite extensive use of this visuomotor adaptation paradigm, adaptation in older adults, specifically with respect to intermanual transfer and retention, has received limited attention with inconsistent findings (Buch et al., 2003; Bock, 2005; Seidler, 2007; Cressman, Salomonczyk, & Henriques, 2010; Wang et al., 2011; Leow et al., 2012, 2013; Pan & Van Gemmert, 2013). In Chapter 4, we looked to determine whether implicit contributions to visuomotor adaptation are transferred to the untrained hand and retained in both hands in both young and older adults. Furthermore, we examined whether providing augmented somatosensory feedback regarding movement endpoint would enhance visuomotor adaptation in both age groups. We had young and older participants train to reach with a small 30° visuomotor distortion, since adaptation to small cursor distortions (i.e., 30° or less) has been shown to be driven implicitly (Neville & Cressman, 2018; Vachon, Modchalingam, ‘t Hart, & Henriques, 2020).

We found that older adults adapted their reaches to a similar extent and exhibited comparable aftereffects as younger adults. These results agree with previous literature examining implicit adaptation in older adults (McNay & Willingham, 1998; Buch et al., 2003; Bock, 2005; Cressman et al., 2010; Vachon et al., 2020). We assume that adaptation was driven implicitly in our study because our participants (1) adapted to small rotation, (2), did not receive prior instructions regarding the distorted cursor feedback, (3) did not report awareness of the visuomotor distortion, and (4) demonstrated aftereffects in the trained hand.

With respect to our questions of interest, we found that implicit adaptation in the form of aftereffects transferred from the right trained hand to the left untrained hand in both young and older individuals and both age groups recalled aftereffects in the right trained hand 24 hours later. Recently, it has been suggested that explicit processes (i.e., engagement of a cognitive strategy) contribute to intermanual transfer in young adults (Poh, Carroll, & Taylor, 2016; Werner, Struder, & Donchin, 2019; Bouchard & Cressman, 2021). While we did find evidence of intermanaul transfer, this transfer was minimal (approximately 23% of the implicit adaptation observed in the right hand), suggesting that explicit processes may be required for greater intermanual transfer (Poh et al., 2016; Bouchard & Cressman, 2021). Alternatively, the untrained hand may not have access to the same information needed to counter the visuomotor distortion as the trained hand. Since an error arises when reach training with the right hand, the trained right hand may be in the appropriate state to incorporate error information, while the untrained left hand is not in a state that is appropriately suited to incorporate this error information. Thus, an error signal, even if transmitted equally to controllers for both hands, may be less effective when applied to a controller that is not fully engaged (Taylor, Wojaczynski, & Ivry, 2011).

Similar to previous literature (Maksimovic & Cressman, 2018; Reuter et al., 2020), we found a decay in retention of implicit adaptation following a delay period. Specifically, the magnitude of aftereffects was significantly less on Day 2 compared to Day 1, with only 25% of initial aftereffects retained for both groups. This decay in implicit learning may reflect a decay of the fast labile component of motor learning (see Hadjiosif & Smith, 2013a). Additionally, we didn't observe recall of aftereffects in the untrained left hand after a 24 hour delay, potentially due to the limited intermanual transfer of implicit visuomotor adaptation to the left hand.

Finally, we showed that participants did not benefit from the augmented somatosensory feedback as performance was similar across all participants regardless of whether participants received augmented somatosensory feedback. These results can be explained by the concept of sensory integration which suggests that the brain assigns more reliable sensory inputs (i.e., sources providing more precise information) a higher weight (i.e., provide more input) (for review see Ernst & Banks, 2002). Within visuomotor adaptation, it has been suggested that updating an internal model relies mostly on visual and less on proprioceptive feedback (Krakauer, Ghilardi, & Ghez, 1999; Krakauer, 2009). The re-weighting of proprioceptive feedback has been found to be most prominent at the beginning of the adaptation period (Bernier, Burle, Vidal, Hasbroucq, & Blouin, 2009). Therefore, a possible interpretation of our results could be that as the afferent proprioceptive signals is attenuated at the beginning of adaptation, the primacy of visual feedback over proprioception masks the potential effects of the augmented feedback. This explanation cannot be fully confirmed from our results since we do not directly measure sensory re-weighting.

In Chapter 5, we extend our findings of Chapter 4 to understand how older adults control their movements during visuomotor adaptation. In particular, we looked to determine if the contributions of online and offline control processes in adapted reaching movements differ from those underlying well-learned movements. To do so, we conducted a detailed analysis of reaching performance by comparing reaction time (RT), movement time (MT), resultant peak velocity (PV), proportional time after peak velocity (pTAPV), and path curvature (PC), between the two age groups, during and after visuomotor adaptation. We found that (1) participants in both age group engaged different control processes for adapted movements compared to well-learned movements, (2) that these control processes underlying adapted movements are flexible.

During reaching in a typical environment (i.e., with aligned cursor feedback), we showed that older adults engaged offline and online control processes to a greater extent compared to young adults since they took significantly longer time to initiate their movements (i.e., slower RT), reached with a lower PV, and had the tendency to spend more time homing in on the target (i.e., had a longer pTAPV) compared to young participants (see Worringham, 1991; Heath et al., 1998; Khan et al., 1998; Elliott, Chua, Pollock, & Lyons, 1995; Khan & Franks, 2000; Elliott, Helsen, & Chua, 2001; Khan et al., 2003; Elliott, Hansen, Mendoza, & Tremblay, 2004; Hansen et al., 2006; Burkitt et al., 2013). On the other hand, we also found that both age groups modified the engagement of these control processes when they started to reach in the novel environment (i.e., with rotated cursor feedback) as demonstrated by a longer time to initiate and complete movements, lower PV, and greater time spent after PV, compared to their reaches in the typical environment. Moreover, older participants' reaches with rotated cursor feedback were significantly more curved than their reaches with aligned cursor feedback, while curvature did not change for young participants between reaching environments. The difference in reaching performance related to increased MT, decreased PV and increased PC continued following rotated reach training even in the no-cursor reaching trials regardless of age. Together, these findings suggest that movements across the two reaching environments were not performed in a similar manner and indicate that participants in both age groups engaged more online control processes when completing adapted movements compared to reaching in a typical manner. Moreover, since older participants did reach with more curved paths, we can assume that they engaged online processes to a greater extent than young adults.

Together, based on the results of Chapters 4 and 5 we conclude that, when visuomotor adaptation is driven implicitly, older adults maintain the ability to adjust their reaches to meet changes in the reaching environment, as well as transfer and retain the newly acquired movement. Moreover, they preserve the flexibility to adjust the control processes underlying these adapted movements to meet the demands of the reaching environment.

6.3. Limitations and Future Directions

There are several limitations in the experimental paradigms described in this dissertation that should be considered and that may warrant further investigation. First, the older participants were relatively healthy volunteers (i.e., had no neurological conditions or cognitive deficits) and thus may not represent the broader population of older adults. Therefore, the results may not necessarily generalize to older adults experiencing cognitive, sensory, or motor deficits. Second, we didn’t objectively measure physical activity levels in older adults, however, they did verbally indicate that they had an active lifestyle. To date, several studies have suggested that an active lifestyle improves motor performance and learning in older adults (Ren et al., 2013; Hübner & Voelcker-Rehage, 2017), suggesting that future research is needed to examine the influence of a sedentary lifestyle on motor adaptation. Finally, within visuomotor adaptation paradigm, we did not directly assess explicit adaptation. Therefore, there is the possibility that explicit processes may have contributed to the transfer and retention of visuomotor adaptation observed. Moving forward, the assessment of explicit adaptation should be considered to further understand the role of implicit and explicit processes in transfer and retention of visuomotor adaptation, as well as their role in the control of adapted movements, especially in older adults.

As a whole, the current series of studies presented in this thesis add to the body of literature by demonstrating that despite sensorimotor changes associated with aging, older adults are able to coordinate and adapt their UL's reaching movements to a similar extent as young adults in order to meet changes in task demand, whether these changes were intrinsic within the body (i.e., trunk motion), or extrinsic in the environment (i.e., visual distortion). Thus, with advanced age, the flexibility in adjusting UL motor performance to successfully achieve the motor task is preserved.

6.4. Conclusion

Carrying out activities of daily living require the ability to coordinate and adapt movements to changes arising within the body or in the environment. In this study we showed that healthy older adults preserved the ability to 1) use the appropriate UL coordination synergy and adjust this synergy based on task demands, and 2) transfer and retain implicit visuomotor adaptation and adjust the control processes underlying adapted movements to meet the demands of the reaching environment. Together, these findings provide evidence that flexibility in modifying motor performance to meet task demands and to accomplish the task goal accurately is maintained in older adults, however, their performance may be less consistent in comparison to young adults.

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7. Chapter 7 Appendices

Appendix A: Clinical Assessments

1. **The Edinburgh Handedness Inventory (Oldfield, 1971)** is a ten-item questionnaire designed to assess whether the participant is right-handed, left-handed, or ambidextrous, when carrying out common activities such as writing, drawing, using a toothbrush or a spoon.

2. **Dizziness Handicap Inventory (DHI) (Jacobson & Newman, 1990)** is a 25-item self-report questionnaire used to assess the impact of dizziness on quality of life; i.e., whether the individual's well-being is affected by dizziness. The DHI consists of three subscales: functional, physical, and emotional impacts on disability. The maximum score is 100 (maximum perceived disability) and the minimum score is 0 (no perceived disability). There are 28 points allocated to physical, 36 points to emotional, and 36 points to functional. Answers are graded 0 (no), 2 (sometimes), or 4 (yes) question. A score between 0 and 16 suggests no dizziness and a score between 16 and 30 suggests a mild handicap.

3. **Montreal Cognitive Assessment (MOCA) (Nasreddine et al., 2005)** is a rapid screening instrument to detect mild cognitive impairment. The MOCA assesses the following cognitive domains: attention and concentration, executive functions, memory, language, visuoconstructional skills, conceptual thinking, calculations, and orientation. There are seven different sections: visuospatial/executive, naming, memory, attention, language, abstraction delayed recall, and orientation.

    a) The visuospatial/executive section requires participants to follow the dots in a logical pattern (e.g., 1, A, 2, B, 3, C, etc.), copy a cube, and draw a clock at 10 minutes past 11. This is scored out of 5 points.
    b) The naming section requires individuals to name a picture of a lion, rhino, and camel. The section is scored out of 3 points.
    c) The memory section requires the examiner to read a list of 5 words, and then repeat them. Two trials are completed, even if the first trial is successful. The participant then must recall the list after 5 minutes. No points for this section.

    d) The attention section requires participants to perform three separate tasks. First, the participant must read a list of digits at the pace of 1 digit/second. The participant then must repeat them in the forward order and then in the backward order. This first task is out of 2 points. Second, the participant must read a list of letters. The individual must tap with their hand at each letter A. They are given no points if there are two or more errors, and this task is out of 1 point. Finally, the third task requires participants to do serial 7 subtraction task, starting from 100. This task is out of 3 points.

e) The language section requires participants to repeat 2 given sentences and then name a maximum number of words in one minute that begin with the letter F. The first task is scored out of 2 points and the second is scored out of 1 point. The abstraction section requires participants to use a word to describe the similarity between two words. For example, if the two words provided are “banana and orange” the connecting word would be “fruit”. This section is out of 2 points.

f) In the delayed recall section, participants are asked to recall words with 1) no cue, 2) a category cue, or 3) a multiple-choice cue. This section is scored out of 5 points.

g) The final section, orientation, requires participants to list their name, the date (the month, year, and day), the place, and the name of the city. This section is scored out of 6 points.

A participant can score a maximum of 30 points. A score of 26 or higher is considered within the normal range. A score between 22 and 26 suggests mild cognitive impairment, but no dementia.

4. **Trail Making Test Parts A & B (TMT) (Arnett & Seth, 1995)** is a neuropsychological test of visual attention and task switching. It involves two parts in which the participant is required to connect a set of 25 dots as fast as possible while still maintaining accuracy (Arnett & Seth, 1995). It provides information about visual search speed, scanning, speed of processing, mental flexibility, and executive functioning. In this test a participant must connect the dots of 25 circles distributed over a sheet of paper. There are two parts to the test: A, in which the circles are numbered 1 – 25, and the participant should draw lines to connect the numbers in ascending order, and B, in which the circles include both numbers (1 – 13) and letters (A – L); as in Part A, the participant draws lines to connect the circles in an ascending pattern, but with the added task of alternating between the numbers and letters (i.e., 1-A-2-B-3-C, etc.). Part A is used primarily to examine cognitive processing speed, while part B is used to examine executive functioning (Tombaugh, 2004). The participant should be instructed to connect the circles as quickly as possible, without lifting the pen or pencil from the paper. The patient should be timed Time as he or she connects the "trail." If the participant makes an error, it should be pointed it out immediately and the patient is allowed to correct it. Results for both Parts A and B are reported as the number of seconds required to complete the task. Thus, higher scores reveal greater impairment (i.e., score of ≤29 seconds on Part A, score ≤75 seconds on Part B).

5. **Rey-Osterrieth Complex Figure (ROCF) (Osterrieth, 1944)** is a neuropsychological assessment in which a participant is asked to reproduce a complicated line drawing, first

by copying it freehand (recognition), and then drawing from memory (recall). The test permits the evaluation of different functions, including visuospatial abilities, memory, attention, planning, and working memory (executive functions). The ROCF consists of three test conditions: Copy, Immediate Recall and Delayed Recall. First, participants are given the ROCF stimulus card, and then asked to draw the same figure. Second, they are asked to draw what they remembered. Then, after a delay of 30 min, they must draw the same figure once again. Each condition of the ROCF takes 10 min to complete and the overall time of completion is about 30 min.

6. **Joint Position Sense (proprioception)** is tested in the sitting or supine positions. The assessment starts by explaining to the participant with his/her eyes open as follows: "I am going to move your arm. This is up; this is down (demonstrate test). I want you to close your eyes and tell me if I am moving you up or down." The joint should be moved through a small range of motion (approximately 10 degrees for the limb joints and 5 degrees for the digit joint). The limb should be moved at least 3 times in random directions. If the participant is wrong on any direction, more repetitions must be added to determine if the accuracy is great than 75% (score 2) or 75% or less (score 1).

7. **Vibration sense (Macleod, Munro, & Campbell, 2000)** is tested by applying the base of a vibrating 128 tuning fork to the bony prominence at the base of one's thumb and ask him/her to describe the sensation. It is best to test participants with their eyes closed and ask them to determine whether the tuning fork is vibrating or not. If no vibration is sensed, the examiner should move to the radial stylus and move successively higher along the body if abnormalities are found distally.

8. **The Ottawa Sitting Scale (Thornton & Sveistrup, 2010)** is a clinical tool that is used to assess sitting balance. The scale consists of ten items of increasing difficulty. The first five items are tested with feet supported and the last five are tested with feet unsupported. In the five items, the participant is asked to: 1) maintain a static sitting position when told to sit tall and hold that position as long as they can, 2) reach the outstretched arm and/or move shoulders 12cm, then told to reach forward, backward, right and left, 3) reach the outstretched arm and/or move shoulders 25cm when told to repeat task 2 but to reach further (only in directions that were successful, able to reach 12cm, in the previous task), 4) rotate the trunk properly when told to turn and look behind to the right and then the left, as far as possible, 5) move forward and backward 12cm when told to walk their hips forward by shifting the body weight from one hip to the other until at the edge of the seat. All tasks are scored from 0-4, where 0 means that the participant is unable to complete the task or they require assistance to prevent falling, and 4 suggests the participant is able to complete the task successfully and independently.

Appendix B: Scoring Sheets

1. The Edinburgh Handedness Inventory (Oldfield, 1971)

Your participant ID:_________________

Please indicate with a one (1) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put a two (2).

If you are indifferent, put a one in each column (1 | 1).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

Please stop here

2. **Dizziness Handicap Inventory (DHI) (Jacobson & Newman, 1990)**

EHABILITATION
Medicine Clinic

Dizziness Handicap Inventory

Instructions: The purpose of this scale is to identify difficulties that you may be experiencing because of your dizziness. Please check "always", or "no" or "sometimes" to each question. Answer each question only as it pertains to your dizziness problem.

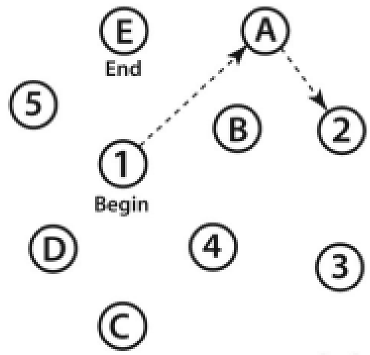
	Questions	Always	Sometimes	No
P1	Does looking up increase your problem?			
E2	Because of your problem, do you feel frustrated?			
F3	Because of your problem, do you restrict your travel for business or pleasure?			
P4	Does walking down the aisle of a supermarket increase your problem?			
F5	Because of your problem, do you have difficulty getting into or out of bed?			
F6	Does your problem significantly restrict your participation in social activities, such as going out to dinner, going to movies, dancing or to parties?			
F7	Because of your problem, do you have difficulty reading?			
F8	Does performing more ambitious activities like sports, dancing, and household chores, such as sweeping or putting dishes away; increase your problem?			
E9	Because of your problem, are you afraid to leave your home without having someone accompany you?			
E10	Because of your problem, have you been embarrassed in front of others?			
P11	Do quick movements of your head increase your problem?			
F12	Because of your problem, do you avoid heights?			
P13	Does turning over in bed increase your problem?			
F14	Because of your problem, is it difficult for you to do strenuous housework or yard work?			
E15	Because of your problem, are you afraid people may think that you are intoxicated?			
F16	Because of your problem, is it difficult for you to go for a walk by yourself?			
P17	Does walking down a sidewalk increase your problem?			
E18	Because of your problem, is it difficult for you to concentrate?			
F19	Because of your problem, is it difficult for you to walk around your house in the dark?			
E20	Because of your problem, are you afraid to stay home alone?			
E21	Because of your problem, do you feel handicapped?			
E22	Has your problem placed stress on your relationship with members of your family or friends?			
E23	Because of your problem, are you depressed?			
F24	Does your problem interfere with your job or household responsibilities?			
P25	Does bending over increase your problem?			

3. Montreal Cognitive Assessment (MOCA) (Nasreddine et al., 2005)

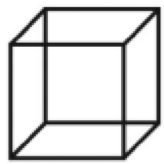
MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 Original Version

NAME :
Education :
Sex :
Date of birth :
DATE :

VISUOSPATIAL / EXECUTIVE



[ ]



Copy cube

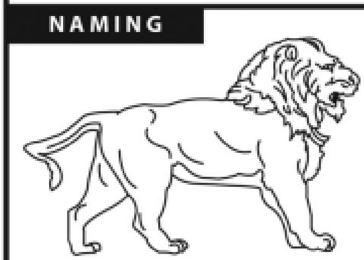
[ ]

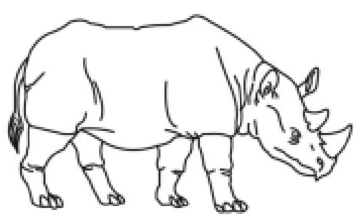
Draw CLOCK (Ten past eleven)
(3 points)

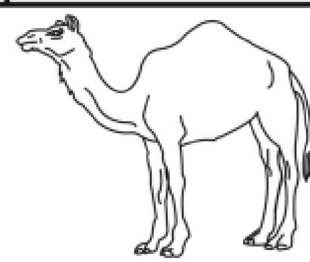
[ ] Contour [ ] Numbers [ ] Hands

POINTS: ___/5

NAMING


[ ]


[ ]


[ ]

___/3

MEMORY Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION Read list of digits (1 digit/ sec.).
Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2
___/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B
___/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt**
___/3

LANGUAGE Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ]
___/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] _____ (N ≥ 11 words)
___/1

ABSTRACTION Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler
___/2

DELAYED RECALL

	FACE	VELVET	CHURCH	DAISY	RED	
Has to recall words **WITH NO CUE**	[ ]	[ ]	[ ]	[ ]	[ ]	Points for UNCUED recall only
Optional Category cue						
Multiple choice cue						

___/5

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City
___/6

 www.mocatest.org Normal ≥26 / 30

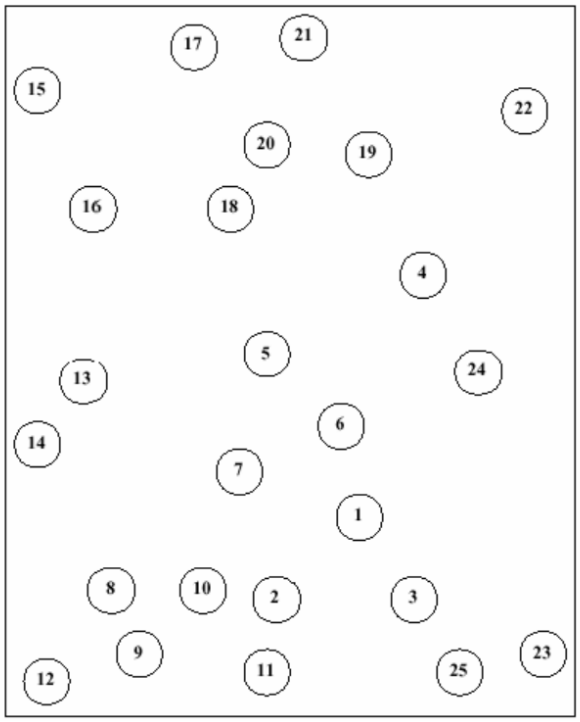
TOTAL ___/30
Add 1 point if ≤ 12 yr edu

Administered by: ________________________________

4. Trail Making Test Parts A & B (TMT) (Arnett & Seth, 1995)

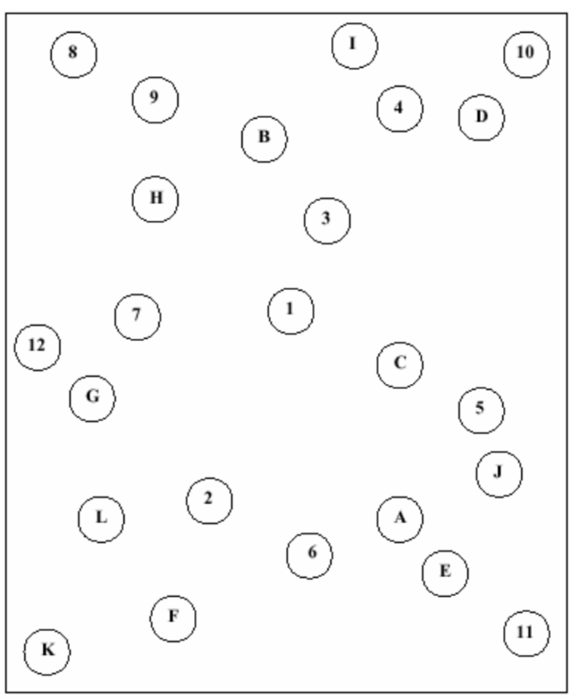
Trail Making Test Part A

Patient's Name: ______________________ Date: ________________

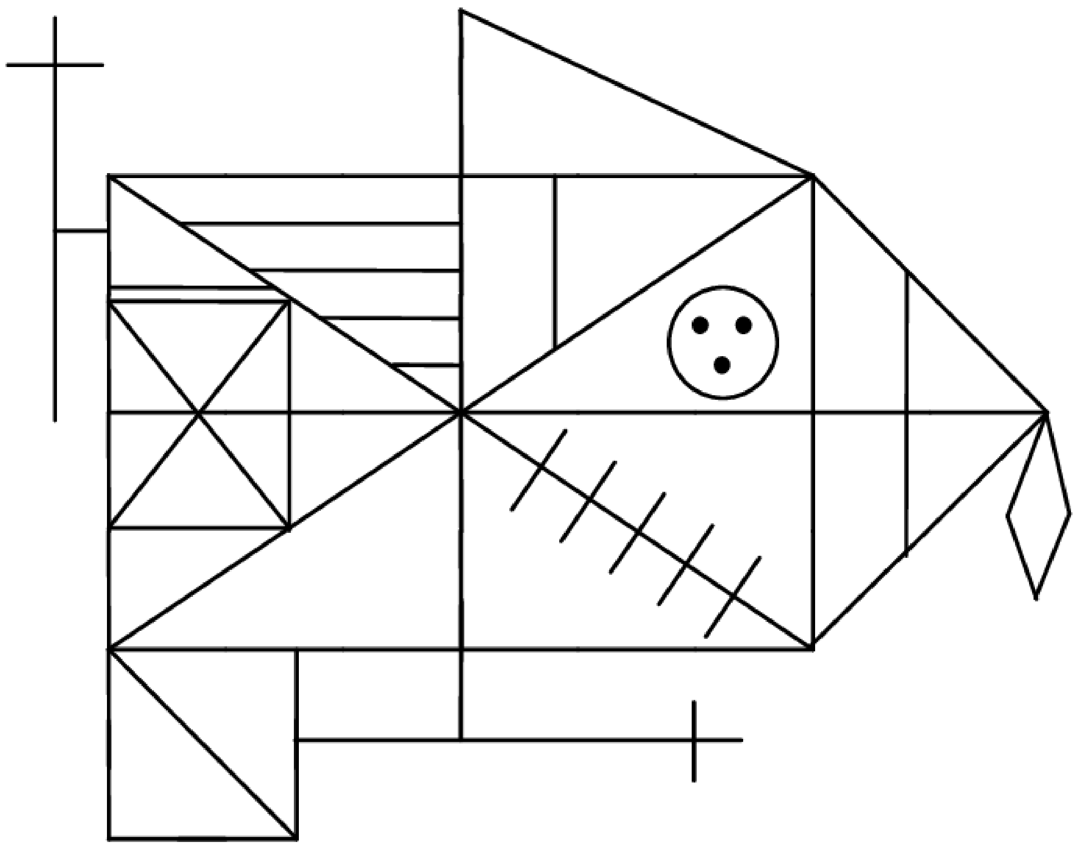


Trail Making Test Part B

Patient's Name: ______________________ Date: ________________



5. Rey-Osterrieth Complex Figure (ROCF) (Osterrieth, 1944)



6. Joint Position Sense (proprioception) (Hall & Mccloskey, 1983)

Participant's Name: Code:

Session: Date:

Hand: Rt. Lt.

Joint's Name	2 (Intact)	1 (Impaired)	0 (Absent)	Comments
Shoulder Joint				
Elbow Joint				
Wrist Joint				
Thumb Joint				

Hand: Rt. Lt.

Joint's Name	2 (Intact)	1 (Impaired)	0 (Absent)	Comments
Shoulder Joint				
Elbow Joint				
Wrist Joint				
Thumb Joint				

7. Vibration sense (Macleod, Munro, & Campbell, 2000)

Participant's Name: Code:

Session: Date:

Rt. Arm:

Trial No.	Vibration On	Vibration Off	Comments
1.			
2.			
3.			
4.			
Total Score	/4	/4	

Lt. Arm:

Trial No.	Vibration On	Vibration Off	Comments
1.			
2.			
3.			
4.			
Total Score	/4	/4	

8. The Ottawa Sitting Scale (Thornton & Sveistrup, 2010)

OTTAWA SITTING SCALE Date:__________________ Patient Name:______________________________

		4	3	2	1	0
1	***FEET SUPPORTED Maintains static sitting position***	( ) Maintains balance with midline posture >60 seconds	( ) Maintains balance 30-60 sec, may have poor posture, increased effort, leans to one side	( ) Maintains balance 5-30 sec, may have poor posture, increased effort, leans to one side	( ) Only able to maintain balance <5 sec	( ) Unable to sit unsupported. Falls and does not demonstrate postural reactions
2	***Reaches outstretched arm and/or moves shoulders 12 cm/5 in***	( ) Successful in all 4 directions	( ) Successful in 3 directions. Circle which directions F B R L	( ) Successful in 2 directions. Circle which directions F B R L	( ) Successful in one direction. Circle which direction F B R L	( ) Falls when trying to reach
3	***Reaches outstretched arm and/or moves shoulders 25 cm/10 in***	( ) Successful in all 4 directions	( ) Successful in 3 directions. Circle which directions F B R L	( ) Successful in 2 directions. Circle which directions F B R L	( ) Successful in one direction. Circle which direction F B R L	( ) Unsuccessful reaching 25 cm
4	***Turning: Trunk rotation***	( ) Able to look behind to both right and left, rotates both shoulders well	( ) Looks behind on one side only, rotates both shoulders with less rotation to one side. Circle successful side R L	( ) Looks sideways to both sides only, unable to rotate shoulders well to look behind but maintains balance well	( ) Looks sideways only R and L, needs supervision when trying to turn shoulders, leans to one side. Circle direction of lean R L	( ) Needs assistance to keep from falling when turning
5	***Scoots forward and backward 12 cm/5 in***	( ) Scoots forward and backward, advancing one hip then the other in continuous motion	( ) Scoots forward and backward, movements not continuous	( ) Scoots forward <12cm/5in. Record distance achieved. May be unable to move backwards	( ) Tries to move forward, but uses sudden trunk movement to slide forward a minimal distance	( ) Unable to try or needs assistance to perform the task

NOTE: "F B R L" stands for "Forward Backward Right Left" **Score feet supported: /20**

		4	3	2	1	0
6	***FEET UNSUPPORTED Maintains static sitting position***	( ) Maintains balance with midline posture >60 sec	( ) Maintains balance 30-60 sec, may have poor posture, increased effort, leans to one side	( ) Maintains balance 5-30 sec, may have poor posture, increased effort, leans to one side	( ) Only able to maintain balance <5 sec	( ) Unable to sit unsupported. Falls and does not demonstrate postural reactions
7	***Reaches outstretched arm and/or moves shoulders 12 cm/5 in***	( ) Successful in all 4 directions	( ) Successful in 3 directions. Circle which directions F B R L	( ) Successful in 2 directions. Circle which directions F B R L	( ) Successful in one direction. Circle which direction F B R L	( ) Falls when trying to reach
8	***Reaches outstretched arm and/or moves shoulders 25 cm/10 in***	( ) Successful in all 4 directions	( ) Successful in 3 directions. Circle which directions F B R L	( ) Successful in 2 directions. Circle which directions F B R L	( ) Successful in one direction. Circle which direction F B R L	( ) Unsuccessful reaching 25 cm
9	***Turning: Trunk rotation***	( ) Able to look behind to both right and left, rotates both shoulders well	( ) Looks behind on one side only, rotates both shoulders but with less rotation to one side. Circle successful side R L	( ) Looks sideways to both sides only, unable to rotate shoulders well to lok behind but maintains balance well	( ) Looks sideways only to R and L, needs supervision when trying to turn shoulders, leans to one side. Circle direction of lean R L	( ) Needs assistance to keep from falling while turning
10	***Scoots forward and backward 12 cm/5 in***	( ) Scoots forward and backward, advancing one hip then the other in continuous motion	( ) Scoots forward and backward, movements not continuous	( ) Scoots forward <12cm/5in. Record distance achieved. May be unable to move backwards	( ) Tries to move forward, but uses sudden trunk movement to slide forward a minimal distance	( ) Unable to try or needs assistance to perform the task

Score feet unsupported: /20

Total Score: /40

Appendix C: Ethics Approval for Chapter 2 and Chapter 3

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Téléc./Fax: 613-562-6367

Hôpital Saint-Vincent Hospital
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Ottawa ON K1R 7A5
Tél./Tel.: 613-562-6262
Téléc./Fax: 613-782-2785

Résidence Élisabeth-Bruyère Residence
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Ottawa ON K1N 5C8
Tél./Tel.: 613-562-6262
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Résidence Saint-Louis Residence
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Ottawa ON K1C 2Z6
Tél./Tel.: 613-562-6262
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Village Bruyère Village
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Bruyère Family Medicine Centre
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Centre de médecine familiale Primrose
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Fondation Bruyère Foundation
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Téléc./Fax: 613-562-6023

December 23, 2014

Dr. Heidi Sveistrup
Full Professor
Health Sciences & University of Ottawa
School of Rehabilitation Sciences
Faculty of Health Sciences

Re: Elucidating the underlying mechanisms of disordered upper limb function in stroke: the relationship between deficits in trunk control and upper limb coordination.
(Bruyère REB Protocol # M16-14-014)

Amendment Approval

Dear Dr. Sveistrup,

Thank you for submitting a request for approval of the items listed below to the above-named study.

☑ Approve the change in location to facilitate acquiring the data for the **motor tasks only** for the stroke participants to Dr. Sveistrup's laboratory at the University of Ottawa (Lees campus)

☑ Approval to modify the equipment (from portable ultrasound system with 5 ultrasound emitters to a 7 camera inferred VICON system) to facilitate data acquisition and to remain within the time allocation proposed

☑ Approve the change in participant sample; stroke inpatients will no longer be included, all participants with stroke will be outpatients

The information received has been reviewed and I hereby give approval on behalf of the REB.

Please note that any future changes to the protocol must be submitted to the Research Ethics Board for approval.

Sincerely,

Dorothy Kessler, M.Sc., O.T. Reg (Ont), PhD Candidate
Chair
Research Ethics Board
Bruyère Continuing Care
(613) 562-6262 ext 1420
dkessler@bruyere.org

Appendix D: Ethics Approval for Chapter 4 and Chapter 5

File Number: H12-14-17

Date (mm/dd/yyyy): 01/28/2015

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
Erin	Cressman	Health Sciences / Human Kinetics	Supervisor
Heidi	Sveistrup	Health Sciences / Rehabilitation Sciences	Co-investigator
Sajida	Khanafer	Health Sciences / Human Kinetics	Student Researcher

File Number: H12-14-17

Type of Project: Independent Student Project

Title: The influence of feedback on motor learning and adaptation

Approval Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
01/28/2015	01/27/2016	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A