UiT

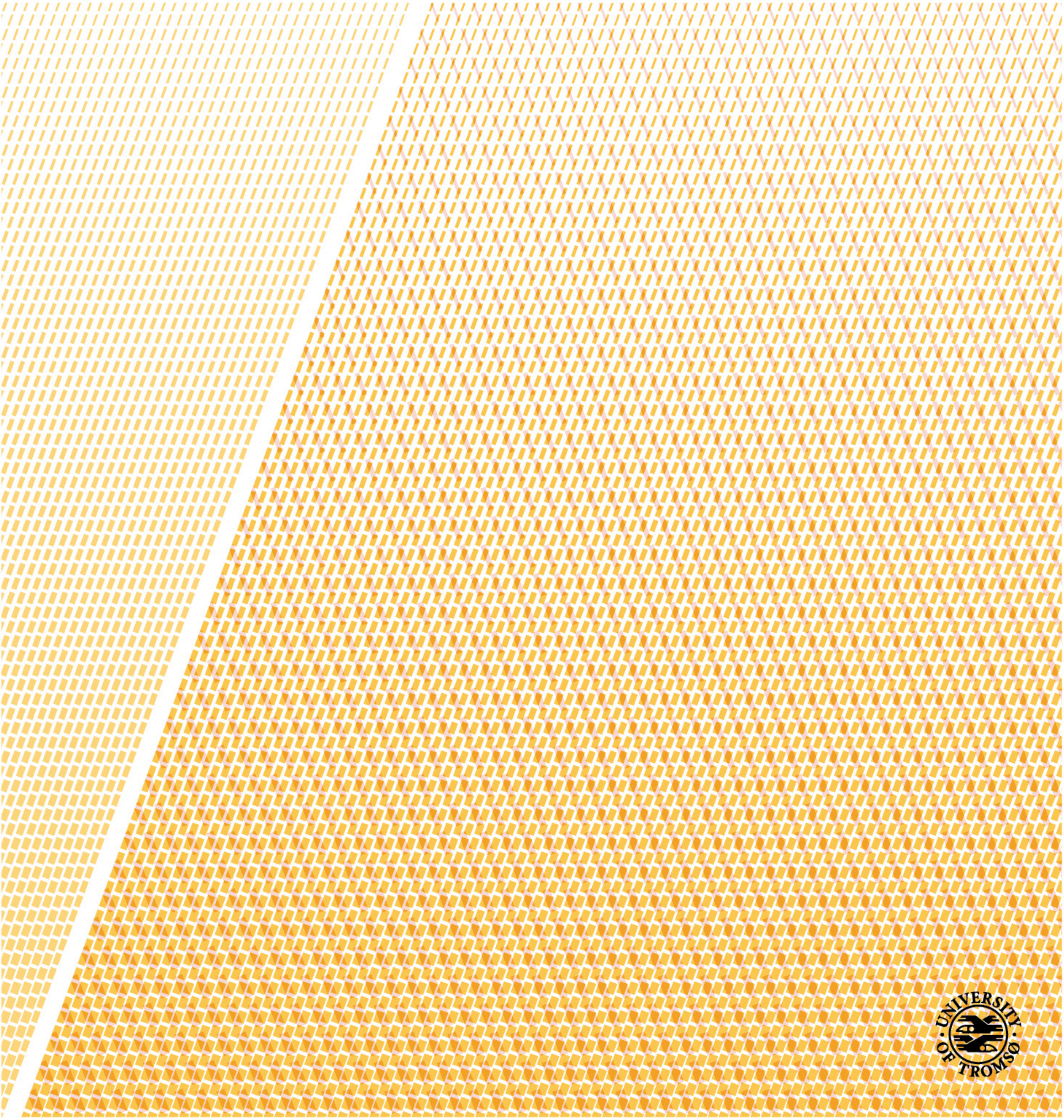
THE ARCTIC
UNIVERSITY
OF NORWAY

Department of Psychology

Manual dexterity in young and healthy older adults and its association with cognitive abilities

—

Olena Vasylenko
A dissertation for the degree of Philosophiae Doctor – February 2019



Acknowledgments

All studies in this dissertation have been conducted at the University of Tromsø. Financial support was received from the Department of Psychology, Faculty of Health Sciences.

I would like to acknowledge all who have contributed to this dissertation. My deepest gratitude goes to my main supervisor, Claudia Rodríguez-Aranda, for sharing her extensive knowledge and providing valuable advice. I would also like to thank my co-supervisor, Knut Waterloo, for his support. Warm thanks to my colleagues and fellow PhD students for their encouragement and helpful discussions.

I am grateful to Louise Matsson at Contemplas for technical help with the motion capture system, and to Thomas Nermo at the Department of Psychology for technical assistance in the lab.

Finally, my appreciation also goes to my family and friends for their kind support. Many thanks to my parents Nataliya and Vasyl Vasylenko, and my partner Kristian Berg for their love and encouragement in my work and life.

Olena Vasylenko

February 2019 Tromsø

Contents

Abstract

Background and aims. Much research has been conducted on age-related changes in cognitive function, but psychomotor abilities, such as manual dexterity, have been less studied. A better understanding is needed of which movement components account for the general slowing of performance and how central factors, such as cognitive decline, contribute to slowing. The aims of this thesis were to evaluate a) differences in manual dexterity of young and healthy older adults and b) the role of cognitive abilities in dexterity performance. Additionally, the contributions of gender and neuromuscular hand function were assessed.

Methods. A novel methodological approach combining the Purdue Pegboard Test and motion capture was employed. Movement times and kinematic parameters were obtained for four actions: reaching, grasping, transport, and inserting of pins, performed both unimanually and bimanually. Cognitive abilities were assessed by a neuropsychological battery. Outcomes were tested as predictors of dexterity measures.

Results. Slowing of performance was found in both unimanual and bimanual tasks, but the amount of slowing differed by type of action. Whereas movement times of grasping and inserting were longer in older adults across all tasks and for both hands, reaching and transport were slower only when performed with the left hand. Kinematic differences were specific to movement type: for reaching and transport, the largest differences were in linear velocity; for grasping and inserting, in path length and angular velocity. Older males showed more slowing compared to females. Executive function significantly predicted dexterity in the older group, but not in the younger. Executive function was related to movement times during reaching and grasping, as well as to path lengths during grasping and inserting pins.

Discussion. These findings advance the current understanding of age-related dexterity decline and identify executive function as an important contributing factor. Results are relevant for dexterity assessment in research and clinical contexts. Future studies should investigate neural mechanisms of dexterity decline and its association with cognitive function.

List of Papers

Paper I

Rodríguez-Aranda, C., Mittner, M., & Vasylenko, O. (2016). Association between executive functions, working memory, and manual dexterity in young and healthy older adults: An exploratory study. *Perceptual and Motor Skills, 122*(1), 165-192. [Published].

Paper II

Vasylenko, O., Gorecka, M. M., & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 1. Age- and gender-related differences in unimanual and bimanual performance. *Developmental Psychobiology, 60*(4), 407-427. [Published].

Paper III

Vasylenko, O., Gorecka, M. M., & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 2. Association with cognitive abilities. *Developmental Psychobiology, 60*(4), 428-439. [Published].

Abbreviations

ADL	Activities of daily living
CV	Coefficient of variability
EF	Executive function
fMRI	Functional magnetic resonance imaging
IADL	Instrumental activities of daily living
MMSE	Mini-Mental State Examination
MT	Movement time
PPT	Purdue Pegboard Test
RT	Reaction time
WM	Working memory

1. Introduction

The process of aging is inevitably accompanied by declines in general health, cognitive, and physical function. These declines may restrict the aging individual's ability to function independently and thus to lead a fulfilling life. Psychology has devoted much attention to studying the causes and mechanisms of age-related changes in cognitive abilities. Psychomotor functions, on the other hand, have been much less studied (Rosenbaum, 2005). Psychomotor functions are "abilities whose performance draws on a combined and coordinated set of cognitive and motor processes." (American Psychological Association, 2007, p. 754). The topic of this thesis is manual dexterity, one of the most essential psychomotor functions. Manual dexterity can be described as the ability to perform skillful movements with the hands and to manipulate objects quickly and efficiently. In our daily lives we must handle hundreds of objects every day while performing our usual tasks such as dressing, preparing meals, typing on keyboards, and many more. Age-related decline compromises older adults' ability to perform these actions swiftly and efficiently, and thus, may reduce their capacity to function independently in the community.

Although a vast body of knowledge exists about hand motor function, the topic of how normal aging affects manual dexterity still has many unanswered questions. Some of these questions concern the exact nature of declines and the underlying factors behind them. Therefore, the present work aimed to fill this gap by addressing two primary questions related to dexterity decline in healthy aging: a) which components of dexterity show slowing? and b) is there an association between cognitive abilities and dexterity decline in older adults? In order to illustrate the importance of these questions, the relevant concepts, approaches, and research conducted on age-related changes in dexterity are summarized. Thereafter, the specific aims of the present thesis, together with an account of the studies included in this work, are presented.

1.1. What is Manual Dexterity?

One of the most detailed definitions of dexterity is "… a manual skill that requires rapid coordination of gross and fine voluntary movements based on a certain number of capacities, which are developed through learning, training, and experience." (Poirier, 1987, pp. 71-72). This definition is particularly suitable because it highlights one of the most important points of the present thesis, namely, that dexterity is a complex skill that comprises different types of movements, which may be differentially affected by the aging process.

The two types of movements involved in dexterity are gross and fine. Gross movements can be defined as large and less precise movements that require the shoulder and elbow joints and the large muscles of the arm to transport the arm and hand over longer amplitudes. (Desrosiers, Hébert, Bravo, & Dutil, 1995). An example of a gross movement is reaching over some distance to point to a target or pick up an object. Fine movements are smaller and more precise, these involve the wrist and finger joints and the small muscles of the hand and fingers (Desrosiers et al., 1995). An example of a fine movement is grasping and lifting a small object such as a pen or a coin.

Furthermore, dextrous movements can be unimanual or bimanual. Unimanual actions are those that are performed with one hand, such as writing. The dominant hand is usually chosen to perform unimanual daily tasks. Bimanual actions are those that require coordinated movements of both hands to be performed efficiently. Bimanual actions can further be subdivided into synchronous and role-differentiated (Maes, Gooijers, de Xivry, Swinnen, & Boisgontier, 2017; Swinnen & Wenderoth, 2004). In synchronous movements both hands perform identical movements at the same time, for example when lifting and moving a large box or washing one's face. In role-differentiated movements the hands perform different but complementary actions. Usually, the dominant hand manipulates the object while the non-dominant hand has a supporting or stabilizing role. An example of a role-differentiated bimanual action is sewing: the dominant hand holds the needle and makes stitches while the non-dominant hand supports the fabric.

1.2. Why is it Important to Study Manual Dexterity in Older Adults?

In order to illustrate the importance of investigating manual dexterity in the present thesis, it is useful to put this topic into a wider perspective by briefly presenting the various research fields concerned with hand function in aging. Both basic and applied fields of research have contributed to an interdisciplinary understanding of how the aging process leads to changes in hand function and how these changes affect the lives of older adults. First, physiological studies have documented age-related changes in the muscles, joints, and motor units of the hand. This research has revealed age-related decreases in hand muscle mass and strength, reduction in muscle contractile speed, deterioration of bones and joints due to osteoarthritis, and decrease in the number of motor units (for a review, see Carmeli, Patish, & Coleman, 2003). Second, studies using kinematics and kinetics have provided detailed descriptions of specific components of older adults' movements. *Kinematics* are spatial and temporal parameters of movement, such as velocities and trajectories, whereas *kinetics* are the forces and torques applied to objects manipulated by the hand. A detailed account of kinematics research on dexterity is given in section 1.5.2 of the present thesis. Kinetics research on hand function has revealed declines in the ability of older adults to control and adapt the amount of force while manipulating objects, which may lead to inefficient grasping patterns and fatigue (for a review, see Diermayr, McIsaac, & Gordon, 2011). Together, physiological studies, kinetics, and kinematics approaches help understand the causes of age-related changes in hand function and advance several applied and clinical lines of research.

For instance, findings of basic research on dexterity decline are relevant for activities of daily living, which is an important topic in gerontology. Activities of daily living (ADL) are basic self-care tasks required for physical self-maintenance, such as feeding, dressing, grooming, toileting, bathing, and locomotion (Lawton & Brody, 1969). Instrumental activities of daily living (IADL) are more complex tasks that individuals need to perform to live independently in their own home. These include shopping, food preparation, doing laundry, housekeeping, transportation, the ability to use telephone, to handle own finances, and responsibility for own medication (Lawton & Brody, 1969). All of the ADL/IADL, except locomotion, are dependent on skillful hand movement. Thus, for older adults, maintenance of hand function is necessary to live independently in the community. Research on ADL/IADL has shown that, with increased age, there is a gradual decline in these abilities (Fried et al., 2001), which leads to disability and increases the risk for long-term nursing home placement (Luppa et al., 2010). In turn, disability is related to low quality of life (Hellstöm, Persson, & Hallberg, 2004), depressive symptoms (Fauth, Gerstort, Ram, & Malmberg, 2012), and mortality (Gill, Han, Gahbauer, Leo-Summers, & Allore, 2018). Because competence in ADL/IADL is to a large degree dependent on intact hand function, research on dexterity has the potential of contributing to prevention or intervention strategies to help preserve functional independence in older adults.

Another applied research field concerned with hand function and aging is that of motor learning and practice. The ability to learn new motor skills is becoming increasingly important for older adults as the demands to handle new technology increase in the workplace and home. Research on motor learning has shown that, in general, healthy older adults are able to learn motor skills, although when learning complex and fine dexterity tasks, they may require more practice than younger adults (e.g., Seidler, 2006, 2007; Voelcker-Rehage, 2008). Finally, dexterity is an important topic for research on rehabilitation of hand function following neurological diseases, such as stroke. More than half of post-stroke patients experience chronic impairments in reaching and grasping (Collins, Kennedy, Clark, & Pomeroy, 2017; Nowak, 2008). Therefore, based on kinematic analyses, researchers have developed rehabilitation strategies such as extensive practice of functional movements and use of assistive robotic devices (Nowak, 2008; Reinkensmeyer & Patton, 2009). Both approaches have been shown to improve the kinematics of functional movements in patients after a few weeks of training (Nowak, 2008; Reinkensmeyer & Patton, 2009).

This short summary of the different fields concerned with hand function and aging illustrates that manual dexterity is an important topic for many areas of research. The respective fields have generated a substantial multidisciplinary knowledge base about dexterity and aging. However, as for the exact nature of normal age-related changes in the kinematics of movement, as well as the different types of factors that contribute to dexterity decline, these issues remain to be fully explained.

1.3. Factors Contributing to Age-Related Dexterity Decline.

Skilled hand movement depends on both central and peripheral neural mechanisms, as well as the physiological properties of the hand. As mentioned in the previous section, much research has been conducted on the peripheral factors that may contribute to age-related dexterity decline. For example, reduction in muscle mass and the number of motor units may result in decreased strength and contractile properties of the muscle, leading to difficulty with proper control of force in object manipulation (Carmeli et al., 2003; Diermayr et al., 2011; Parikh & Cole, 2012). Additionally, reduction in the number of mechanoreceptors decreases tactile sensitivity (Tremblay, Wong, Sanderson, & Coté, 2004), which may explain why older adults more often drop an object after grasping it (Kinoshita & Francis, 1996).

Among the central factors contributing to decline in dexterity, slowing of information processing is probably the most explored one. A detailed account of the slowing phenomenon is provided in the next subsection. To a much lesser extent, the involvement of specific cognitive functions, such as executive function and working memory, has been taken into account (e.g., Bangert et al., 2010; Corti et al., 2017; Fraser, Li, & Penhune, 2010; Kobayashi-Cuya et al., 2018).

Finally, demographic factors, such as gender, may contribute to dexterity decline. Results on this topic have been inconsistent: some researchers showed more declines in females (Sebastjan, Skrzek, Ignasiak, & Slawinska, 2017), but others suggested the opposite pattern (Desrosiers, Hébert, Bravo, & Dutil, 1995; Lezak, Howieson, Bigler, & Tranel, 2012; Ranganathan et al., 2001). In the present thesis, all three aforementioned types of factors were taken into account, but special emphasis was placed on evaluating the role of different cognitive abilities in dexterity performance of older adults.

1.4. The Behavioral Slowing Phenomenon.

Early research on psychomotor skills showed that dexterity performance declines with age (Miles, 1931a, 1931b; Griew, 1959; for a review, see Welford, 1959). Most of these studies used reaction time (RT) to measure performance. RT is the amount of time from the presentation of a stimulus until a motor response is executed. Longer RTs are assumed to reflect decline in cognitive processing speed. Generally, early investigations showed that, compared to young adults, older adults had longer RTs in tasks that required perceiving a stimulus, choosing a response, and executing that response. Commonly used stimuli were visual (e.g., light) or auditory (e.g., click), and the responses required were finger tapping or pointing to a close target (Welford, 1959). Longer RT in older adults was particularly apparent in complex tasks involving multiple stimuli or several rules for responding (Griew, 1959). Although most of the early studies used RT as the primary way to measure behavioral slowing, a few researchers also assessed movement times (MT) (e.g., Griew, 1959; Szafran, 1951). In contrast to RT, which comprises the time to perceive the stimulus, plan and execute the response, MT only includes the time from the initiation to the completion of the movement itself. Both Griew (1959) and Szafran (1951) observed that older adults had longer RTs than younger, particularly in more complex tasks. However, neither study reported age-related differences in MTs. It should be noted however, that the lack of findings could be due to sample characteristics: for example, the oldest participants in Szafran's (1959) study were only 60 years old. Another reason that MT slowing was not found could be that these studies employed relatively simple movements, i.e., pointing to a close target with a stylus.

Based on the aforementioned studies, early findings showed that RT slowed with age, but movement itself did not. This lack of age-related differences in MT suggested that the main aspect of dexterity affected by aging was the choice and planning of movement, and therefore, did not provide further motivation to study hand movements in detail. At the time being, RT continued to be the most common measure to evaluate slowing of behavior and it remains commonly used in more current research as well (Burgmans et al., 2011; Deary & Der, 2005; Deary, Der, & Ford, 2001; Kerchner et al., 2012; Spirduso, Francis, & McRae, 1995, for a review, see Salthouse, 2017). These and other studies consistently show longer RTs in older adults in a variety of tasks. Indeed, slowing of RT in older adults is one of the most universal findings in gerontology (Salthouse, 2017; Spirduso et al., 1995), which highlights the importance of further exploring the mechanisms and causes of the age-related slowing phenomenon.

In summary, RT has an important role in research on behavioral slowing. However, RT only provides an overall measure of performance and is therefore less suitable for studying complex psychomotor functions, such as dexterity. To fully understand how and why dexterity performance slows with aging, the actual hand movements involved in complex tasks need to be analyzed in detail.

1.5. Current Approaches to Assessment of Dexterity Slowing.

1.5.1. Movement times (MT). MT measures the amount of time required by a participant to perform a task. This approach to measuring performance is the same as in early investigations that employed MT (Griew, 1959; Szafran, 1951), but tasks in current studies are typically more complex, reflecting the diversity of hand movements in daily activities.

Studies using MT measures have demonstrated age-related slowing of dexterity in a variety of tasks (Almuklass, Feeney, Mani, Hamilton, & Enoka, 2018; Bowden & McNulty, 2013; Desrosiers, Hébert, Bravo, & Rochette, 1999; Pennathur, Contreras, Arcaute, & Dowling, 2003; Serbruyns et al., 2013; Smith et al., 1999; for a review, see Ketcham & Stelmach, 2001). Some studies investigated performance of IADL in healthy older adults. For example, in a longitudinal study, Desrosiers et al. (1999) assessed older adults' performance on tasks such as handling coins, writing on an envelope, tying a scarf, and opening a jar. This assessment was repeated three years later. Results revealed between 10% and 16% longer MTs for all the aforementioned IADL tasks, indicating that age-related decline in dexterity is progressive and apparent even over relatively short periods of time. Other researchers studied manipulation of small objects in laboratory tasks. For example, Smith et al. (1999) designed a task which required participants to remove small, hollow cylinders placed on curved rods. Their older participants showed almost 50% longer MTs compared to young adults, suggesting that manipulation of small objects becomes particularly difficult with aging.

In general, MT is a useful overall measure of performance because it is easy to obtain and interpret. However, MT provides no information about why performance becomes slower, i.e., which specific movement parameters contribute to the overall slowing. To answer this question, more detailed analysis of movement is necessary.

1.5.2. Kinematic analysis. The second approach to assessment of dexterity is to measure kinematic parameters of movement such as velocity, trajectory, position, and variability. Although kinematic analyses are more complex to perform and interpret than temporal measures such as RT and MT, their clear advantage is the capacity to identify the specific components of movement that show decline. Kinematic analyses have been conducted for a variety of actions, such as reaching and aiming at targets, drawing lines to connect targets, grasping and manipulating objects. For gross movements, such as reaching and aiming, results have shown that older adults have lower velocity, longer and more variable movement trajectories, spend longer time in the deceleration phase, and make more submovements. (Bellgrove, Phillips, Bradshaw, & Galucci, 1998; Bennett & Castiello, 1994; Cooke, Brown, & Cunningham, 1989; Morgan et al., 1994). All these kinematic differences indicate slower, less accurate, and less economic movements. For example, a typical reach consists of an acceleration phase, in which the hand speeds up as it starts to move toward the target, and a deceleration phase, in which the hand slows down as it approaches and 'homes in' on the target. Prolonged deceleration phases indicate movement planning errors (Bennett & Castiello, 1994). Submovements are indicated by shifts in the direction of movement and occur in older adults to correct errors in trajectory, for example after "overshooting" or "undershooting" the target (Bellgrove et al., 1998).

A few studies have examined kinematic properties of object manipulation (Cicerale, Ambron, Lingnau, & Rumiati, 2014; daSilva & Bagesteiro, 2016; Grabowski & Mason, 2014; Wong & Whishaw, 2004). These findings have shown that older adults' manipulative movements are not always slower (Cicerale et al., 2014; Grabowski & Mason, 2014), but may be less efficient and qualitatively different. For example, when grasping objects, older adults are less likely to select the optimal grasping pattern (Wong & Whishaw, 2004), and their grasp patterns are often spatially misaligned (Parikh & Cole, 2012). Cicerale et al. (2014) measured grip aperture and wrist rotation in young and older adults during grasping of common objects (paint brush, tweezers, fork). Results showed larger apertures and less wrist rotation in older adults as the hand approached the target, which suggests that they were less able to adapt their hand and fingers position to the type of object. Most interestingly, however, older adults did not spend longer time than the younger group on the task. This suggests that older adults may use a different grasping strategy than young participants, possibly to compensate for spatial errors in trajectory. Consistently, in a study of reaching and grasping, Grabowski and Mason (2014) showed that older adults had larger grip apertures and spent longer time in deceleration phase but did not have lower velocity during reaching and grasping.

1.5.3. Unimanual vs. bimanual assessment. In sum, kinematic analyses have significantly contributed to a better understanding of how dexterity changes with aging, but a comprehensive assessment of both hands in unimanual and bimanual tasks is still lacking in the literature. All of the kinematic studies described in the previous subsection have studied unimanual performance, most commonly with the dominant (right) hand. In daily life, many tasks require using both hands simultaneously. Therefore, to fully understand age-related changes in dexterity, more research should be conducted on bimanual object manipulation. Currently, research on this type of movement in aging is scarce. In a recent meta-analysis, Krehbiel, Kang, & Cauraugh (2017) concluded that, in general, older adults' performance in bimanual tasks is slower and less accurate, as shown by longer MTs, more variable movements, and higher error rates. However, other evidence is inconsistent with this, suggesting that decline in performance may be dependent on the type of task. Specifically, older adults seem to experience difficulty with temporally asynchronous, anti-phase movements, while performing similarly to younger adults on synchronous, in-phase tasks (Bangert, Reuter-Lorenz, Walsh, Schachter, & Seidler, 2010; Wishart, Lee, Murdoch, & Hodges, 2000; Woytowicz, Whitall, & Westlake, 2016). Anti-phase and asynchronous movements are assumed to be more complex because they involve alternating movements of each hand and require temporal coordination (e.g., using a steering wheel while driving, tapping different sequences with different hands). In contrast, synchronous and in-phase tasks pose less demands on temporal coordination because they involve simultaneous performance of the same movement with both hands (e.g., carrying a tray, tapping the same sequence with both hands) (Woytowicz et al., 2016). In sum, current evidence on age-related differences in bimanual movements is inconsistent, possibly because of the large variety of tasks used in different studies. Furthermore, very few researchers investigated bimanual object manipulation, which is essential for daily tasks (Maes et al., 2017). Some exceptions exist (Bernard & Seidler, 2012; Serbruyns et al., 2015). These two studies measured bimanual dexterity of older adults with the Purdue Pegboard Test (PPT) (Tiffin & Asher, 1948). The PPT includes two bimanual tasks: one is manipulating pins with both hands simultaneously (symmetrical and synchronous task), and the other involves role-differentiated movements of both hands cooperating to assemble units of different pegs in a fixed sequence (asymmetrical and asynchronous task). Findings showed that older adults manipulated significantly fewer pegs in both the symmetrical and asymmetrical tasks (Bernard & Seidler, 2012). These results are important because they suggest that bimanual object manipulation is affected in older adults independently of the type of task. However, a detailed analysis of dexterity was not the purpose of these studies, thus, only an overall performance measure was used for each task (i.e., the number of pegs manipulated in 30 s. and one min., respectively). More detailed kinematic analyses of bimanual tasks are necessary to describe in detail how dexterity changes with age.

1.5.4. Standardized dexterity tests. The main types of standardized dexterity tests used in research are self-report questionnaires and performance-based tests. For example, in clinical assessment and research, hand function is often evaluated by questionnaires, such as the Upper Extremity Functional Index (Stratford, Binkley, & Stratford, 2001) and the Disabilities of the Arm, Shoulder, and Hand Questionnaire (Hudak, Amadio, & Bombardier, 1996). In these measures, participants rate their ability to perform skilled hand movements on a 4- or 5-point scale. Although brief and easy to administer, questionnaires only provide a subjective, qualitative description of hand function and thus, they are not suitable for detailed and objective assessment of manual dexterity. In contrast to self-report measures, performance-based tests are more likely to provide valid and objective evaluation of hand function. Examples of performance-based tests include the Jebsen-Taylor Hand Function Test (Jebsen, Taylor, & Trieschmann, 1969) and the Upper Extremity Performance Test for the

Elderly (Desrosiers, Hebert, Dutil, & Bravo, 1993). Both tests measure the amount of time needed to perform common daily tasks. Among performance-based tests, pegboard tasks such as the Grooved Pegboard Test (Kløve, 1963) and the PPT are also commonly used. Pegboard tasks require participants to manipulate small pegs as fast as possible. Compared to other performance tests, pegboard tasks provide more detailed assessment by separately measuring the dexterity of each hand. Studies comparing young and older adults' performance in these tasks have consistently showed that older adults manipulate about 20% fewer pegs within a given amount of time (Almuklass, Feeney, Mani, Hamilton, & Enoka, 2018; Bowden & McNulty, 2003; Pennathur, Contreras, Arcauta, & Dowling, 2003; Serbruyns et al., 2015).

1.6. Theoretical Explanations of Age-Related Dexterity Decline.

To my knowledge, there is no theory in psychology exclusively related to dexterity decline in aging. However, as a psychomotor skill, its decline can be explained by general theories addressing age-related changes that rely on cognitive and motor function. I summarize here two of the accounts that give a good frame for the studies in this thesis.

1.6.1. The processing speed theory. The general slowing, or the processing speed theory, is an account that may be applied to age-related decline in both cognitive and psychomotor functions. The processing speed theory (Birren, 1974; Salthouse, 1996) poses that, with advanced age, there is a generalized slowing in the speed of processing in the central nervous system which leads to less efficient cognitive processes and slower behavior. Processing speed can be characterized as the speed with which an individual can perform simple mental operations such as searching for a stimulus or comparing a stimulus to another (Salthouse, 2017). Processing speed is assumed to be a general and limited resource which is necessary for more complex cognitive processes, such as reasoning and memory. Therefore, age-related decline in processing speed is seen as a common cause for decline in many aspects of cognition and behavior (Salthouse, 1996).

Evidence for the processing speed theory comes from studies that compared RTs in a variety of tasks in young and older adults. This research has been summarized in section 1.4. Because the theory poses that many cognitive processes are affected by the slowing of processing, several studies have explored the association between measures of processing speed and performance on different cognitive tasks in older adults (Bryan & Luszcz, 1996; Hertzog, 1989; Hertzog & Bleckley, 2001; Lindenberger et al., 1993; Salthouse, 1993, 1994; Verhaegen & Salthouse, 1997; Zimprich & Martin, 2002). Findings provide substantial evidence that processing speed is related to performance in various cognitive domains in older adults, such as verbal skills, reasoning, memory, and decision making.

In sum, the processing speed account has an important role in explaining age-related decline. However, most studies have been concerned with the relation between processing speed and cognitive abilities, with little focus on psychomotor performance. Importantly, Birren (1974) hypothesized that decline in processing speed would lead to an overall slowing of movement and this effect would be largest for complex movements that require conscious decisions. However, current evidence of this relationship is lacking. One exception is a recent study that examined the effect of processing speed on IADL performance (Fauth, Schaefer, Zarit, Ernsth-Bravell, & Johansson, 2017). Their findings showed that performance on a time-limited picture matching task (measure of processing speed) significantly predicted MTs on IADL tasks such as inserting a key into a slot, dialing on a phone, and handling coins. These results suggest that slowing of processing may be an important factor in explaining age-related dexterity decline, but more research should be conducted on this relationship.

The main advantage of the processing speed theory is its parsimony: accounting for decline in many functions by a single factor would provide a simple and clear description of age-related changes. However, this account has been challenged by research showing that processing speed alone cannot explain decline in all types of cognitive tasks (Keys & White 2000; Park et al., 1996). Changes in other cognitive abilities such as working memory (Park et al., 1996) and executive function (Keys & White, 2000; Salthouse, Atkinson, & Berish, 2003) have been identified as important independent predictors of performance deficits in older adults.

The processing speed account is mainly a behavioral approach, which uses measures such as RT to assess slowing of behavior. At the time the theory was developed, this type of measures was the most conventional. However, using exclusively behavioral measures limits the potential to fully explain the mechanisms and causes of slowing. Recently, some researchers have employed advanced neuroimaging techniques, such as diffusion tensor imaging and analyses of cortical thickness, to study neural substrates of processing speed (Bucur et al., 2008; Burgmans et al., 2011; Deary et al., 2006; Ferreira et al., 2014; Kerchner et al., 2012). This research has revealed that deterioration of white and gray matter, especially in frontal and callosal brain regions, is related to measures of processing speed and performance on various cognitive tasks in older adults. Use of modern neuroscientific techniques is important to advance the processing speed theory because of their potential to identify the mechanisms of behavioral slowing.

1.6.2. The supply-and-demand framework. Another theoretical approach that can be used to explain age-related dexterity decline is the supply-and-demand framework proposed by Seidler et al. (2010). Compared to the processing speed theory, this account is a more modern approach that has been specifically developed to explain age-related declines in psychomotor abilities, such as dexterity and gait. This approach uses findings from neuroscientific studies that employ advanced neuroimaging techniques and attempts to explain psychomotor decline in terms of age-related changes in the brain. The supply-and-demand-framework poses that control of skilled movements becomes qualitatively different in older adults due to deterioration in brain motor areas, i.e., the motor cortex, the cerebellum, and the basal ganglia. When these areas function normally, control of skilled movement is relatively automatic and requires little effort. But when the motor areas become compromised due to aging, skilled movement becomes more dependent on effortful, cognitive control. Thus, the *demand* for cognitive resources to achieve efficient control of movement increases in aging. Cognitive control processes are assumed to rely on frontal and parietal brain areas. Importantly, these areas also show deterioration with aging, which causes cognitive control processes to become less efficient. This results in a lack of *supply* of cognitive resources necessary for efficient control of skilled movement. The consequence is decline in dexterity in older adults.

Evidence for the supply-and-demand framework comes from research that has documented changes in the aging brain. First, the primary motor cortex, the cerebellum, and the basal ganglia all show volume reductions in aging (Salat et al., 2004; Sullivan, Rohlfing, & Pfefferbaum, 2010). Furthermore, the frontal and parietal areas, which are important for cognitive control, also deteriorate (Salat et al., 2004). In addition, aging is associated with degeneration of the dopaminergic neurotransmitter system, which particularly affects the basal ganglia, a structure that is essential for fine motor control (Emborg et al., 1998). Equally, age-related dopamine depletion has been critically implicated in higher-order cognitive functioning (Cropley, Fujita, Innis, & Nathan, 2006). Together, these findings provide support for the idea that the supply of resources necessary for efficient motor control diminishes with aging. Evidence for the suggestion that additional brain areas become involved in motor control with aging is provided by research that has shown increased recruitment of frontal and parietal brain areas during hand coordination tasks in older adults (Heuninckx, Wenderoth, Debaere, Peeters, & Swinnen, 2005; Heuninckx, Wenderoth, & Swinnen, 2008). Importantly, increased frontoparietal recruitment was related to better task performance in these studies, confirming its compensatory nature. Together, these findings support the assumption that the supply of resources necessary for control of movement is decreased and the demand for cognitive control is increased in aging. The supply-and-demand framework offers a clear prediction that cognitive abilities are associated with dexterity performance in older adults. A number of studies have been conducted to test this prediction. Their findings are summarized in the next section.

In sum, both the processing speed theory and the supply-and-demand framework emphasize that cognitive processes play an essential role in psychomotor performance. Both approaches predict that with aging, skilled motor performance is increasingly connected with cognitive decline. Compared to the processing speed theory, the supply-and-demand framework is more specific in its explanation of age-related decline in psychomotor abilities.

1.7. Cognitive Decline and Its Association with Dexterity.

Age-related decline is well-documented for several cognitive abilities. However, researchers have only recently begun to explore the role of cognitive decline in complex psychomotor functions. Age-related changes have been documented in various aspects of attentional control and memory. Attention is a multi-faceted ability that is closely related to other cognitive functions. Aging is associated with declines in selective and divided attention (Drag & Bieliauskas, 2010; Zanto & Gazzaley, 2017). Both attention and working memory are essential for normal control of reaching and grasping (Baldauf & Deubel, 2010). Working memory (WM) is the ability concerned with active maintenance and manipulation of information that is used to guide ongoing and intended actions (Reuter-Lorenz & Lustig, 2017), and its capacity declines with aging, especially in tasks that also involve executive functions (Reuter-Lorenz & Park, 2010). Executive functions (EF) are high-level cognitive abilities that regulate behavior by goal formation, planning, and carrying out goal-directed plans flexibly (Jurado & Rosselli, 2007). Inhibition and switching are the first EF to decline in the course of aging (Craik & Bialystok, 2006; Jurado & Rosselli, 2007). In the domain of memory, episodic memory (i.e., memory of events) is the ability most affected by aging (Reuter-Lorenz & Park, 2010; Wang & Cabeza, 2017). Because these cognitive abilities are necessary for the planning and execution of skilled movements, it is important to establish the role of cognitive changes in age-related dexterity decline.

Several studies have provided evidence for the involvement of cognitive abilities in dexterity performance of older adults (e.g., Bangert et al., 2010; Corti et al., 2017; Curreri et al., 2018; Fraser et al., 2010; Kobayashi-Cuya et al., 2018). For example, Corti et al. (2017) found a significant association between one executive ability (planning) and performance on both unimanual and bimanual subtests of the PPT. Kobayashi-Cuya et al. (2018) documented a similar association between performance of the Trail Making Test and the PPT. Curreri et al. (2017) performed a longitudinal study to assess the association between cognitive and dexterity decline in older adults over 4 years. Their findings showed that changes in MMSE scores were significantly associated with changes in time needed to perform two dexterity tasks: a unimanual pegboard task and to put on and button up a shirt. In an experimental study, Fraser et al. (2010) confirmed the involvement of EF in dexterity. These researchers showed that increasing cognitive load by adding a dual task resulted in poorer performance of a sequential finger tapping task in older adults. Finally, in a study of bimanual coordination, Bangert et al. (2010) found that WM and EF scores were associated with asynchronous circle tracing and finger tapping performance, respectively.

1.8. Interest of the Present Thesis.

When addressing age-related decline in any motor function, including manual dexterity, it is evident that one of the most reliable findings in the literature is slowing of performance. However, for a thorough understanding of the slowing phenomenon, it is necessary to explore in detail exactly which parameters of movement are affected by aging. For example, do all movements become slower, or is decline specific to some types of actions? Are the movements of older adults just slower or are they also performed in a qualitatively different way? Are these changes equal for both hands? How does age-related cognitive decline contribute to the slowing of dexterity? To answer these questions, we combined detailed dexterity and cognitive assessments of young and older adults. Because a limitation of existing research is the lack of integrative approach to explain the nature and causes of behavioral slowing, the present project was conducted to broaden our current understanding of these issues.

Thus, an important objective of the present project was to develop a detailed and objective method for assessment of dexterity in healthy older adults. The overall goal was to quantify age-related decline in gross and fine movements by using a comprehensive approach that relies not only on the standard measures of time for task performance, but also on acquiring information about how movements are executed. To achieve this, we combined MT and kinematic analyses of performance on a modified version of the PPT. We measured MTs and kinematics of four types of actions performed both unimanually, including the non-dominant hand, and bimanually. To our knowledge, there are no studies in the literature that account for both MTs and kinematics of unimanual and bimanual performance in a healthy aging sample. Moreover, research in the present project focused on actions involved in the manipulation of small objects (Papers I and II), which are similar to many daily tasks. This makes the findings of this thesis relevant for applied and clinical research. Regarding the assessment of cognitive abilities, we selected a broader neuropsychological battery (Papers I and III), compared to earlier studies. The reason for this was that most of the previous studies only assessed EF (Fraser et al., 2010; Corti et al., 2017, Kobayashi-Cuya et al., 2018), although some researchers also measured global cognitive function (Curreri et al., 2018) and WM (Bangert et al., 2010). To provide a more thorough understanding of the association between cognitive abilities and dexterity decline in aging, other cognitive functions that show substantial age-related decline, such as attention and memory, need to be evaluated.

1.9. Assessment of Dexterity in the Current Project.

1.9.1. Motion capture. Motion capture is a widely used technique in biomechanics (Winter, 2009), and it has increasingly been applied in gerontology studies to analyze gait (Kressig et al., 2004; You et al., 2009) and hand movements (Gulde & Hermsdörfer, 2017; Seo, Kim, Oh, Ryu, & Choi, 2017). In motion capture studies, reflective markers are attached to participant's limbs and video recordings of movement are obtained in real time. After recording, coordinates of the markers are located in each video frame and kinematic parameters of movement are calculated based on these coordinates. Motion capture with kinematic analysis has clear advantages for assessment of dexterity. For example, current performance-based tests only use a single time measure per task. In contrast, motion capture followed by kinematic analysis permits measurement of multiple spatiotemporal parameters of movement in addition to the time taken to perform the movement. Although kinematic analyses are more complex to perform and interpret, their clear advantage is the capacity to describe several parameters of movement simultaneously. The high level of detail (i.e., 50 images per second in the present thesis) is an advantage because in this way it is possible to detect even subtle differences in dexterity of young and older adults and identify the parameters that best differentiate their movements.

1.9.2. The Purdue Pegboard Test. The PPT is a commonly used measure of dexterity in gerontology research and clinical assessment. The PPT is brief and easy to administer and it has good reliability (Lezak, Howieson, Bigler, & Tranel, 2012). Another advantage of the PPT is that it provides a comprehensive measure of dexterity by assessing both hands separately, and by assessing both unimanual and bimanual performance. The standard scoring of the PPT is the number of pegs inserted in 30 seconds. However, for the present investigation it was important to include MTs because these are good overall measures of speed. Therefore, we modified the instructions of the PPT, such that participants were required to manipulate a fixed number of pins, instead of inserting as many pins as possible in

30 seconds. Combining assessment of MTs and kinematics provided a more thorough description of performance than using only one type of measure.

The PPT tasks involve four repetitive actions: reaching for pegs, grasping a peg, transporting it to the row of holes, and inserting the peg into the hole. In the present project, these four types of movements were analyzed separately, based on the assumption that they are qualitatively different. This assumption has some support in the literature. For example, the reach to grasp movement consists of two components: the first is bringing the hand to the target in a fast movement and the second is preparing the grip to match the object and 'homing in' on the target in a slower fashion (Jeannerod, 1984). Furthermore, studies investigating neural control of dexterity have shown that, although the brain networks involved in reaching and grasping movements overlap, it is nevertheless possible to distinguish different areas and patterns of activation selectively involved in the different movement types (Battaglia-Mayer, Babicola, & Satta, 2016; Cavina-Pratesi et al., 2018). In a study by Binkofski et al. (1998), patients with lesions of the anterior intraparietal sulcus showed impaired performance of the grasping movement, whereas reaching was much less affected. These researchers also performed an fMRI analysis in healthy participants, which revealed a specific activation of the anterior intraparietal sulcus during grasping. Together, these findings support the assumption that dexterity performance comprises qualitatively different types of movements. Therefore, to investigate how each type of movement contributes to dexterity decline in aging, separate analysis of the four actions involved in the PPT tasks was performed in the present project.

1.10. Aims of the Studies.

1. To evaluate age-related differences in MTs and kinematics of dexterity during execution of the PPT. Age differences were evaluated:

   a) In unimanual and bimanual tasks involving manipulation of small pins.

b) In four specific actions: reaching, grasping, transporting, and inserting pins.

c) By taking into account additional factors known to affect dexterity in aging, such as neuromuscular hand function and gender.

2. To determine the relationship of various cognitive abilities, including attention, executive function, and memory, with age-related differences in dexterity.

2. General Method

This thesis is based on data from two studies: Study 1 was the pilot study (Paper I) and Study 2 was a more comprehensive analysis of dexterity and cognitive function (Papers II and III).

2.1. Participants, screening, and exclusion criteria

Both Study 1 and Study 2 were cross-sectional investigations, comparing young and healthy older adults. In both studies, the young samples consisted of students at the University of Tromsø, and the older samples were community-dwelling older adults. Participants completed a semi-structured interview to collect information about demographics, current health conditions and medication, sleep quality, and pain. Also, in both studies, participants were screened for depression and cognitive decline. Visual acuity was assessed by self-report in Study 1, but in Study 2, Snellen charts (Snellen, 1862) were employed to provide a more objective assessment. Additionally, to better characterize health status of the participants, the SF-36 questionnaire (Hays, Sherbourne, & Mazel, 1993) was employed in Study 2. Exclusion criteria for both studies were: previous stroke, head trauma, or injuries of the hands; currently taking medication that affects the central nervous system; current hand pain; impaired visual acuity (i.e., > 20/40); signs of global cognitive deterioration (i.e., Mini-Mental State Examination scores ≤ 27 (Petersen et al., 1999)); self-report of left-handedness (i.e., scores < +9 on the Briggs-Nebes Handedness Inventory (Briggs & Nebes, 1975)); and depression (i.e., Beck Depression Inventory scores > 13 (Beck et al., 1996)). Because Study 1 was a pilot project aimed at evaluating the techniques for assessment of dexterity, its sample size was rather limited. For Study 2, a larger sample was recruited. A detailed description of participant characteristics is available in the appropriate subsections of the respective papers.

2.2. Measures

2.2.1. Dexterity assessment. In both studies, dexterity performance was assessed with a modified version of the PPT and recorded with Vicon Motus 10.1 2D Motion Capture for subsequent kinematic analysis. Detailed descriptions of the PPT tasks are presented in the Methods sections of Papers I and II. In Study 1, only performance with the right hand was assessed. Two PPT tasks were selected: inserting pins and assembly. In the standard version of the PPT, the assembly task requires both hands, however, in Study 1 it was performed with the right hand only. The reason was that we aimed to test the methodological approach while controlling for as many factors as possible. By analyzing only the right hand, it was possible to reach conclusions about the usefulness of the method in analyzing unimanual performance. In Study 2, we assessed both hands, unimanually and bimanually, by using only the pins tasks. Here, we emphasized the different aspects of unimanual and bimanual performance while controlling for the type of object to be manipulated. From recordings of performance, the four different movement types were identified, and MT and kinematic measures were obtained for each movement type. Detailed descriptions of the PPT tasks, dexterity recording, and measures are provided in the appropriate subsections of Papers I and II.

2.2.2. Neuropsychological measures. Both studies included evaluation of attention, WM, and EF. However, for Study 2, a larger battery was selected, with additional tests of memory. To assess the role of neuromuscular changes, both studies included assessment of hand grip strength and finger tapping speed. All of the neuropsychological measures used in both studies were standardized tests, commonly used in clinical assessment and research

(Lezak et al., 2012; Romero, Hayes, & Welsh-Bohmer, 2011). Detailed descriptions of the neuropsychological batteries used in each study are provided in the appropriate subsections of Papers I and III.

2.3. Procedure.

Data collection for both studies was performed at the Department of Psychology, University of Tromsø. For Study 1, the duration of the procedure was about one hour for young and 1.5 hour for older adults. Because Study 2 involved more dexterity and cognitive measures, and more comprehensive screening, the procedure took about 30 min longer. In both studies, interview and screening were performed first, followed by dexterity assessment and cognitive testing.

2.4. Statistical Analyses.

In Study 1, Bayesian statistics were employed, due to the complexity of design (i.e., different types of pegs in the assembly task) and limited sample size. For this analysis, Bayesian mixed multivariate regression was conducted in R. In Study 2, multivariate analyses of variance and hierarchical regression were performed in SPSS using the traditional null-hypothesis testing approach.

2.5. Ethical Considerations.

The present project is part of an umbrella project which was approved by the Regional Committee for Medical and Health Research Ethics – REK South East A (2009/1427a). Standard procedures were followed with regard to informed consent, voluntary participation, the opportunity for withdrawal, the anonymity and privacy of the participants (World Medical Association, 2001). Specifically, all participants received written and oral information about the study before signing informed consent forms. They were also informed about the opportunity to withdraw their consent at any time without any explanation necessary.

Moreover, when conducting research with potentially vulnerable participants, additional ethical issues must be considered (Council for International Organizations of Medical Sciences, 2002), such as risk for harm or discomfort (Bozarro, Boldt, & Schweda, 2018). Older participants may be at higher risk for experiencing discomfort because age-related cognitive decline leads to diminished cognitive resources and this may cause fatigue during participation. Research has shown that performing a cognitive task is associated with more fatigue in older adults and it also takes longer for older adults to recover from fatigue (Hess & Ennis, 2011). The present project included extensive testing, sometimes lasting up to two hours. To ensure older participants' comfort, we provided breaks whenever participants asked for a break or otherwise showed signs of fatigue.

3. Summary of Papers

3.1. Paper I

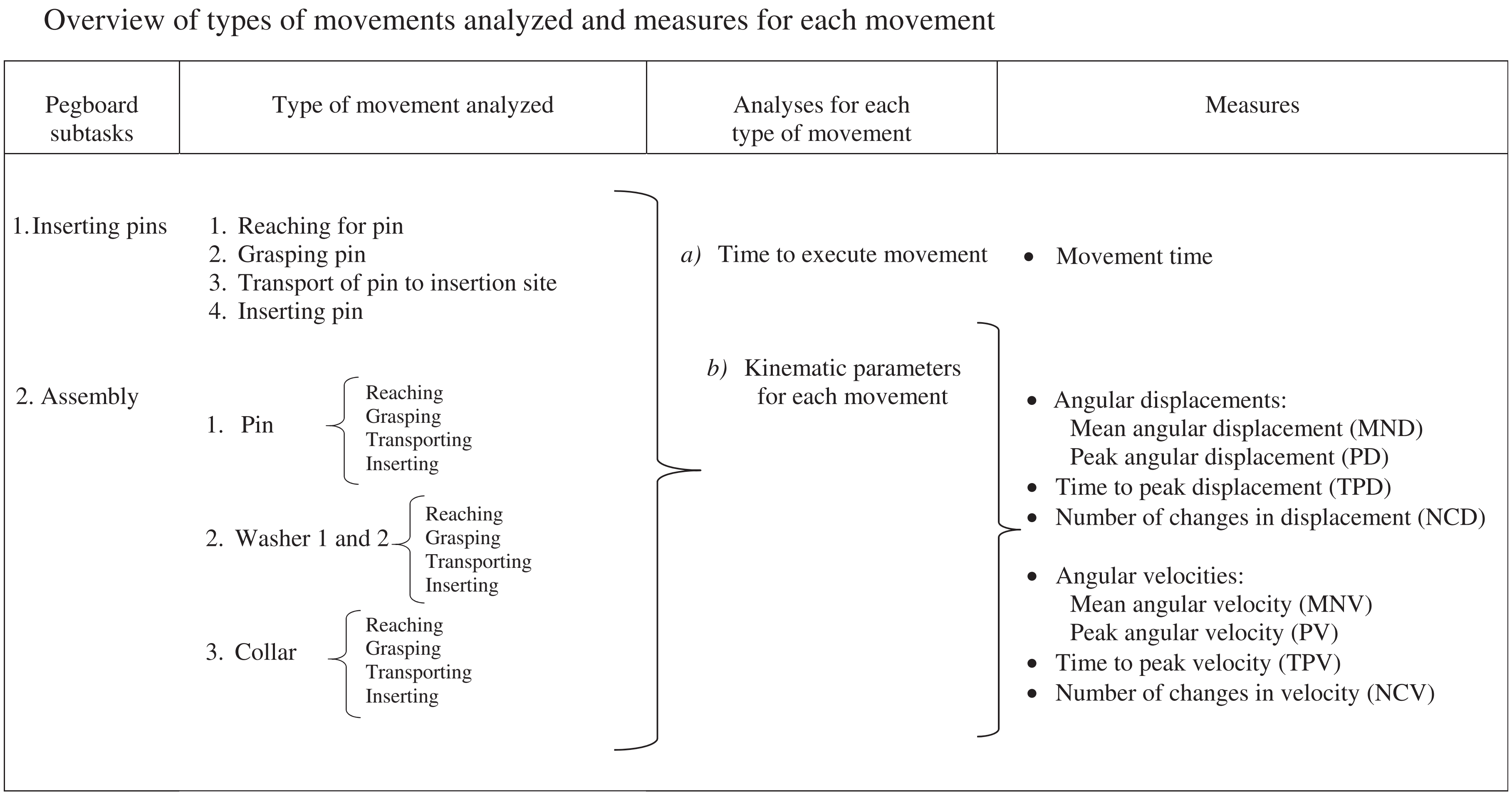
Rodríguez-Aranda, C., Mittner, M., & Vasylenko, O. (2016). Association between executive functions, working memory, and manual dexterity in young and healthy older adults: An exploratory study. *Perceptual and Motor Skills, 122*(1), 165-192.

3.1.1. Aims and hypotheses. The aims of Study 1 were to explore age-related differences in dexterity of the right hand and to analyze the association between dexterity and the cognitive abilities attention, WM, and EF. Specifically, we expected to identify the kinematic parameters that could explain age-related dexterity decline established in the existing literature. We also expected to show associations between specific dexterity parameters and cognitive functions. As this was the first study in our lab using the motion capture method, this was also a pilot investigation with the aim of optimizing and adapting the method for later studies.

3.1.2. Methods and measures. Fifteen young and fifteen healthy older adults underwent dexterity assessment with a modified PPT that included two tasks: inserting pins and assembly. Both tasks were performed with the right hand. Temporal and kinematic measures were used for each of the four actions involved in the tasks (reaching, grasping, transport, and inserting of pegs). The kinematics measured mean and peak angles, angular velocities, times to peak angle and angular velocity, and the variabilities in angles and angular velocities. See Table 1 below (from Paper I, p. 172) for a detailed overview of design and measures. Given the complexity of design and the limited sample size, we chose to use Bayesian ANOVA and multiple regression to analyze the data. The reason for this was that complex designs with small group sizes require many comparisons and when using traditional p-values, effect sizes are likely to be overestimated. But by using Bayesian Factors there is less probability for overestimation of effects in this situation (Wetzels et al., 2011).

3.1.3. Results and discussion. Results confirmed age-related differences in dexterity established by previous research. The novel finding was that only the grasping and inserting actions took longer to complete for older adults, but not reaching or transport. This result was consistent across tasks and types of peg. Kinematic results were inconclusive, revealing more variability in older adults, but also higher angular velocity, which was unexpected because it suggested better performance in the older group. The association between cognitive abilities and dexterity was obtained in both groups, but the direction of the association was unexpected, showing that better EF was related to lower angular velocity in the young group and to more variable angles in the older group.

Table 1. Overview of types of movements analyzed and measures for each movement.



Overview of types of movements analyzed and measures for each movement

Pegboard subtasks	Type of movement analyzed	Analyses for each type of movement	Measures
1. Inserting pins	1. Reaching for pin 2. Grasping pin 3. Transport of pin to insertion site 4. Inserting pin	*a)* Time to execute movement	• Movement time
2. Assembly	1. Pin: Reaching Grasping Transporting Inserting	*b)* Kinematic parameters for each movement	• Angular displacements: Mean angular displacement (MND) Peak angular displacement (PD) • Time to peak displacement (TPD) • Number of changes in displacement (NCD) • Angular velocities: Mean angular velocity (MNV) Peak angular velocity (PV) • Time to peak velocity (TPV) • Number of changes in velocity (NCV)
	2. Washer 1 and 2: Reaching Grasping Transporting Inserting		
	3. Collar: Reaching Grasping Transporting Inserting		

3.2. Paper II

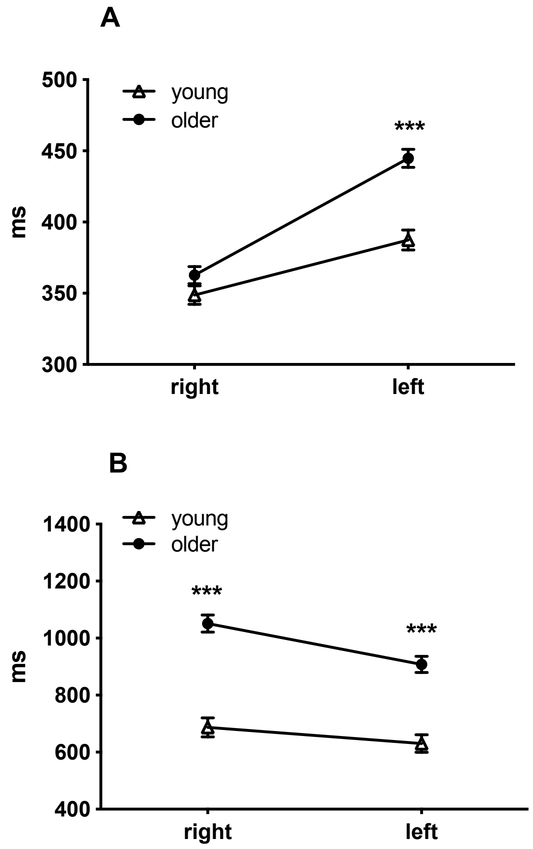
Vasylenko, O., Gorecka, M. M., & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 1. Age- and gender-related differences in unimanual and bimanual performance. *Developmental Psychobiology, 60*(4), 407-427.

3.2.1. Aims and hypotheses. In Study 2, we further investigated age-related differences in MTs and kinematics of dexterity of both hands in unimanual and bimanual tasks of the PPT. We expected to 1) replicate and clarify the age-related differences found in Study 1 by employing a larger sample of young and older adults; 2) to extend previous findings by describing both unimanual and bimanual performance of both hands; and 3) to determine the role of gender and neuromuscular hand function in dexterity decline.

3.2.2. Methods and measures. Forty-five young and 55 older adults participated in this study. Based on the results of Paper I, four modifications were made to the design and measures of dexterity assessment. First, to obtain a comprehensive description of dexterity, we added two tasks: inserting pins with the left hand and inserting pins bimanually, in addition to inserting pins with the right hand, which was used in Study 1. The assembly task was not used in this study, because in Study 1 we found no differences between the different pegs of this task, therefore, the assembly task would only add to the complexity of design without providing additional information. Using tasks with only pins allowed to compare dexterity under different conditions while controlling for the type of object. Secondly, we expanded the number of kinematic measures, adding linear velocity and path length, to better describe the speed and trajectory of hand movements. Third, we used a somewhat different marker arrangement (see Fig. 1 of Paper II), that better captured the shape of the hand. Finally, we only used the mean values of kinematic measures and not peak values, because these were highly correlated in Paper I. We also used a different measure of variability, the coefficient of variation (CV), as opposed to the number of changes which was used in Paper I. This was done to facilitate comparison with other research, because the CV is a more commonly used measure of variability. See Table 1 of Paper II for a detailed overview of design and measures.

3.2.3. Results and discussion. MT results obtained in Paper I were replicated in Paper II: reaching and transport movements of the right hand did not differ between young and older adults (see Fig. 1A and 1C[1]) but grasping and inserting were slower in the older group compared to the younger (see Fig. 1B and 1D). A novel finding concerning left-hand dexterity was that when performing with the left hand, older adults were slower in all four movement types (see Fig. 1A-D). Thus, we confirmed decline in fine movements but also found relative preservation of gross movements, at least for the right hand.

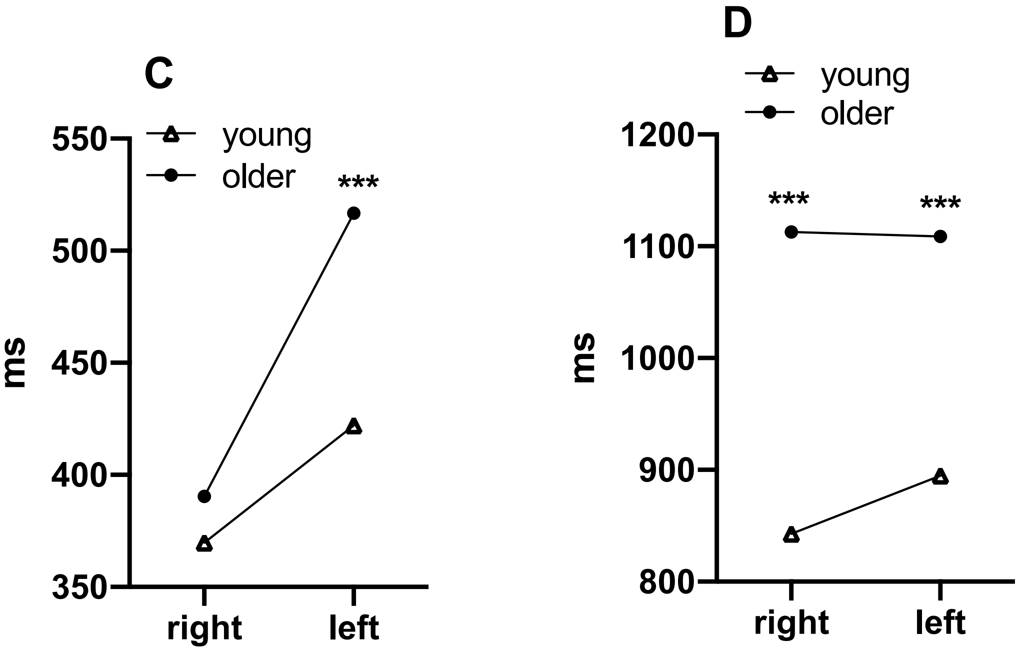
Figure 1. A. Time spent on reaching. B. Time spent on grasping.



---

[1] Error bars in all figures represent SEM (standard error of the mean). *** $p < 0.001$, ** $p < 0.01$. Error bars in Fig. 1C and 1D are too short to appear on the graphs.

Figure 1. C. Time spent on transport. D. Time spent on inserting.



Kinematic results obtained in Paper II extended and clarified the findings from Paper I. Specific patterns of kinematic differences were identified, depending on movement type. For the gross movements reaching and transport, the largest differences were in linear velocity (see Fig. 2 and 3). For grasping, the largest differences were in path length and angular velocity (see Fig. 4A and 4B), and for inserting, in path length and CV of angular velocity (see Fig. 5A and 5B). Thus, the results of Paper II showed that gross movements are primarily associated with slower speed in older adults, whereas fine movements are associated with slower rotation and less precise trajectory of the hand.

Regarding the effects of gender, more slowing was found in older males compared to females, in all movements except inserting. The age- and gender-related results were consistent across unimanual and bimanual tasks, indicating that these types of dexterity decline similarly in older adults.

Figure 2. Linear velocity during reaching.

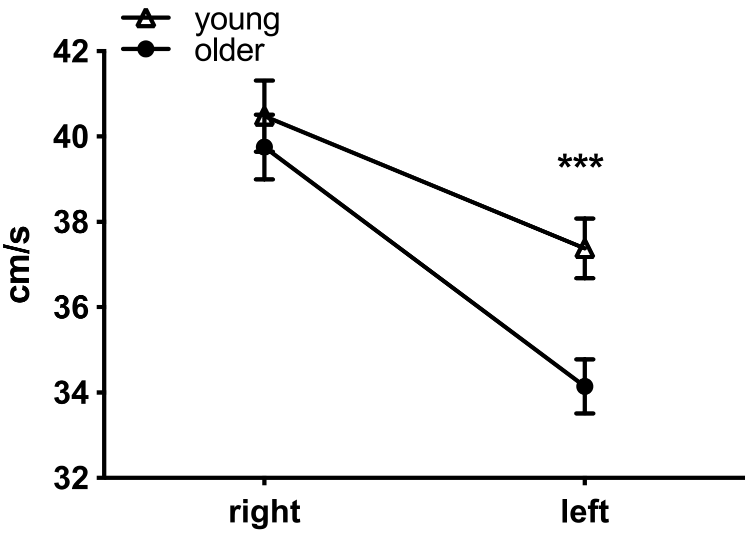


Figure 3. Linear velocity during transport.

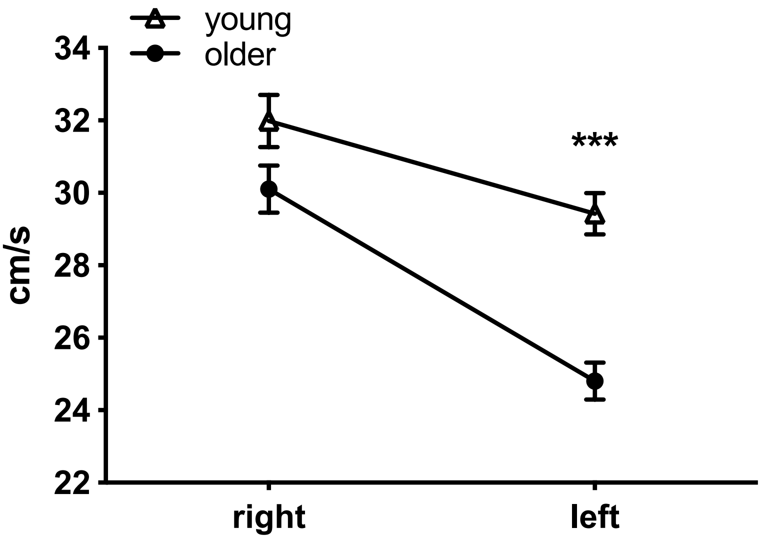


Figure 4A. Path length during grasping.

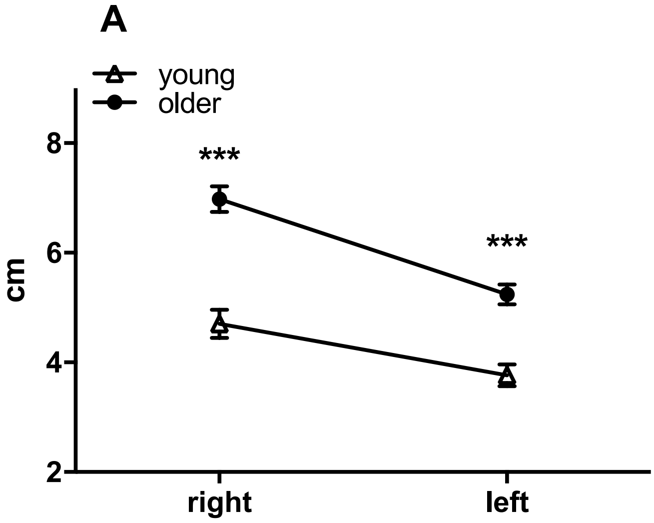


Figure 4B. Angular velocity during grasping.

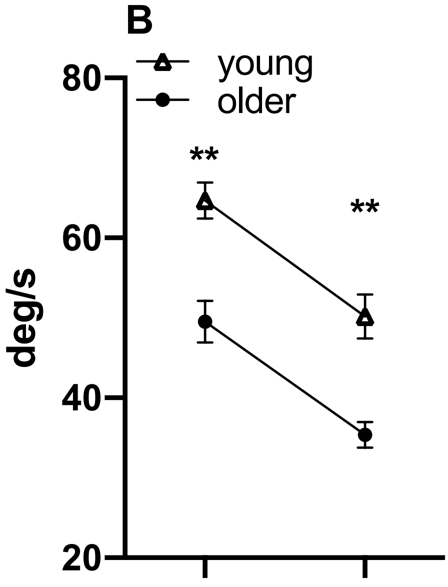
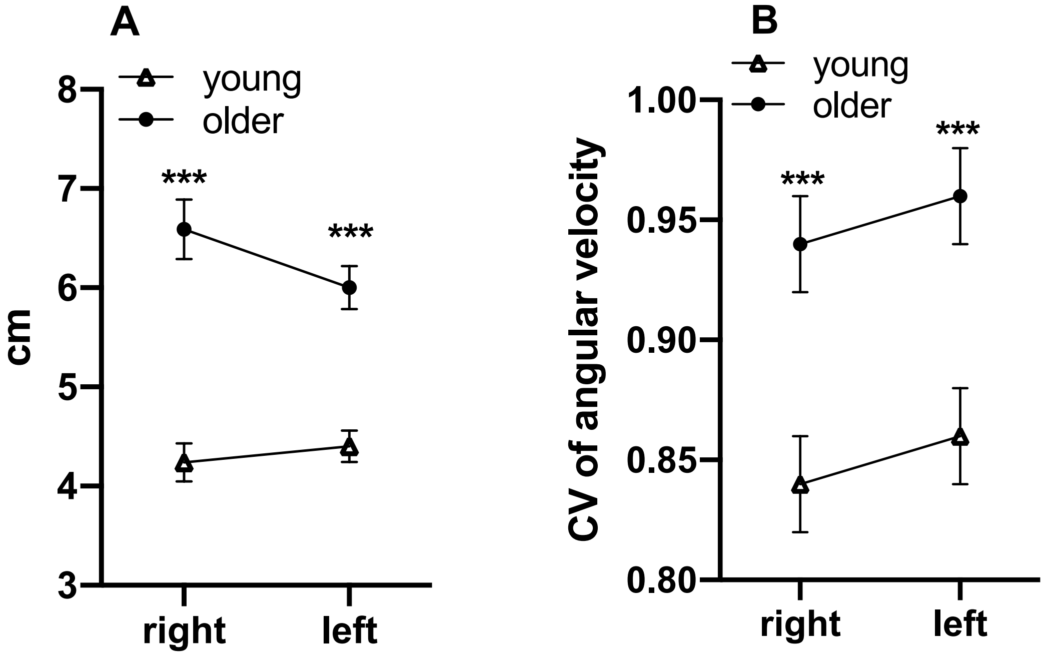


Figure 5. A. Path length during inserting. B. Variability in angular velocity during inserting.



3.3. Paper III

Vasylenko, O., Gorecka, M. M., & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 2. Association with cognitive abilities. *Developmental Psychobiology, 60*(4), 428-439.

3.3.1. Aims and hypotheses. The main purpose of Paper III was to further investigate the association between dexterity parameters obtained in Paper II and the cognitive abilities attention, WM, memory, and EF assessed in Study 2. Specifically, we aimed to describe the relationship between cognitive function and dexterity in more detail than in previous research. To do this, we investigated the relationships between cognitive abilities and the dexterity parameters that showed age-related differences in Paper II. We expected to confirm the relationship between attention, EF, and overall dexterity performance in older adults, but due to lack of existing evidence, we had no a priori hypothesis about the role of WM or memory, or about which kinematic parameters are most related to cognitive abilities. The second aim was to assess the role of gender in the association between cognitive function and dexterity. Based on the finding in Paper II that older males showed more slowing than older females, we expected to find gender differences in the relationship between dexterity and cognitive abilities.

3.3.2. Methods and measures. Paper III is based on the same sample as Paper II, i.e., 45 young and 55 older adults. Data collection of both dexterity and cognitive abilities was performed in a single session, but the results were split into two reports due to the quantity and complexity of the data. To assess the association between dexterity and cognitive abilities, dexterity measures that showed age-related differences in Paper II were used in the multiple regression analyses of Paper III as dependent variables to be explained by the cognitive measures. Attention and WM were assessed by the Block Design Test and the Digit Span Test, memory by the Logical Memory Test, and EF by the Trail Making Test and the Stroop Color and Word Test. For details on measures and administration, see the Methods section of Paper III.

3.3.3. Results and discussion. Results revealed an association between EF and MTs of reaching and inserting with either hand in the older group. A weaker association was also obtained of the same MTs with attention and WM in the older group, but no association was found between MTs and cognitive abilities in the young group. Regarding kinematics, EF best predicted path lengths of the left hand during grasping and inserting in the older group. Memory also predicted these parameters, but to a lesser extent. In the young group, no association between EF and dexterity was found, instead, attention and WM were weak predictors of path length in this group. In contrast to the pilot study, all obtained relationships were in the predicted direction, such that better cognitive function was associated with shorter MTs and shorter paths, indicating more efficient and precise movements. Overall, the results of Paper III demonstrated a significant involvement of cognitive abilities in dexterity in older adults, with especially strong evidence for the role of EF. The results also confirmed the existence of different association patterns between dexterity and cognitive abilities in young and older adults. The novel finding was that EF may be a particularly useful predictor of not only overall dexterity performance in older adults, but also of movement precision, at least for the left hand. The hypothesis about gender differences in the relationship between dexterity and cognitive function was not supported, as no gender differences in the strength of the association were found.

4. General Discussion

The present work provided two main findings: 1) dexterity performance of older adults was slower and qualitatively different compared to younger adults; and 2) EF predicted several dexterity parameters in older, but not in younger adults. In the following discussion, each of these main findings are addressed, followed by methodical considerations, limitations of the present work, and suggestions for future research.

4.1. Age-related Differences in Dexterity

The present project revealed age-related differences in dexterity performance in all PPT tasks. This finding is consistent with the general slowing account which poses that with aging, there is an overall slowing of movement. Furthermore, this finding is consistent with previous research that has documented slower performance by older adults in a variety of tasks. However, a novel finding provided by the present project was that some types of movements declined more than other. Specifically, larger group differences were found in the manipulative movements of grasping and inserting as compared to the aiming movements reaching and transport. In fact, no group differences were found in MTs of reaching or transporting pins with the right hand. This finding is in agreement with recent research (Greve, Hortobágyi, & Bongers, 2017), and indicates that slowing of dexterity is not generalized, but specific to the fine movements required for object manipulation. Thus, because slowing was not found in all movement types, our results seem inconsistent with the general slowing theory. On the other hand, within the general slowing framework, Birren (1974) hypothesized that slowing would be largest in complex movements. Arguably, grasping and inserting are more complex than reaching and transport, because they involve manipulation of an object. For efficient object manipulation, several types of sensory information must be processed and integrated. These include visual information about the position of the object, tactile information about its texture and weight, as well as proprioceptive information about the grip pattern and force applied to the object. In contrast, reaching and transport may pose less demands on information processing, because these actions are concerned mainly with transporting the arm and hand to the target position, and to a lesser extent with processing the properties of the object.

In line with this interpretation, Salthouse (1991) proposed that, although all types of tasks are constrained by processing speed, behavioral slowing might not be observed in less complex tasks. Although both simple and complex tasks rely on the same resource (i.e., processing speed), they pose differential demands on it. Complex tasks require more information processing than simple tasks. When processing speed is reduced, behavioral slowing affects complex tasks first, followed by slowing in simpler tasks as processing speed declines further (Salthouse, 1991). In addition to this argument, support for the suggestion that fine manipulative movements are more complex than gross movements comes from research on development of dexterity in children. This research has shown that fine movements take longer to develop and mature in childhood (Olivier, Hay, Bard, & Fleury, 2007; Kutz-Buschbeck, Stolze, Jöhnk, Boczed-Funcke, & Illert, 1998). For instance, Olivier et al. (2007) studied children of different ages and found that whereas reaching movements were fully developed by the age of 8, grasping movements were not yet mature at the age of 11. The finding that fine movements take longer to develop could be partly due to the fact that they involve many small muscles of the hand and fingers that need to be controlled and mastered. Moreover, fine movements require different forms of sequencing that are dependent on hierarchical levels of control, which seem to be related to different cognitive processes (Krampe, 2002). Therefore, in accordance with earlier research (Smith et al., 1999), fine movements are more likely to decline earlier with aging than the less complex gross movements involving the entire upper limb.

The present work not only confirms earlier findings regarding slowing of dexterity in older adults, but, additionally, it identifies the parameters that account for slowing in different movement types. For the gross movements reaching and transport (when performed with the left hand), slowing seems to be due to reduction in the speed of movement, as indicated by differences in linear velocity. For the fine movements grasping and inserting, slower rotation and less trajectory of the hand, as indicated by lower angular velocity and longer path length, seem to be the most important deteriorating aspects. These findings provide important information about specific age-related constraints that account for the slowing in different types of dextrous movements.

4.2. Association between EF and Dexterity

The present work provided evidence for the involvement of EF in dexterity of older adults, whereas the other cognitive abilities (WM and memory) were not consistent predictors. Our results are in agreement with earlier research that provides evidence for the association between EF and dexterity in older adults. In younger adults, EF was not significantly associated with performance. This finding is consistent with the supply-and-demand framework, which predicts that effortful cognitive control is required for motor performance only when the usual automatic control processes deteriorate.

An important finding of the present work was that EF seemed to be important only for left-hand kinematics in older adults, specifically for path length of grasping and inserting. This suggests that cognitive control is particularly involved in complex movements. As mentioned in the previous subsection, grasping and inserting are likely to be more complex than reaching and transport because of the additional requirements for integrating several types of sensory information, controlling fine movements of the fingers, and adapting the grasp pattern to the properties of the object (Holt et al., 2013). Performing these movements with the left hand adds even more complexity because the left hand is less practiced for precise movements in right-handed individuals. Thus, our findings indicate that EF is involved in the control of precision in the most demanding movements in older adults. However, EF was also involved in the MT of reaching with the right hand, which arguably is a less complex movement, and on which older adults did not perform slower than younger. To fully understand this pattern of results, the role of EF in dexterity should be studied further by exploring the neural mechanisms underlying this association and by assessing further aspects of EF.

It is important to note that the results obtained in the present work might have been due to the specific neuropsychological measures employed. To measure EF, we selected the Stroop Color and Word Test and the Trail Making Test. These are only two of the most common tests of EF in aging studies, used to assess inhibition and switching, respectively. However, many other measures exist, for example the Wisconsin Card Sorting Task and the different Tower tests (Delis, Kaplan, & Kramer, 2001), thus, the obtained results could have been different with different tests. Therefore, to establish the generalizability of our findings, they need to be replicated by further research using other tests of EF.

4.3. Methodology and Suitability of the Assessment Approach

In the present work we employed a multidisciplinary approach, combining neuropsychological assessment with motion capture to evaluate both cognitive abilities and dexterity in the same sample. Overall, this approach worked well and allowed us to provide a thorough description of dexterity decline and various cognitive factors that contribute to it. Furthermore, separate kinematic analyses of different movement types provided detailed information about which particular movements and kinematic parameters are the most important to describe slowing in dexterity. Separate analyses of different movement types should be employed in future studies that aim to obtain detailed measures of dexterity.

The motion capture technique employed in the present work had both advantages and disadvantages. The main advantage was objective and precise recording of hand movements, which enabled a detailed analysis of kinematics. The main disadvantage was that tracking of the markers was time-consuming. Hand movements involved in the PPT are relatively complex, which sometimes leads to difficulties tracking markers automatically. For example, markers can become occluded, participants' hands sometimes move outside the camera view, or markers come too close to each other, which causes the algorithm to confuse their coordinates. In all these cases, manual tracking was required. This limitation in motion capture processing is relevant for its applications in research and clinical studies. For example, it has been argued that kinematic analysis of hand movements could be a valuable tool in clinical contexts, such as evaluation of movement disorders and physical therapy (Niedau, Guerreiro, Pereira, Goncalves, & Jorge, 2013; vanAndel, Wolterbeek, Doorenbosch, Veeger, & Harlaar, 2008). Clinical evaluation of movement is currently based on rating scales and notes taken by the therapist (Niedau et al., 2013). Objective and precise recording of patients' movements would enable therapists to more accurately evaluate movement parameters, as well as to compare movements across sessions, making it easier to evaluate patients' progress (Niedau et al., 2013). However, for clinical applications, it is important that recording and analysis techniques are time-efficient, therefore motion capture techniques should be adapted to ensure automatic tracking and analysis. For example, clinicians could use simpler marker arrangements or fewer kinematic parameters to reduce time demands.

Another issue related to the use of kinematic analysis is its sensitivity. In general, a sensitive technique is an advantage because it offers the possibility to detect subtle differences in movement. In the present work, even relatively small differences in kinematic parameters were statistically significant. However, we should not conclude that statistical significance equals practical or clinical significance. From the present work, it is unclear whether observed differences in kinematics correspond to older adults' own perceptions of dexterity competence, or whether these differences affect their performance of ADL/IADL. To address these issues, kinematic analyses should be supplied with self-report measures or performance-based analyses of ADL/IADL tasks.

4.4. Limitations

The present work had some limitations. First, we did not evaluate the role of declines in visual perception or visuomotor processing in dexterity performance. Although all participants in the present project had normal or corrected-to-normal visual acuity, we did not account for other aspects of vision. Age-related decline has been documented in the perception of brightness and contrast, as well as depth and motion (Schieber, 2006). These aspects of visual perception could have affected older adults' performance. Furthermore, some studies suggest that older adults rely more than younger on visual feedback in dexterity tasks (Lyons, Elliott, Swanson, & Chua, 1996; Rand & Stelmach, 2011; Seidler & Stelmach, 1995; Seidler-Dobrin & Stelmach, 1998). Specifically, when precise movements are required, older adults fixate their gaze on targets for a longer time (Rand & Stelmach, 2011), and if visual information is restricted or removed, this produces a more detrimental effect on performance of older adults compared to younger (Seidler & Stelmach, 1995; Seidler-Dobrin & Stelmach, 1998). Therefore, visual processing and use of visual feedback are likely to affect older adults' performance in complex visuomotor tasks such as the PPT and this should be taken into account in dexterity studies. For example, the role of visuospatial processing in dexterity performance can be analyzed by synchronized tracking of eye and hand movements (Lavoie et al., 2018).

The second limitation concerns the motion capture system employed in the present work. This system only provides two-dimensional coordinates of markers, which limits the accuracy of estimation for some kinematic parameters. Because of the two-dimensional system, our kinematic analysis was based on the assumption that movement only occurs in one plane. However, for some parameters, such as angles and angular velocity, this assumption may not hold, because these parameters describe rotational movements which could involve three dimensions. Therefore, our results for these parameters should be interpreted with caution.

A further limitation concerns the design of the studies in this work. Both studies were cross-sectional comparisons. The main drawbacks of cross-sectional designs are that obtained age-related differences may be due to cohort effects, and the size of the differences may be overestimated. (Hedden & Gabrieli, 2004). Therefore, longitudinal studies are needed to confirm our results and further estimate the progression of decline in cognitive and psychomotor functions over time. The final limitation was the unequal gender ratios in both samples. Specifically, more females than males participated in both studies. This could have led to an overestimation of gender-related differences in dexterity. Therefore, our findings regarding gender should be tested in future studies.

4.5. Applications and future research

The main contributions of the present work are the decomposition of hand movements and their detailed analysis, together with a comprehensive description of the relationship between cognitive and dexterity declines in healthy older adults. The obtained results could serve as a reference for evaluation of dexterity in research and clinical assessment. Because the assessment technique was sensitive to small differences in movement, it may be applied to evaluate patients’ progress in interventions and physical therapy.

The present work did not address the mechanisms behind age-related changes in dexterity or their relationship with cognitive function. To explore these mechanisms, neuroimaging studies should assess the relationship between dexterity decline and gray and white matter changes in different brain regions. Such investigations are currently being performed in our laboratory. Moreover, future research should employ longitudinal designs to analyze temporal and causal relationships between cognitive and psychomotor decline, i.e., whether decline in one domain precedes or causes decline in the other. Currently, longitudinal evidence on this issue is scarce, and results are inconsistent (Finkel, Ernsth-Bravell, & Pedersen, 2016; Stjintjes et al., 2017). Longitudinal data collection is currently underway in our laboratory, comprising evaluation of both healthy older adults and patients with mild cognitive impairment.

5. Conclusion

In conclusion, the present work contributes to the current literature by replicating and extending evidence on two main topics: age-related decline in dexterity and the relationship between dexterity and EF in older adults. Slowing was found to some extent in all tasks, consistently with the generalized slowing theory. However, not all movement types or kinematics contributed to slower performance. Thus, when dexterity is analyzed in detail, slowing appears to be specific rather than general, which is in agreement with earlier reports (e.g., Krampe et al., 2002). Our findings advance the current understanding of age-related dexterity decline in healthy aging. The methodology used in the present work could be applied in clinical assessment and rehabilitation of patients with upper limb disorders. The second contribution of the present work is to provide further evidence of the relationship between EF and dexterity decline in healthy older adults. Our findings are consistent with previous research and with the supply-and-demand framework. Importantly, we showed that cognitive control is involved both in general performance and, more specifically, in the control of precision for fine movements. These associations may be useful for assessment of dexterity decline in healthy aging. Future research should employ neuroimaging techniques and longitudinal designs to explore the mechanisms of age-related changes in dexterity and the role of cognitive function in its decline.

References

Almuklass, A. M., Feeney, D. F., Mani, D., Hamilton, L. D., & Enoka, R. M. (2018). Peg-manipulation capabilities of middle-aged adults have a greater influence on pegboard times than those of young and old adults. *Experimental Brain Research,* 1-8.

American Psychological Association. (2007). *APA Dictionary of Psychology.* Washington, DC: American Psychological Association.

Baldauf, D., & Deubel, H. (2010). Attentional landscapes in reaching and grasping. *Vision Research, 50,* 999-1013.

Bangert, A. S., Reuter-Lorenz, P. A., Walsh, C. M., & Schachter, A. B. (2010). Bimanual coordination and aging. *Neuropsychologia, 48,* 1165-1170.

Battaglia-Mayer, A., Babicola, L., & Satta, E. (2016). Parieto-frontal gradients and domains underlying eye and hand operations in the action space. *Neuroscience, 334,* 76-92.

Beck, A. J., Steer, R. A., & Brown, G. (1996). BDI-II, Beck depression inventory: manual. Psychological Corp. *San Antonio, TX.*

Bellgrove, M. A., Phillips, J. G., Bradshaw, J. L., & Galucci, R. M. (1998). Response (re-) programming in aging: A kinematic analysis. *Journal of Gerontology: Medical Sciences, 53A*(3), 222-227.

Bennett, K. M. B., & Castiello, U. (1994). Reach to grasp: Changes with age. *Journal of Gerontology: Psychological Sciences, 49*(1), 1-7.

Bernard, J. A., & Seidler, R. D. (2012). Hand dominance and age have interactive effects on motor cortical representations. *PLoS One, 7*(9), e45443.

Binkofski, F., Dohle, C., Posse, S., Stephan, K. M., Hefter, H., ... & Freund, H. J. (1998). Human anterior intraparietal area subserves prehension: A combined lesion and functional MRI activation study. *Neurology, 50*(5), 1253-1259.

Birren, J. E. (1974). Translations in gerontology – from lab to life. Psychophysiology and speed of response. *American Psychologist,* 808-815.

Bowden, J. L., & McNulty, P. A. (2013). The magnitude and rate of reduction in strength, dexterity, and sensation in the human hand vary with ageing. *Experimental Gerontology, 48*(8), 756-765.

Bozarro, C., Boldt, J., & Schweda, M. (2018). Are older people a vulnerable group? Philosophical and bioethical perspectives on ageing and vulnerability. *Bioethics, 32,* 233-239.

Briggs, G. G., & Nebes, R. D. (1975). Patterns of hand preference in a student population. *Cortex, 11*(3), 230-238.

Bryan, J., & Luszcz, M. A. (1996). Speed of information processing as a mediator between age and free recall performance. *Psychology and Aging, 11,* 3-9.

Burgmans, S., Gronenschild, E. H., Fandakova, Y, Shing, Y. L., van Boxtel, M. P., Vuurman, E. F., ... & Raz, N. (2011). Age differences in speed of processing are partially mediated by differences in axonal integrity. *Neuroimage, 55,* 1287-1297.

Carmeli, E., Patish, H., & Coleman, R. (2003). The aging hand. *Journal of Gerontology: Medical Sciences, 58A*(2), 146-152.

Cavina-Pratesi, C., Connolly, J. D., Monaco, S., Figley, T., Milner, A. D., Schenk, T., & Culham, J. C. (2018). Human neuroimaging reveals the subcomponents of grasping, reaching, and pointing actions. *Cortex, 98,* 128-148.

Cicerale, A., Ambron, E., Lingnau, A., & Rumiati, R. (2014). A kinematic analysis of age-related changes in grasping to use and grasping to move common objects. *Acta Psychologica, 151,* 134-142.

Collins, K. C., Kennedy, N. C., Clark, A., & Pomeroy, V. M. (2017). Getting a kinematic handle on reach-to-grasp: a meta-analysis. *Physiotherapy, 104*(2), 153-166.

Cooke, J. D., Brown, S. H., & Cunningham, D. A. (1989). Kinematics of arm movements in elderly humans. *Neurobiology of Aging, 10*(2), 159-165.

Corti, E. J., Johnson, A. R., Riddle, H., Gasson, N., Kane, R., & Loftus, A. M. (2017). The relationship between executive function and fine motor control in young and older adults. *Human Movement Science, 51,* 41-50.

Council for International Organizations of Medical Sciences. (2002). International ethical guidelines for biomedical research involving human subjects. *Bulletin of Medical Ethics, 182,* 17.

Craik, I. M., & Bialystok, E. (2006). Cognition through the lifespan: mechanisms of change. *Trends in Cognitive Sciences, 10*(3), 131-138.

Cropley, V. L., Fujita, M., Innis, R. B., & Nathan, P. J. (2006). Molecular imaging of the dopaminergic system and its association with human cognitive function. *Biological Psychiatry, 59,* 898-907.

Curreri, C., Trevisan, C., Carrer, P., Facchini, S., Giantin, V., Maggi, S., ... & Sergi, G. (2017). Difficulties with fine motor skills and cognitive impairment in an eldrely population: The Progetto Veneto Anziani. *Journal of the American Geriatric Society, 66,* 350-356.

daSilva, M. V., & Bagesteiro, L. B. (2016). Effects of aging on interjoint coordination during arm reaching. *Research on Biomedical Engineering, 32*(3), 223-233.

Deary, I. J., & Der, G. (2005). Reaction time, age, and cognitive ability: Longitudinal findings from age 16 to 63 years in representative population samples. *Aging, Neuropsychology, and Cognition, 12*(2), 187-215.

Deary, I. J., Der, G., & Ford, G. (2001). Reaction times and intelligence differences: a population-based cohort study. *Intelligence, 29,* 389-399.

Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). *The Delis-Kaplan Executive Function System: Examiner's manual.* San Antonio, TX: The Psychological Corporation.

Desrosiers, J., Hébert, R., Bravo, G., & Dutil, E. (1995). The Purdue Pegboard Test: normative data for people aged 60 and over. *Disability and Rehabilitation, 17*(5), 217-224.

Desrosiers, J., Hebert, R, Dutil, E., & Bravo, G. (1993). Development and reliability of an Upper Extremity Function Test for the Elderly: The TEMPA. *Canadian Journal of Occupational Therapy, 60*(1), 9-16.

Desrosiers, J., Hébert, R., Bravo, G., & Dutil, E. (1995). The Purdue Pegboard Test: normative data for people aged 60 and over. *Disability and Rehabilitation, 17*(5), 217-224.

Desrosiers, J., Hébert, R., Bravo, G., & Rochette, A. (1999). Age-related changes in upper extremity performance of elderly people: A longitudinal study. *Experimental Gerontology, 34,* 393-405.

Diermayr, G., McIsaac, T. L., & Gordon, A. M. (2011). Finger force coordination underlying object manipulation in the elderly – a mini-review. *Gerontology, 57,* 217-227.

Drag, L. L., & Bieliauskas, L. A. (2010). Contemporary review 2009: cognitive aging. *Journal of Geriatric Psychiatry and Neurology, 23*(2), 75-93.

Emborg, M. E., Ma, S. Y., Mufson, E. J., Levey, A. I., Taylor, M. D., Brown, W. D., ... Kordower, J. H. (1998). Age-related declines in nigral neuronal function correlate with motor impairments in rhesus monkeys. *Journal of Computational Neurology,* 401(2), 253-265.

Fauth, E. B., Gerstort, D., Ram, N., Malmberg, B. (2012). Changes in depressive symptoms in the context of disablement processes: Role of demographic characteristics, cognitive function, health, and social support. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 67*(2), 167-177.

Fauth, E. B., Schaefer, S. Y., Zarit, S. H., Ernsth-Bravell, M., & Johansson, B. (2017). Associations between fine motor performance in activities of daily living and cognitive ability in a non-demented sample of older adults: Implications for geriatric physical rehabilitation. *Journal of Aging and Health, 29*(7), 1144-1159.

Finkel, D., Ernsth-Bravell, M., & Pedersen, N. L. (2016). Temporal dynamics of motor functioning and cognitive aging. *Journal of Gerontology A: Biological Sciences and Medical Sciences, 71*(1), 109-116.

Fraser, S. A., Li, K. Z., & Penhune, V. B. (2010). Dual-task performance reveals increased involvement of executive control in fine motor sequencing in healthy aging. *Journal of Gerontology: Psychological Sciences, 65B*(5), 526-535.

Fried, L. P., Tangen, C. M., Walston, J., Newman, A. B., Hirsch, C., Gottdiener, J., ... & McBurnie, M. A. (2001). Frailty in older adults: Evidence for a phenotype. *Journal of Gerontology: Medical Sciences, 56A*(3), 146-156.

Gill, T. M., Han, L., Gahbauer, E. A., Leo-Summers, L., Allore, H. G. (2018). Prognostic effect of changes in physical function over prior year on subsequent mortality and long-term nursing home admission. *Journal of American Geriatric Society.*

Grabowski, P. J., & Mason, A. H. (2014). Age differences in the control of a precision reach to grasp task within a desktop virtual environment. *International Journal of Human-Computer Studies, 72,* 383-392.

Greve, C., Hortobágyi, T., & Bongers, R. M. (2017). Old adults preserve motor flexibility during rapid reaching. *European Journal of Applied Physiology, 117,* 955-967.

Griew, S. (1959). Complexity of response and time of initiating responses in relation to age. *The American Journal of Psychology, 72*(1), 83-88.

Gulde, P., & Hermsdörfer, J. (2017). Both hands at work: the effect of aging on upper-limb kinematics in a multi-step activity of daily living. *Experimental Brain Research, 235*(5), 1337-1348.

Hays, R. D., Sherbourne, C. D., & Mazel, R. H. (1993). The RAND 36-Item Health Survey 1.0. *Health Economics, 2,* 217-227.

Hedden, T., & Gabrieli, J. D. (2004). Insights into the ageing mind: A view from cognitive neuroscience. *Nature Reviews: Neuroscience, 5,* 87-97.

Hellström, Y., Persson, G., & Hallberg, I. R. (2004). Quality of life and symptoms among older people living at home. *Journal of Advanced Nursing, 48,* 584-593.

Hess, T. M., & Ennis, G. E. (2011). Age differences in the effort and costs associated with cognitive activity. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 67*(4), 447-455.

Hertzog, C. (1989). Influences of cognitive slowing on age differences in intelligence. *Developmental Psychology, 25*(4), 636-651.

Hertzog, C., & Bleckley, K. M. (2001). Age differences in the structure of intelligence: Influences of information processing speed. *Intelligence, 29,* 191-217.

Heuninckx, S., Wenderoth, N., Debaere, F., Peeters, R., & Swinnen, S. P. (2005). Neural basis of aging: the penetration of cognition into action control. *Journal of Neuroscience, 25*(29), 6787-6796.

Heuninckx, S., Wenderoth, N., & Swinnen, S. P. (2008). Systems neuroplasticity in the aging brain: recruiting additional neural resources for successful motor performance in elderly persons. *Journal of Neuroscience, 28*(1), 91-99.

Holt, R. J., Lefevre, A. S., Flatters, I. J., Culmer, P., Wilkie, R. M., Henson, B. W., ... & Mon-Williams, M. (2013). Grasping the changes seen in older adults when reaching for objects of varied texture. *PLoS One, 8*(7), e69040.

Hudak, P. L., Amadio, P. C., & Bombardier, C. (1996). Development of an upper extremity outcome measure: the DASH (disabilities of the arm, shoulder and hand). *American Journal of Industrial Medicine, 29,* 602-608.

Jeannerod, M. (1984). The timing of natural prehension movemements. *Journal of Motor Behavior, 16,* 235-254.

Jebsen, R. H., Taylor, N., Trieschmann, R. B., Trotter, M. J., & Howard, L. A. (1969). An objective and standardized test of hand function. *Archives of Physical Medicine and Rehabilitation, 50,* 311-319.

Jurado, M. B., & Rosselli, M. (2007). The elusive nature of executive functions: a review of our current understanding. *Neuropsychologia Review Articles, 17,* 213-233.

Kerchner, G. A., Racine, C. A., Hale, S., Wilheim, R., Laluz, V., Miller, B. L., & Kramer, J. H. (2012). Cognitive processing speed in older adults: Relationship with white matter integrity. *PLoS One, 7*(11), e50425.

Ketcham, C. J., & Stelmach, G. E. (2001). Age-related declines in motor control. In J. E. Birren (Ed.), *Handbook of the Psychology of Aging,* (pp. 313-348). San Diego, CA: Academic Press.

Keys, B. A., & White, D. A. (2000). Exploring the relationship between age, executive abilities, and psychomotor speed. *Journal of the International Neuropsychological Society, 6,* 76-82.

Kinoshita, H., & Francis, P. R. (1996). A comparison of prehension force control in young and elderly individuals. *European Journal of Applied Physiology and Occupational Physiology, 74*(5), 450-460.

Kløve, H. (1963). Clinical neuropsychology. *Medical Clinics of North America, 46,* 1647-1658.

Kobayashi-Cuya, K. E., Sakurai, R., Sakuma, N., Suzuki, H., Yasunaga, M., Ogawa, S., ... &

Fujiwara, Y. (2018). Hand dexterity, not handgrip strength, is associated with executive function in Japanese community-dwelling older adults: a cross-sectional study. *BMC Geriatrics, 18, 192.*

Krampe, R. T. (2002). Aging, expertise and fine motor movement. *Neuroscience and Biobehavioral Reviews, 26*(7), 769-776.

Krehbiel, L. M., Kang, N., & Cauraugh, J. H. (2017). Age-related differences in bimanual movements: A systematic review and meta-analysis. *Experimental Gerontology, 98,* 199-206.

Kressig, R. W., Gregor, R. J., Oliver, A., Waddell, D., Smith, W., O'Grady, M., ... & Wolf, S. L. (2004). Temporal and spatial features of gait in older adults transitioning to frailty. *Gait and Posture, 20,* 30-35.

Kuhtz-Buschbeck, J. P., Stolze, H., Jöhnk, K., Boczed-Funcke, A., & Illert, M. (1998). Development of prehension movements in children: a kinematic study. *Experimental Brain Research, 122,* 424-432.

Lavoie, E. B., Valevicius, A. M., Boser, Q. A., Kovic, O., Vette, A. H., Pilarsko, P. M., ... & Chapman, C. S. (2018). Using synchronized eye and motion tracking to determine high-precision eye-movement patterns during object interaction tasks. *Journal of Vision, 18*(6), 1-20.

Lawton, M. P., & Brody, E. M. (1969). Assessment of older people: Self-maintaining and instrumental activities of daily living. *The Gerontologist, 9*(3, part 1), 179-186.

Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D. (2012). Construction and motor performance. In *Neuropsychological Assessment, 5th ed.,* (pp. 568-617). New York, NY: Oxford University Press.

Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D. (2012). *Neuropsychological Assessment, 5th ed.* New York, NY: Oxford University Press.

Lindenberger, U., Mayr, U., & Kliegl, R. (1993). Speed and intelligence in old age. *Psychology and Aging, 8,* 207-220.

Luppa, M., Luck, T., Weyerer, S., König, H-H., Brähler, E., Reidel-Heller, S. G. (2010). Prediction of institutionalization in the elderly. A systematic review. *Age and Ageing, 39,* 31-38.

Lyons, J., Elliott, D., Swanson, L. R., & Chua, R. (1996). Use of vision in manual aiming by young and older adults. *Journal of Aging and Physical Activity, 4*(2), 165-178.

Maes, C., Gooijers, J., de Xivry, J., Swinnen, S., & Boisgontier, M. (2017). Two hands, one brain, and aging. *Neuroscience and Biobehavioral Reviews, 75*, 234-256.

Martin, J. A., Ramsay, J., Hughes, C., Peters, D. M., & Edwards, M. G. (2015). Age and grip strength predict hand dexterity in adults. *PLoS ONE, 10*(2), e0117598.

Miles, W. R. (1931a). Correlation of reaction and coordination speed with age in adults. *The American Journal of Psychology, 43*(3), 377-391.

Miles, W. R. (1931b). Measures of certain human abilities throughout the life span. *Proceedings of the National Academy of Sciences of the United States of America, 17*(12), 627.

Morgan, M., Bradshaw, J. L., Phillips, J. G., Mattingley, J. B., Iansek, R., & Bradshaw, J. (1994). Effects of hand and age upon abductive and adductive movements: A kinematic analysis. *Brain and Cognition, 25*, 194-206.

Niedau, H., Guerreiro, T., Pereira, R., Goncalves, D., & Jorge, J. (2013). Computer-assisted rehabilitation: towards effective evaluation. *International Journal of Cognitive Performance Support, 1*(1), 11-26.

Nowak, D. A. (2008). The impact of stroke on the performance of grasping: Usefullness of kinetic and kinematic motion analysis. *Neuroscience and Biobehavioral Reviews, 32,* 1439-1450.

Olivier, I., Hay, L., Bard, C., Fleury, M. (2007). Age-related differences in the reaching and grasping coordination in children: unimanual and bimanual tasks. *Experimental Brain Research, 179,* 17-27.

Parikh, P. J., & Cole, K. J. (2012). Handling objects in old age: Forces and moments acting on the object. *Journal of Applied Physiology, 112,* 1095-1104.

Park, D. C., Smith, A. D., Lautenschlager, G., Earles, J. L., Frieske, D., Zwahr, M., & Gaines, C. L. (1996), Mediators of long-term memory performance across the life span. *Psychology and Aging, 11*(4), 621-637.

Pennathur, A., Contreras, L. R., Arcauta, K., & Dowling, W. (2003). Manual dexterity of older Mexican American adults: a cross-sectional pilot experimental investigation. *Industrial Ergonomics, 32,* 419-431.

Petersen, R. C., Smith, G. E., Waring, S. C., Ivnik, R. J., Tangalos, E. J., & Kokmen, E. (1999). Cognitive impairment: clinical characterization and outcome. *Archives of Neurology, 56*(3), 303-308.

Poirier, F. (1987). Dexterity as a valid measure of hand function: A pilot study. *Occupational Therapy in Health Care, 4,* 69-83.

Rand, M., & Stelmach, G. E. (2011). Effects of hand termination and accuracy requirements on eye-hand coordination in older adults. *Behavioural Brain Research, 219*(1), 39-46.

Ranganathan, V. K., Siemionow, V., Sahgal, V., & Guang, H. Y. (2001). Effects of aging on hand function. Journal of the American Geriatrics Society, *49*, 1478-1484.

Reinkensmeyer, D. J., & Patton, J. L. (2009). Can robots help the learning of skilled actions? *Exercise and Sport Sciences Reviews, 37*(1), 43-51.

Reuter-Lorenz, P. A., & Lustig, C. (2017). Working memory and executive functions in the aging brain. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive Neuroscience of Aging, 2nd ed.,* (pp. 235-258). New York, NY: Oxford University Press.

Reuter-Lorenz, P. A., & Park, D. C. (2010). Human neuroscience and the aging mind: A new look at old problems. *Journals of Gerontology: Psychological Sciences, 65B*(4), 405-415.

Romero, H. R., Hayes, S. M., & Welsh-Bohmer, K. A. (2011). Cognitive domains affected by conditions of ageing and the role of neuropsychological testing. In Abou-Saleh, M. T., & Katona, C. (Eds.) *Principles and Practice of Geriatric Psychiatry, 3rd ed.,* (pp. 389-396). John Wiley & Sons.

Rosenbaum, D. A. (2005). The Cinderella of psychology: The neglect of motor control in the science of mental life and behavior. *American Psychologist, 60*(4), 308-317.

Salat, D. H., Buckner, R. L., Snyder, A. Z., Greve, D. N., Desikan, R. S., Busa, E., ... & Fischl, B. (2004). Thinning of the cerebral cortex in aging. *Cerebral Cortex, 14*(7), 721-730.

Salthouse, T. A. (1991). *Theoretical Perspectives on Cognitive Aging.* New York, NY: Lawrence Erlbaum Associates, Inc.

Salthouse, T. A. (1993). Speed mediation of adult age differences in cognition. *Developmental Psychology, 29,* 722-738.

Salthouse, T. A. (1994). The nature of the influence of speed on adult age differences in cognition. *Developmental Psychology, 30,* 240-259.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*(3), 403-428.

Salthouse, T. A. (2017). Neural correlates of age-related slowing. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive Neuroscience of Aging, 2nd ed.,* (pp. 259-272). New York, NY: Oxford University Press.

Salthouse, T. A., Atkinson, T. M., & Berish, D. E. (2003). Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *Journal of Experimental Psychology: General, 132*(4), 566-594.

Schieber, F. (2006). Vision and aging. In J. E. Birren, K. w. Schaie, R. P. Abeles, M. Gatz, & T. A. Salthouse (Eds.), *Handbook of the Psychology of Aging, 6th ed.,* (pp.129-161). San Diego, CA: Elsevier.

Sebastjan, A., Skrzek, A., Ignasiak, S., & Slawinska, T. (2017). Age-related changes in hand dominance and functional asymmetry in older adults. *PloS one*, *12*(5), e0177845.

Seidler, R. D. (2006). Differential effects of age on sequence learning and sensorimotor adaptation. *Brain Research Bulletin, 70*(4), 337-346.

Seidler, R. D. (2007). Older adults can learn to learn new motor skills. *Behavioural Brain Research, 183,* 118-122.

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., ... & Lipps, D. B. (2010). Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. *Neuroscience and Biobehavioral Reviews, 34,* 721-733.

Seidler, R. D., & Stelmach, G. E. (1995). Reduction in sensorimotor control with age. *QUEST, 47,* 386-394.

Seidler-Dobrin, R. D., & Stelmach, G. E. (1998). Persistence in visual feedback control by the elderly. *Experimental Brain Research, 119*(4), 467-474.

Seo, K., Kim, J., Oh, D. H., Ryu, H., & Choi, H. (2017). Virtual daily living test to screen for mild cognitive impairment using kinematic movement analysis. *PLoS One, 12*(7) e0181883.

Serbruyns, L., Gooijers, J., Cayenberghs, K., Meesen, K. L., Cuypers, K., Sisti, H. M., ... & Swinnen, S. (2015). Bimanual motor deficits in older adults predicted by diffusion tensor imaging metrics of corpus callosum subregions. *Brain Structure and Function, 220,* 273-290.

Smith, C. D., Umberger, G. H., Manning, E. L., Slevin, J. T., Wekstein, D. R., Schmitt, F. A., ... & Gash, D. M. (1999). Critical decline in fine motor hand movements in human aging. *Neurology, 53*(7), 1458-1461.

Snellen, H. (1862). Probebuchstaben zur Bestimmung der Selschärfe [Sample Letters for the Determination of Visual Acuity]. Utrecht.

Spirduso, W. W., Francis, K. L., & MacRae, P. G. (1995). *Physical Dimensions of Aging.* Human Kinetics, Champaign, IL.

Stjintjes, M., Aartsen, M. J., Taekema, D. G., Gussekloo, J., Huisman, M., Meskers, C. G., ... & Maier, A. B. (2017). Temporal relationship between cognitive and physical performance in middle-aged to oldest-old people. *Journals of Gerontology A: Biological Sciences and Medical Sciences, 72*(5), 662-668.

Stratford, P. W., Binkley, J. M., & Stratford, D. M. (2001). Development and initial validation of the upper extremity functional index. *Physiotherapy Canada, 53*(4), 259-267.

Sullivan, E. V., Rohlfing, T., & Pfefferbaum, A. (2010). Quantitative fiber tracking of lateral and interhemispheric white matter systems in normal aging: Relations to timed performance. *Neurobiology of Aging, 31*(3), 464-481.

Swinnen, S., & Wenderoth, N. (2004). Two hands, one brain: Cognitive neuroscience of bimanual skill. *Trends in Cognitive Sciences, 8*(1), 18-25.

Szafran, J. (1951). Changes with age and with exclusion of vision in performance at an aiming task. *Quarterly Journal of Experimental Psychology, 3*(3), 111-118.

Tiffin, J., & Asher, E. J. (1948). The Purdue Pegboard. Norms and studies of reliability and validity. *Journal of Applied Psychology, 32*(3), 234-247.

Tremblay, F., Wong, K., Sanderson, R., & Coté, L. (2003). Tactile spatial acuity in elderly persons: assessment with grating domes and relationship with manual dexterity. *Somatosensory & Motor Research, 20*(2), 127-132.

van Andel, C. J., Wolterbeek, N., Doorenbosch, C. A., Veeger, D. J., & Harlaar, J. (2008). Complete 3D kinematics of upper extremity functional tasks. *Gait & Posture, 27,* 120-127.

Verhaegen, P., & Salthouse, T. A. (1997). Meta-analyses of age-cognition relations in adulthood: Estimates of linear and nonlinear age effects and structural models. *Psychological Bulletin, 122,* 231-249.

Voelcker-Rehage, C. (2008). Motor-skill learning in older adults – a review of studies on age-related differences. *European Review of Aging and Physical Activity, 5,* 5-16.

Wang, W.-C., & Cabeza, R. (2017). Episodic memory encoding and retrieval in the aging brain. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive Neuroscience of Aging, 2nd ed.,* (pp. 301-335). New York, NY: Oxford University Press.

Welford, A. T. (1959). Psychomotor performance. In Birren, J. E. (ed.), *Handbook of Aging and the Individual: Psychological and Biological Aspects.* (562-613). Chicago, IL: The University of Chicago Press.

Wetzels, R., Matzke, D., Lee, M. D., Rouder, J. N., Iverson, G. J., & Wagenmakers, E. J. (2011). Statistical evidence in experimental psychology: An empirical comparison using 855 t tests. *Perspectives on Psychological Science, 6,* 291-298.

Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement.* John Wiley & Sons, Inc.: New Jersey, NY.

Wishart, L. R., Lee, T. D., Murdoch, J. E., & Hodges, N. J. (2000). Effects of aging on automatic and effortful processes in bimanual coordination. *Journal of Gerontology: Psychological Sciences, 55B*(2), 85-94.

Wong, Y. J., & Whishaw, I. Q. (2004). Precision grasps of children and young and old adults:

Individual differences in digit contact strategy, purchase pattern, and digit posture. *Behavioral Brain Research, 154,* 113-123.

World Medical Association (2001). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *Bulletin of the World Health Organization, 79*(4), 373-374.

Woytowicz, E., Whitall, J., & Westlake, K. P. (2016). Age-related changes in bilateral upper extremity coordination. *Current Geriatrics Reports, 5,* 191-199.

You, J. H., Shetty, A., Jones, T., Shields, K., Belay, Y., & Brown, D. (2009). Effects of dual-task cognitive-gait intervention on memory and gait dynamics in older adults with a history of falls: A preliminary investigation. *Neurorehabilitation, 24,* 193-198.

Zanto, T. P., & Gazzaley, A. (2017). Selective attention and inhibitory control in the aging brain. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive Neuroscience of Aging, 2nd ed.,* (pp. 207-234). New York, NY: Oxford University Press.

Zimprich, D., & Martin, M. (2002). Can longitudinal changes in processing speed explain longitudinal age changes in fluid intelligence? *Psychology and Aging, 17*(4), 690.

Paper I

Rodríguez-Aranda, C., Mittner, M. & Vasylenko, O. (2016). Association between executive functions, working memory, and manual dexterity in young and healthy older adults: An exploratory study. *Perceptual and Motor Skills, 122*(1), 165-192.

Perceptual and Motor Skills
2016, Vol. 122(1) 165–192
© The Author(s) 2016
Reprints and permissions:
sagepub.com/journalsPermissions.nav
DOI: 10.1177/0031512516628370
pms.sagepub.com

Association Between Executive Functions, Working Memory, and Manual Dexterity in Young and Healthy Older Adults: An Exploratory Study

Claudia Rodríguez-Aranda, Matthias Mittner, and Olena Vasylenko
University of Tromsø, The Arctic University of Norway, Norway

Abstract

Aging is accompanied by declines in cognitive and sensorimotor functions. However, at present, the interrelation between attentional processes and dexterity in aging has not been thoroughly addressed. This study explored the relationship between executive function, working memory, and dexterity performance in 15 young and 15 healthy elderly, right-handed participants. A modified version of the Purdue Pegboard Test was used for dexterity assessment. Two subtasks were selected to calculate temporal and kinematic parameters of reaching, grasping, transport, and insertion of pegs. Evaluation of executive function and working memory was performed using neuropsychological tests. The relationship between dexterity and cognitive outcomes were also examined. Results showed that the prehensile movements involved in grasping and their speed significantly differed between groups and correlated with executive function in the young group. For elderly adults, variability of hand movements turned out to be associated with executive abilities.

Keywords

normal aging, dexterity, executive functions, working memory, kinematics

---

Corresponding Author:
Claudia Rodríguez-Aranda, Department of Psychology, UiT The Arctic University of Norway, N-9037 Tromsø, Norway.
Email: claudia.rodriguez-aranda@uit.no

Introduction

The normal process of aging involves declines in cognitive and sensorimotor functions (Ketcham & Stelmach, 2001) that affect performance of activities of daily living. A relevant decline occurs in dexterity, jeopardizing the quality of life and autonomy of older adults (Hardin, 2002). Dexterity is defined as the ability to manipulate objects rapidly and efficiently using different prehensile patterns (Shumway-Cook & Woollacott, 2007). In normal aging, changes in hand dexterity have been demonstrated in gripping, pinching, grasping, lifting, and manipulation of objects (Hackel, Wolfe, Bang, & Canfield, 1992). Some examples of the difficulties with manual ability experienced by elderly adults are handling small objects such as coins or buttons, telephoning, and preparing meals (Spector & Fleishman, 1998). Previous studies have found that loss of hand/finger strength, precision, and manual speed are the principal declines observed in subjects over 65 years of age (Ranganathan, Siemionow, Sahgal, & Yue, 2001; Carmeli, Patish, & Coleman, 2003). In particular, declines in grip strength are relevant for dexterity in older adults as there is a loss of muscle mass (i.e., sarcopenia) from the fifth decade that disturbs activation and recruitment of muscles supporting rapid and precise coordinated movements (Metter, Conwit, Metter, Pacheco, & Tobin, 1998; Charlier, Mertens, Lefevre, & Thomis, 2015). A recent study has demonstrated that declines in grip strength have a deleterious effect on hand steadiness, aiming, tapping and tracking in healthy elderly (Martin, Ramsay, Hughes, Peters, & Edwards, 2015). Other causes behind dexterity decline in aging have been attributed to, morphological changes in finger and wrist joints, deteriorating vision (Carmeli et al., 2003), lack of tactile sensation (Desrosiers, Hebert, Bravo, & Dutil, 1995), and cognitive deterioration (Scherder, Dekker, & Eggermont, 2008). Among the above causes, the role of cognitive decline is the least understood.

Evidence exists about the involvement of cognitive dysfunction in dexterity decline. For example, Kluger and coworkers (1997), demonstrated that elderly patients with varying degrees of cognitive dysfunction performed more poorly than healthy elderly adults on tasks requiring fine motor control, including dexterity tests. Moreover, these authors suggested that the application of complex motor tasks may serve to differentiate normal aging from dementia. However, there is currently no empirical basis to rule out the effect of normal cognitive decline on fine motor control and specifically on dexterity. Accordingly, it is important to investigate whether normal cognitive decline affects, to any extent, dexterity performance in healthy older adults.

The question is relevant not only in clinical settings where the detection of pathological symptoms, in this case dexterity and cognitive changes, can be used for diagnostic purposes. Rather, the matter is also of importance to address the needs of the aging population that remains active. For instance, new technological devices are being designed to help elderly adults remain independent in the society (Piau, Campo, Rumeau, Vellas, & Nourhashemi, 2014). Some of these devices compensate for age-related declines in motor function. However, elaboration of new technologies is seldom based on a thorough understanding of the central and peripheral changes affecting the older adult (Higgins & Glasgow, 2012). Therefore, unraveling the role that exerts normal cognitive decline on manual dexterity is of importance, especially since appropriate hand function predicts the capacity to perform activities of daily living and life independence (Williams, Hadler, & Earp, 1982). A first step is then, to assess whether age-related cognitive decline is associated to objective measurements of dexterity. In an earlier investigation, Strenge and coworkers addressed the relationship between cognitive functioning and manual ability in young healthy adults (Strenge, Niederberger, & Seelhorst, 2002). In that study, two pegboard tests and an attentional task were used. Results showed a moderate correlation between dexterity and attention. In spite of being an interesting finding, the measurement of attention was restricted to simple and complex response times and thus, results could not be generalized to other aspects of attention, such as divided attention, working memory or executive functioning. To our knowledge, beside this study, there are no further investigations evaluating the association between dexterity and formal assessment of attention.

Because attention is the cognitive ability most recurrently related to general motor control (Lajoie, Teasdale, Bard, & Fleury, 1996; Woollacott & Shumway-Cook, 2002), extending Strenge et al.'s study is important. Attention is affected in the course of normal aging (Drag & Bieliauskas, 2010), as reflected in declines in working memory and executive functions (Andres, Guerrini, Phillips, & Perfect, 2008; Drag & Bieliauskas, 2010). Working memory involves the active use and maintenance of information in short-term memory during concurrent processing (Reuter-Lorenz & Park, 2010), and executive functions are essential abilities for complex planning and monitoring of actions (Strauss, Sherman, & Spreen, 2006). Previous research has shown that spatial working memory is involved in the execution of precise movements such as in grasping objects (Baldauf & Deubel, 2010). Furthermore, the influence of executive functions on daily tasks that rely on upper limb movements has been highlighted (Cahn-Weiner, Malloy, Boyle, Marran, & Salloway, 2000; Scherder et al., 2008; Bramell-Risberg, Jarnlo, & Elmstahl, 2010).

Besides the studies reviewed here, there is limited empirical evidence evaluating the connection between working memory, executive functions and dexterity in normal aging. Taking into account that declines in attention and dexterity happen in the normal course of aging, it is important to evaluate to which extent this co-occurrence is more than incidentally related. Thus, the purpose of the present study was to investigate the association between working memory, executive functions and dexterity in healthy young and healthy older adults. To this end, working memory and executive functions were assessed using selected neuropsychological tests. Cognitive results were then analyzed together with dexterity outcomes. Dexterity was assessed using a psychomotor task of fine motor control, the Purdue Pegboard Test (Tiffin, 1968). It has been shown repeatedly that stable age-related differences between young and older adults emerge in this task (Lezak, 1995; Scuteri, Palmieri, Lo Noce, & Giampaoli, 2005). In the present study, dexterity is investigated by a detailed kinematic analysis during performance of two subtasks of the Purdue Pegboard Test (see methods). The rationale behind adding the use of kinematics during dexterity performance is to obtain detailed information about the type of movements and changes in speed that may explain why older adults insert a lower number of pegs on each task. In order to minimize heterogeneity, only right-handed individuals were invited to the study because it is known that left-handed individuals tend to present atypical lateralization of brain functions including attention (Willems, Van der Haegen, Fisher, & Francks, 2014; Buckingham & Carey, 2015). Finally, dexterity assessments were restricted to the right, dominant hand. This was deemed necessary to control for expertise of hand function. Moreover, this constraint does not seem to pose a fundamental limitation, as it still allows to generalize to the vast majority of right-handed adults.

Method

Participants

Thirty healthy, right-handed individuals participated in the study. Participants were 15 young adults with a mean age of 26.1 yr (*SD* = 3.4, range 22–33; nine women) and 15 healthy elderly with a mean age of 74 yr (*SD* = 6.9, range 67–93; 10 women). The older group comprised community-dwelling individuals who were recruited through advertisements at the local senior citizens' center. The young group was recruited from the campus of the University of Tromsø through flyers and advertisements as well as through information given during lectures and student meetings. Participation in the study was voluntary and all participants signed informed consent forms before the study. An interview was conducted to gather demographic and health information. Sensory loss and other health conditions were self-rated by the participants. None of the participants reported sensory declines that interfered with dexterity, and no participants were taking medication known to affect the central nervous system, had suffered any stroke or head trauma, or had any health problem that may interfere with the study. To ensure that all participants were right-handed, the Handedness Inventory (Briggs & Nebes, 1975) was administered. The Beck Depression Inventory (BDI) (Beck, Steer, & Garbin, 1988), and the Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975), were used as screening measures for depression and mental status, respectively. None of the participants scored below the cut-off criteria for exclusion on the MMSE (<25) or the BDI (see, Rodriguez-Aranda, 2003, for cut-off details) and thus, no participants were excluded from the study. The present investigation was approved by the Regional Research Ethics Committee and carried out in accordance with the Helsinki guidelines.

Measures

Neuropsychological test battery. To evaluate short-term attentional abilities and working memory, the Digit Span Forward and Backward tests from the Wechsler Adult Intelligence Scale-Revised (WAIS-R) (Wechsler, 1981) were selected. For the assessment of executive functions, the Norwegian translations of the Stroop Test (Golden, 1978) and the Trail Making Test (Reitan & Wolfson, 1993) were used. Complete descriptions of the tests have been given elsewhere (MacLeod, 1991; Tombaugh, 2004). Moreover, because muscular strength is a prerequisite for dexterity performance, grip strength was measured with a hand dynamometer (Halstead, 1947).

Purdue Pegboard Test. The Purdue Pegboard Test (Lafayette Instrument Model 32020) is among the most widely used dexterity tests for research, employee selection and clinical purposes (Yancosek & Howell, 2009). It consists of a 29.7 × 44.9 cm board with four cups at the upper end, which contain three different types of metal pegs: pins, collars, and washers (see Figure 1). From left to right, the first cup contains pins, the second washers, the third collars, and the fourth pins. Two parallel lines of holes, with 25 holes in each line, run down the middle of the board. Originally, the pegboard was white and the pegs shiny, but for the present study the pegboard was painted black and the pegs red, to be able to differentiate between shiny reflective markers on participants' hands and the rest of the image when performing video analysis.

Standard evaluation of performance on the Purdue Pegboard Test is quantified by measuring the total number of pegs inserted in a limited period of time in four different subtasks. The first two subtasks require participants to place pins as fast as possible in the right or left lines of holes with right and left hand, respectively. The third subtask demands insertion of pins using both hands at the same time. The fourth subtask requires to alternate both hands to assemble a pin, a washer, a collar and another washer on the right line of holes.

For this study, two of the four tasks from the Purdue Pegboard Test were used: the inserting pins task and the assembly task. Both tasks were performed with the right hand.

Insertion of pins and assembly of pegs were convenient tasks to evaluate the relationship between right-hand dexterity and attentional demands in a simple and a complicated task. The inserting pins task evaluates same type of movements performed repeatedly at high speed. This action relies on precision and quickness to manipulate the same type of peg. In contrast, in the assembly task, different movements and pegs are required to be handled at fast rates. Thus, proper manipulation of various pegs is required, which relies on good planning

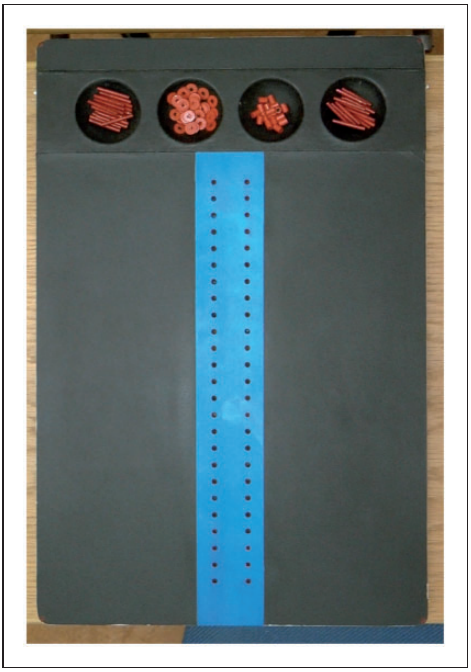


Figure 1. Purdue pegboard.

of finger and hand movements as well as coordination of type of movements in the right order. The assembly task, in fact, involves higher degree of cognitive functioning than the pins task. Also, the assembly is relevant as it comprises various representative movements underlying everyday activities (Lindstrom-Hazel & Veenstra, 2015).

Following standard procedures, in the pins subtask, participants were required to grasp pins, one by one, from the right-hand cup and place each pin in the right line of holes, beginning with the top hole. Performance was video recorded for 15 sec. In the assembly task, participants were instructed to construct assemblies by first inserting a pin into a hole, then a washer over the pin, then a collar on top of the washer and finally another washer on top of the collar. For this task, participants were given 45 sec. It is important to highlight that a further adaptation of the standard Purdue Pegboard concerned the time windows. In the standard version, the pins subtask is given 30 sec, while the assembly subtask allows performance for 60 sec. In the present study, time limits for each of the two subtasks were shortened. The reason is that the processing of kinematic data is highly time consuming, and thus, a proper trade-off among substantial time to acquire enough kinematic data and keeping time processing to a minimum was important. Participants were asked to perform the tasks as rapidly and accurately as possible, and were allowed to practice before each task until they were able to insert three pins in a row, or until they were able to complete an assembly. In the regular application of the Purdue Pegboard, total number of pegs serves as the measure of overall dexterity performance. In the present study, total performance time and speed together with angular measurements for displacement and velocity during different movement episodes were calculated for each subtask in the actions of reaching and grasping pegs.

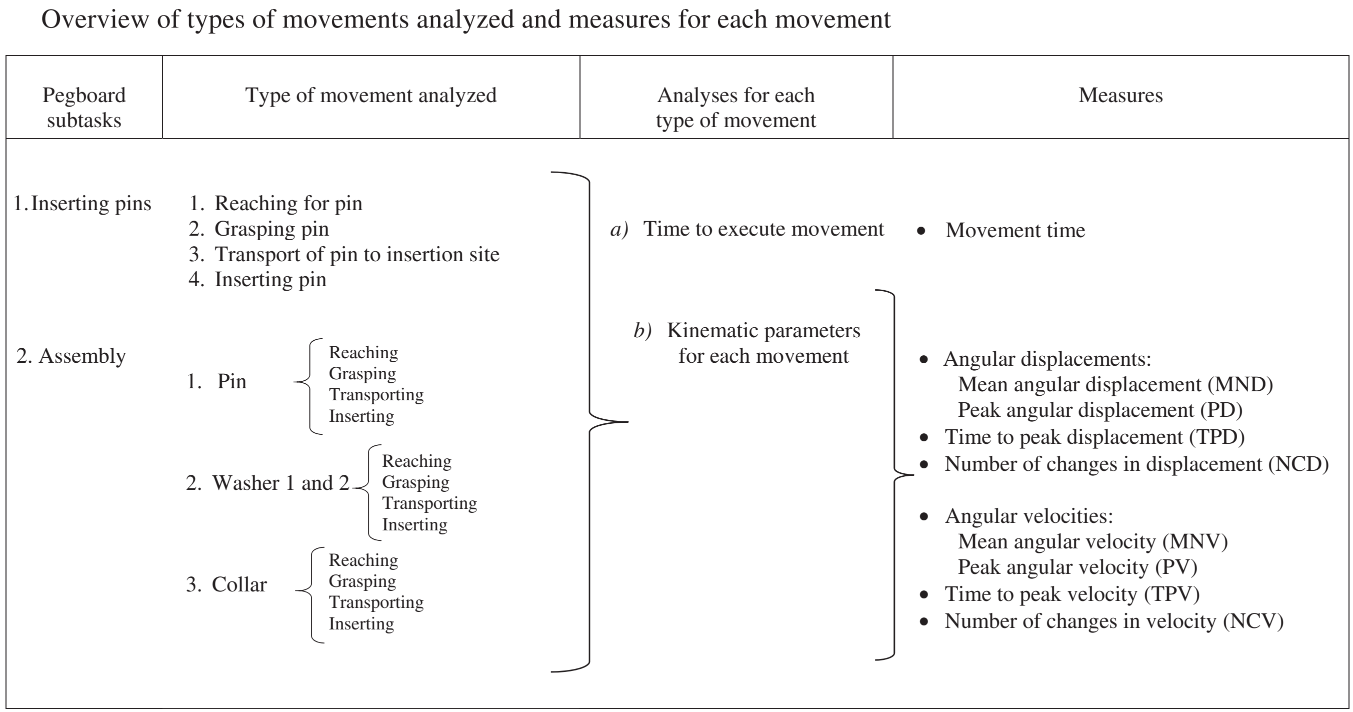
Temporal measures. Two-dimensional kinematic data were acquired during each subtask. Performance was video recorded with a Sony Handycam DCR-PC100E at the frequency of 25 Hz. The camera was attached on a rack above the pegboard, thus hand movements were recorded from a dorsal view.

From the video data, movement times were obtained for four types of movements on the pins task and eight types of movements on the assembly task. For the pins task the types of movements were: 1) reaching for pins, 2) grasping pins, 3) transporting pins to the site of insertion, and 4) inserting pins. For the assembly task, the same movements for pins were registered in addition to the movements related to the extra pegs required in this task. The additional movements were: 5) reaching washers, 6) grasping washers, 7) transporting washers, 8) inserting washers, 9) reaching collars 10) grasping collars, 11) transporting collars and 12) inserting collars. Movements for all washers (washer 1 and washer 2) were taken together as this is the same object. Time required to perform each movement was recorded in milliseconds. These results are referred to as *movement times* throughout the manuscript (see left side of Table 1). Movements were manually defined from the video recordings using the following criteria: Onset for "*reaching*" toward the cup/hole was recorded when the hand began to move toward the cup/hole until the fingers were above the cup/hole. Onset for "*grasping*" was defined as the time when fingers were above the cup and it lasted until the peg was lifted out of the cup. Actions coded as "*inserting*" started when the fingers were above the hole and ended when the fingers were lifted off the peg.

Kinematic measures. The Vicon Motus 2D system was used (*Vicon Motion Systems, Inc.*, CO. USA) to record and analyze dexterity performance. This motion tracking software performs kinematic analysis based on the coordinates of reflective markers as they move in the camera view. Figure 2 shows the placement of markers for the present study. Three markers measuring 6.4 mm each were attached above the following anatomical landmarks: The proximal interphalangeal joint of index finger, the metacarpophalangeal joint of thumb, and the interphalangeal joint of thumb. Figure 2 also shows the angle used for kinematic analysis.

Table 1 summarizes the types of movements analyzed and the measures calculated for each type of movement. Prior to the analysis, kinematic data were

Table 1. Overview of types of movements analyzed and measures for each movement.



Overview of types of movements analyzed and measures for each movement

Pegboard subtasks	Type of movement analyzed	Analyses for each type of movement	Measures
1. Inserting pins	1. Reaching for pin 2. Grasping pin 3. Transport of pin to insertion site 4. Inserting pin	*a)* Time to execute movement	• Movement time
2. Assembly	1. Pin: Reaching, Grasping, Transporting, Inserting 2. Washer 1 and 2: Reaching, Grasping, Transporting, Inserting 3. Collar: Reaching, Grasping, Transporting, Inserting	*b)* Kinematic parameters for each movement	• Angular displacements: Mean angular displacement (MND) Peak angular displacement (PD) • Time to peak displacement (TPD) • Number of changes in displacement (NCD) • Angular velocities: Mean angular velocity (MNV) Peak angular velocity (PV) • Time to peak velocity (TPV) • Number of changes in velocity (NCV)

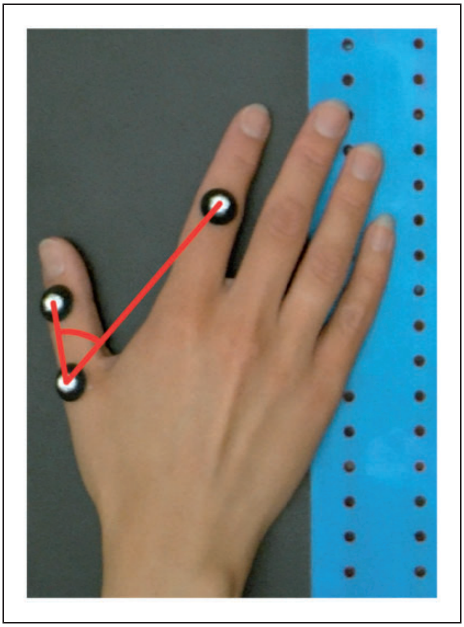


Figure 2. Positions of markers with the angle used in kinematic analysis overlaid.

low-pass filtered with a Butterworth filter at the cut-off frequency of 10 Hz. As with the temporal measures, the kinematic parameters were calculated for each repetition of each type of movement. The selected kinematic parameters are measures regularly employed in studies of hand function (e.g., Grabowski & Mason, 2014). These included a) mean angular displacement, defined as the mean size of the angle in degrees; b) peak angular displacement, defined as the largest size of the angle in degrees; c) time to peak displacement, defined as the proportion of the movement time before peak displacement was reached; and d) number of changes in displacement, defined as the proportion of the movement time in which the angle changed between increasing and decreasing. Amount of rotation of the hand is represented by mean and peak angular displacements with respect to initial point. Number of changes in displacement represents the frequencies in variability of rotational movement.

To measure the speed of movements, the mean angular velocity was calculated. This parameter is defined as the average speed of rotation of the angle in degrees/sec. Peak angular velocity is defined as the highest speed of rotation of the angle in degrees/sec. Time to peak angular velocity is defined as the proportion of the movement time before reaching peak velocity and number of changes in angular velocity is defined as the proportion of the movement time in which angular velocity changed direction between positive (i.e., counter-clockwise rotation) and negative (i.e., clockwise rotation) values. Speed of hand rotation is reflected by mean and peak angular velocities, while number of changes in velocity represents the variability in rotation speed. Displacement and velocity of time peak as well as number of changes in both displacement and velocity are presented in proportions ranging between 0 and 1 in order to account for individual differences in movement times.

Procedure

The study took place at the Department of Psychology, University of Tromsø. Duration of the study was approximately 1 to 1.5 hrs, taking longer times for the elderly. After participants signed the consent form, the demographic and health interview were administered. Subsequently, the cognitive test battery was administered. Afterwards, dexterity tests with the Purdue Pegboard Test took place. Following standard procedures for neuropsychological testing with older adults (Woodruff-Pak, 2004), special care was taken to avoid fatigue in the elderly and a 15-minute break was allowed between the cognitive test battery and dexterity tests. The same brake was also given to the young participants. Demonstration of the dexterity tasks was given before the assessment, as well as sufficient time to practice. Participants were told to rest their hand at the right side of the board with the palm facing down and to start the task at the experimenter's signal.

Statistical Method

Motivation and interpretation of Bayesian analysis. Due to the complexity of the acquired dataset and the small sample sizes of the study, it was deemed appropriate to employ Bayesian statistics. This approach, allows to tailor the analysis model specifically to the requirements of the complex dataset and hence, it was possible to integrate cognitive and kinematic data to evaluate their relationship. Recent developments in the literature on methods in the field of psychology strongly favor Bayesian analyses over the more commonly employed null-hypothesis testing (NHST) approach (Wagenmakers, Lodewyckx, Kuriyal, & Grasman, 2010; Kruschke, 2010b; Dienes, 2011; Kruschke, 2013). Multiple shortcomings of classical statistical methods have been revealed (many of them related to incorrect interpretation and usage of statistical indices, (Hoekstra, Morey, Rouder, & Wagenmakers, 2014) and solutions employing Bayesian methods have been proposed. In this paper, only Bayesian methods are used for data analysis (Kruschke, 2010a; Gelman, Carlin, Stern, & Rubin, 2014) and, correspondingly, results are reported in terms of Bayes factors (BF), posterior estimates and highest-density intervals (HDIs).

Bayes factors quantify the degree of evidence that the data provide for one hypothesis (e.g., H_0) over another (e.g., H_1). Therefore, the shortcut BF_{10} refers

Table 2. Evidence categories for Bayes Factors (adapted from Wetzels et al., 2011).

Bayes Factor	Interpretation
>100	Decisive evidence for H_1
30–100	Very strong evidence for H_1
10–30	Strong evidence for H_1
3–10	Substantial evidence for H_1
1–3	Anecdotal evidence for H_1
1	No evidence
1/3–1	Anecdotal evidence for H_0
1/10–1/3	Substantial evidence for H_0
1/30–1/10	Strong evidence for H_0
1/100–1/30	Very strong evidence for H_0
$<1/100$	Decisive evidence for H_0

to the Bayes factor testing H1 over H0 while BF_{01} refers to the opposite. It is therefore possible to quantify evidence both in support of the null- and the alternative hypothesis. Jeffreys (1998) discussed how Bayes factors could be interpreted in terms of strength of evidence for and against a hypothesis by assigning labels to the strength of evidence inherent to BFs of different magnitude. While these labels are controversial as they add a discrete interpretation to the continuous "degree of evidence" that the BF represents, they are helpful to guide interpretation of the effects and will be reported along with the BFs (see Table 2). Another advantage of BFs over p-values is that they are less prone to overestimating effects (Wetzels et al., 2011). Besides BFs, posterior mean and associated HDI are important summary statistics when reporting Bayesian statistics. The posterior mean is a point estimate of the size of the effect and is interpreted similar to classical coefficient estimates, e.g., in regression models. The associated uncertainty is expressed in terms of the 95% highest-density interval which quantifies the interval in which the real value falls with probability 0.95 given the data and the model structure (this is the interpretation that is often but falsely assigned to classical confidence intervals; Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2015). An effect was considered to be sufficiently likely to be reported and interpreted whenever its HDI excludes zero.

Statistical Analysis

All statistical analyses were run using the R programming language (R Core Team, 2015) using the BayesFactor (Morey & Rouder, 2015) and the rstan packages (Carpenter et al., 2015) and JASP (Love et al., 2015). The Stan-models

Table 3. Demographics, MMSE, BDI, Handedness and Grip strength by group.

	Young ($n=15$)	Elderly ($n=15$)	BF_{10}
F/M Ratio	9/6	10/5	0.4
	M (SD)	*M (SD)*	
Age	26.07 (3.43)	74.00 (6.88)	7.19×10^{16}
Years of education	16.37 (1.49)	13.03 (3.88)	9.7
MMSE	29.47 (0.64)	28.13 (1.60)	7.9
BDI	3.13 (2.90)	5.47 (3.54)	1.4
Handedness	19.33 (3.02)	22.27 (2.69)	5.6
Grip strength			
Right hand	28.44 (9.66)	40.98 (12.14)	10.10
Left hand	25.98 (10.14)	38.28 (13.83)	4.62

where fit using the Hamiltonian Monte-Carlo techniques implemented in the Stan software (Hoffman & Gelman, 2014). Eight parallel chains were run for each model and sampling continued until 2000 samples had been obtained for each chain. The first half of the samples was treated as burn-in and discarded from the analysis. All chains for all variables were visually inspected for artifacts (such as trends, autocorrelation or other signs of poor convergence) and it was ensured that the Gelman-Rubin diagnostic $\hat{R}$ (Gelman & Rubin, 1992) was lower than 1.05 for all variables. Thus, in total 8000 independent samples from the posterior distribution were analyzed.

Results

Demographics and Neuropsychological Results

Table 3 presents results for the demographic, mental status, depression, handedness and grip strength variables in the two groups. There was substantial evidence that the younger group had more years of education (16.4 vs. 13.0 years; $BF_{10}=9.7$) and scored higher on the MMSE (29.5 vs. 28.1 points; $BF_{10}=7.9$) than the older group. In addition, the elderly showed higher right-hand tendency in the Handedness Inventory than the younger group (young: 19.3, old: 22.3; $BF_{10}=5.6$).

Results for the cognitive tests and grip strength are summarized in Table 4. As expected, the elderly group showed lower performance compared to the younger participants on most of the cognitive tests. Results from the Digits forward ($BF_{10}=0.38$) and backward ($BF_{10}=1.03$), as well as the Stroop Word subtest ($BF_{10}=1.15$) were inconclusive.

Table 4. Group Differences in Cognitive Test Scores and Grip Strength.

Variable	Elderly *M (SD)*	Young *M (SD)*	BF_{10}	Cohen's *d*
Digits forward	7.60 (1.88)	7.93 (1.91)	0.38	−0.18
Digits backward	5.60 (1.50)	6.67 (1.88)	1.03	−0.65
Stroop Word	94.93 (10.57)	101.53 (9.35)	1.15	−0.68
Stroop Color	62.40 (10.62)	73.07 (5.75)	18.15	−1.29
Stroop W/C	31.00 (6.59)	46.53 (7.51)	7262.21	−2.28
TMT A	39.70 (9.99)	19.77 (6.28)	25271.45	2.47
TMT B	102.20 (28.54)	44.37 (8.49)	253944.14	3.76
Grip strength				
Right hand	28.44 (9.66)	40.98 (12.14)	10.10	−1.18
Left hand	25.98 (10.14)	38.28 (13.83)	4.62	−1.07

Note. Stroop W/C = Stroop Word/Color; TMT = Trail Making Test.

Overall Dexterity Performance

As expected, younger adults inserted more pins ($M = 7.1$, $SD = 3.35$) than the older ($M = 4.47$, $SD = 2.33$; $BF_{10} = 49.52$, directional) on the inserting pins task and they likewise completed more assemblies than the older group (young: $M = 4.13$, $SD = 2.69$; elderly: $M = 2.67$, $SD = 1.63$; $BF_{10} = 14.65$, directional).

Movement Times

Movement times for the pin task were subjected to a Bayesian ANOVA with factors movement-type (reaching, grasping, transporting, inserting) and group (young, old) and a random factor for each participant. For a descriptive summary, see Figure 3. On the pins task, the main effect of action ($BF_{inclusion} = 6.01 \times 10^{15}$), group ($BF_{inclusion} = 1413.0$) and their interaction ($BF_{inclusion} = 656.2$) received decisive evidence. A comparison of the posterior means indicated that older adults needed more time for grasping (difference = 228 msec, HDI = [77, 389]) and inserting pins (difference = 350 msec, HDI = [185, 519]). No group differences were found for reaching (difference = 7 msec, HDI = [−158,164]) or transport (difference = 17 msec, HDI = [−152, 173]).

Similarly, the movement times for the assembly task were subjected to a Bayesian ANOVA with the same factors plus a factor coding the object of the assembly (pin, collar, washer). A descriptive summary is provided in Figure 4. There was decisive evidence for a main effect of group ($BF_{inclusion} = 2.8 \times 10^9$) and action ($BF_{inclusion} = \infty$) as well as for their interaction ($BF_{inclusion} = 7.2 \times 10^8$). There was strong evidence for a main effect of object ($BF_{inclusion} = 12.6$). In addition, there was anecdotal evidence for the presence of an

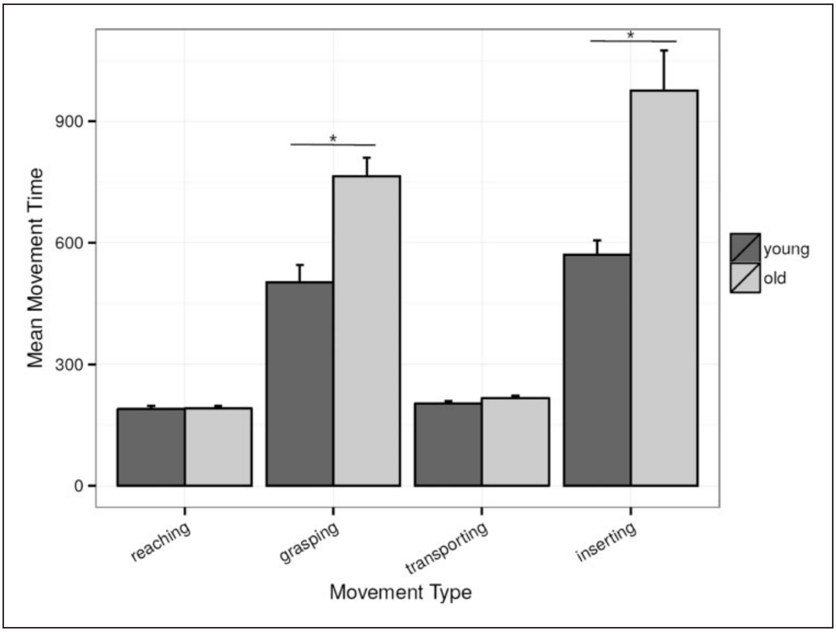


Figure 3. Movement times in the pins task. Asterisk indicates that the correponding posterior HDIs of the difference excluded zero.

object × action interaction ($BF_{inclusion} = 3.9$). Finally, there was substantial evidence *against* the presence of an object × group interaction ($BF_{inclusion} = 0.27$) and the three-way object × group × action interaction ($BF_{inclusion} = 0.14$).

The posterior analyses yielded results similar to those in the pins task. The group differences in movement times were substantially different for grasping (pin: difference = 313 msec, HDI = [141, 495]; washer: difference = 430 msec, HDI = [258, 614]; collar: difference = 426 msec, HDI = [257, 608]) and inserting (pin: difference = 286 msec, HDI = [111, 462]; washer: difference = 255 msec, HDI = [80, 443]; collar: difference = 381 msec, HDI = [208, 564]) but not for reaching (pin: difference = −10 msec, HDI = [−191, 162]; washer: difference = −11 msec, HDI = [−182, 171]; collar: difference = 5 msec, HDI = [−179, 178]) and transporting (pin: difference = 2 msec, HDI = [−172, 185]; washer: difference = 3 msec, HDI = [−175, 188]; collar: difference = 24 msec, HDI = [−157, 202]).

Kinematic Results

Kinematic variables were: mean angular displacement, peak angular displacement, time to peak displacement, number of changes in displacement, mean angular velocity, peak angular velocity, time to peak velocity, and number of changes

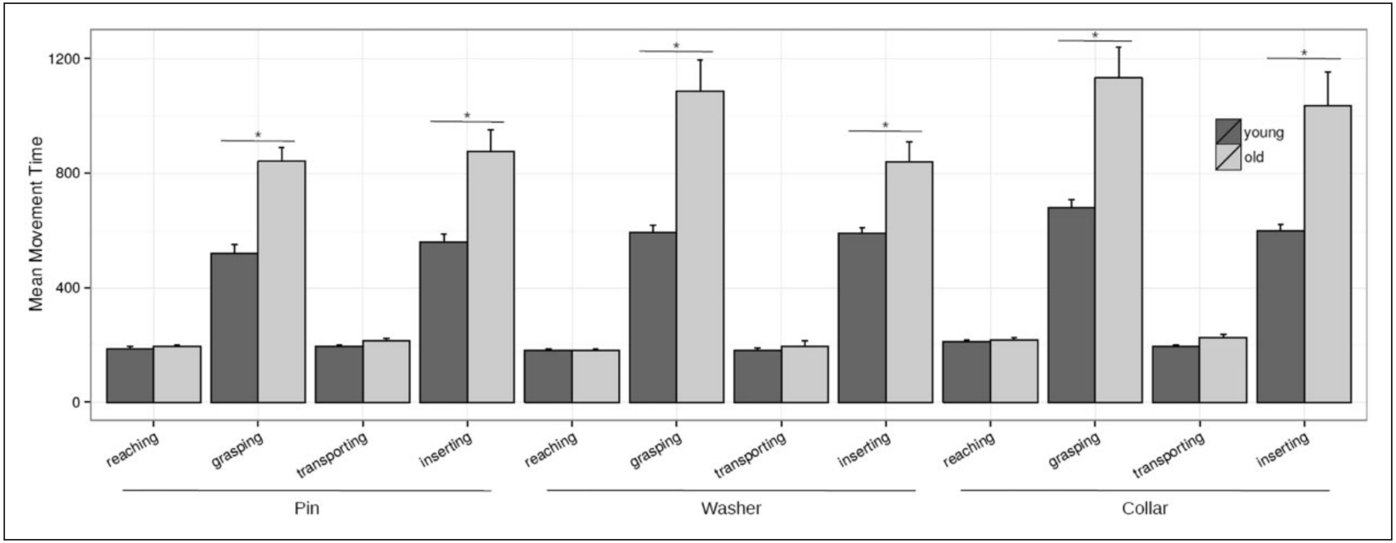


Figure 4. Movement times in the complex assembly task. Asterisk indicates that the correponding posterior HDIs of the difference excluded zero.

in velocity. All individual measurement were submitted to a Bayesian multivariate mixed linear regression model with the following regressors: a random intercept for each participant (constrained by a group-level Cauchy-distribution with unit-information priors), task (pins vs. assembly), movement type (reaching, grasping, transporting, inserting), object (pin, washer, collar), group (young, old), scores from the Stroop Word/Color task, Trail Making Test part B, Digits Forward and Digits Backwards (all cognitive variables z-scored within age-group), and group interactions with all the cognitive variables. Baseline was set to the young group with movement type reaching and object pin (all coefficients have to be interpreted relative to that baseline). Before the kinematic variables entered the regression model, they were log-transformed (after offsetting by 1) to account for non-normality in the data (except peak displacement and mean angular displacement which were already normally distributed) and standardized. All regression coefficients received independent Cauchy(0,1) priors.

The main effects of group and of task are depicted in Figure 5. Generally, the elderly showed increases in peak velocity ($\beta = 0.38$, HDI = [0.12, 0.61]), mean angular velocity ($\beta = 0.58$, HDI = [0.35, 0.80]), time to peak velocity ($\beta = 0.22$, HDI = [0.12, 0.33]), number of changes in velocity ($\beta = 0.40$, HDI = [0.28, 0.52]), time to peak displacement ($\beta = 0.26$, HDI = [0.15, 0.38]) and number of changes in displacement ($\beta = 0.47$, HDI = [0.35, 0.60]) but not in peak displacement ($\beta = 0.02$, HDI = [−0.15, 0.20]) and mean angular displacement ($\beta = 0.13$,

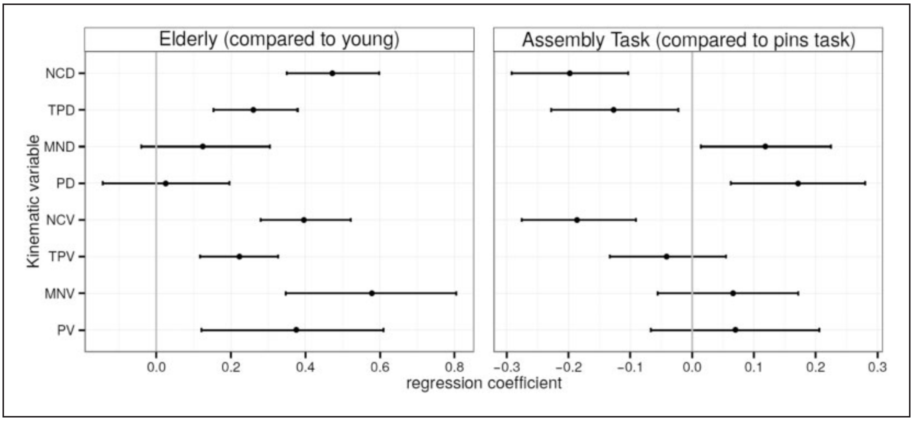


Figure 5. Regression coefficients for factors group and task. Coefficients code the difference between elderly and young subjects (left) and difference between simple and complex assembly task (right). Points signify the posterior mean, flanker are 95% posterior highest-density intervals (HDI). NCD = number of changes in displacement, TPD = time to peak displacement, MND = mean angular displacement, PD = peak displacement, NCV = number of changes in velocity, TPV = time to peak velocity, MNV = mean angular velocity, PV = peak velocity.

HDI = [−0.04, 0.30]). In the assembly task, number of changes in velocity, time to peak displacement and number of changes in displacement were reduced (number of changes in velocity: β = −0.19, HDI = [−0.28, −0.09]; time to peak displacement: β = −0.13, HDI = [−0.23, −0.02]; number of changes in displacement: β = −0.20, HDI = [−0.29, −0.10]) while mean angular displacement and peak displacement were increased (mean angular displacement: β = 0.12, HDI = [0.01, 0.22], peak displacement: β = 0.17, HDI = [0.06, 0.28]).

Unsurprisingly, each of the different movement types showed a different profile in the kinematic variables. These profiles are summarized in Appendix 1. The same is true for the different types of objects (pins, collars and washers) which required slightly different movements as reflected in systematic differences in the kinematic variables. These coefficients are summarized in Appendix 2.

Association between kinematics and cognitive scores

Finally, the regression coefficients for the cognitive variables were analyzed (summarized in Figure 6). Performance in the Digits Forward task was associated with increases in peak velocity and mean angular velocity in the young group (peak velocity: β = 0.58, HDI = [0.11, 0.95]; mean angular velocity: β = 1.10, HDI = [0.71, 1.44]) but not in the elderly (peak velocity: β = 0.02, HDI = [−0.11, 0.14]; mean angular velocity: β = 0.06, HDI = [−0.05, 0.18]). Performance in the Digits Backwards task was associated with increased peak displacement in the young (β = 0.29, HDI = [0.05, 0.54]) but not in the elderly (β = 0.00, HDI = [−0.11, 0.11]). Higher scores in the Stroop Word/Color task led to higher values of number of changes in displacement in the elderly (β = 0.16, HDI = [0.06, 0.26]) but not the young group (β = 0.01, HDI = [−0.07, 0.10]). Conversely, higher scores in the Stroop task were associated with lower values of mean angular velocity and peak velocity in the young group (mean angular velocity: β = −0.54, HDI = [−0.71, −0.37]; peak velocity: β = −0.33, HDI = [−0.51, −0.10]) but not for the elderly (mean angular velocity: β = 0.00, HDI = [−0.14, 0.14]; peak velocity: β = 0.00, HDI = [−0.14, 0.14]).

Finally, higher performance in the Trail-Making Test B was associated with higher levels of mean angular velocity and peak velocity in the young group (mean angular velocity: β = 0.46, HDI = [0.24, 0.69]; peak velocity: β = 0.30, HDI = [0.06, 0.53]) but not the elderly for whom a tendency to the opposite was present (mean angular velocity: β = −0.14, HDI = [−0.30, 0.01]; peak velocity: β = −0.08, HDI = [−0.23, 0.09]).

Discussion

Dexterity Results

As expected, the present study confirmed age-related differences in dexterity performance between younger and older adults. In accordance with earlier

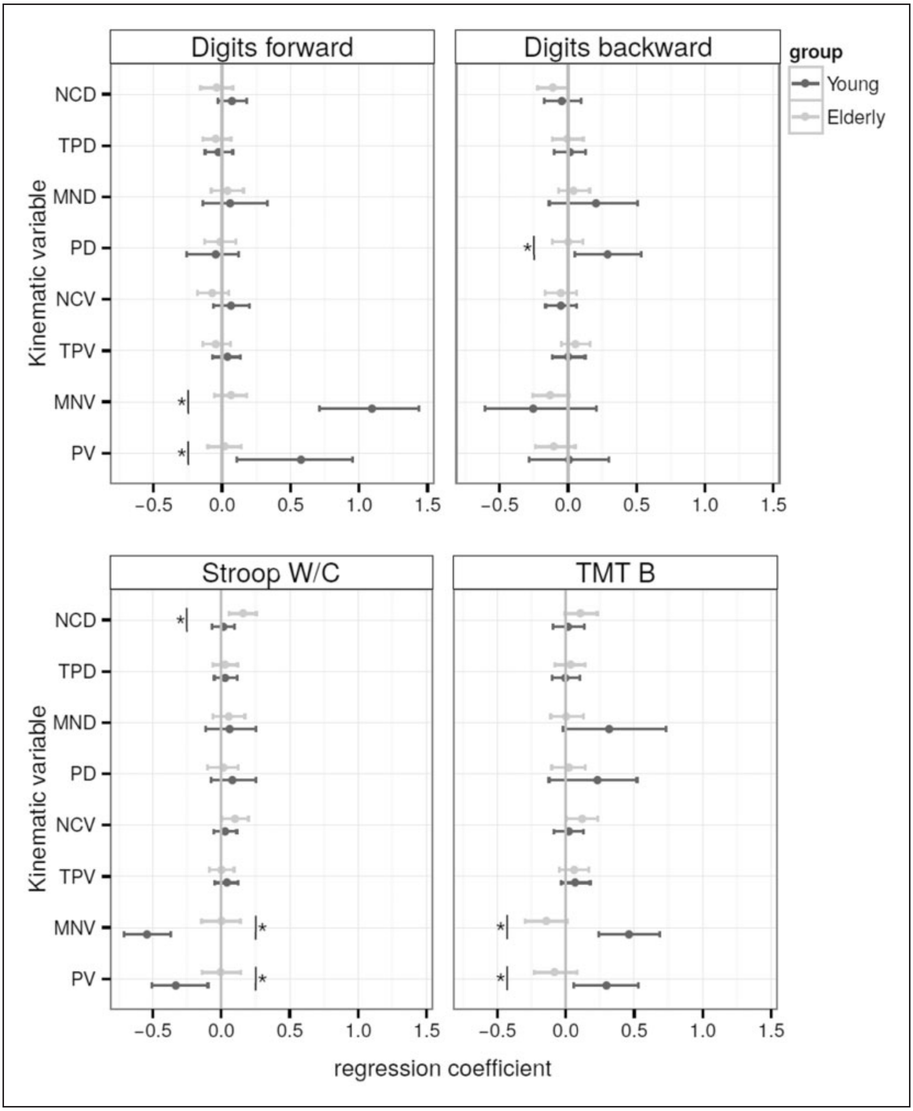


Figure 6. Regression coefficients for cognitive variables per group. Points signify the posterior mean, flankers are 95% posterior highest-density intervals (HDI). Asterisks indicate that the 95% HDI of the group × cognitive variable interaction coefficient excludes zero. NCD = number of changes in displacement, TPD = time to peak displacement, MND = mean angular displacement, PD = peak displacement, NCV = number of changes in velocity, TPV = time to peak velocity, MNV = mean angular velocity, PV = peak velocity.

data, it was observed that younger subjects managed to complete insertion of more pegs in both dexterity subtasks than elderly participants. Importantly, the data showed that group differences in time spent to perform both tasks were related exclusively to the actions of grasping and inserting pegs. Contrary to existent data (Bennett & Castiello, 1994) no group differences were found in the time spent on reaching for pegs or transport of pegs. These results are in agreement with a recent study (Cicerale, Ambron, Lingnau, & Rumiati, 2014), which indicate that older adults are equally fast to displace the arm and hand at different locations but that they become slower in performing finger movements involved in grasping and inserting objects. The findings might be explained by the difficulty of older adults to manipulate unknown small objects presenting different features (Gentilucci et al., 1991) and by increased slipperiness on their fingers (Diermayr, McIsaac, & Gordon, 2011).

Regarding the specific kinematic data for each task, it is evident that during performance of the assembly task, there was less variability of displacement and velocity, but more rotation of the hand was demanded due to the diversity of the pegs. Concerning the manipulation of pegs across tasks, older adults had higher values on most of the kinematic measurements, excepting for peak and mean angular displacement, which possibly indicates a less efficient use of the hand. Although the elderly showed faster peak velocities, this was characterized by an increased number of changes of velocity indicating that they had to correct their movements more often. Interestingly, both groups had almost similar outcomes on the displacement of each movement. The only strong difference between groups regarding displacement was observed in the variability of displacement. It was also confirmed that older adults showed higher variability in both velocity and displacement, which advocates for the fact that older adults not only experience fluctuations in speed while performing hand movements but also non-negligible changes during movement trajectory. These data confirms the higher variability in healthy elderly reported in the literature (Diermayr et al., 2011).

Cognitive Results

The cognitive outcomes demonstrated that older adults scored lower than younger in tests of executive functions, but not on the Digits Span subtests. The lack of evident differences in Digits Span between young and older subjects is not common, but exceptions exist (Wingfield, Stine, Lahar, & Aberdeen, 1988) and in general, Digits Span only shows a small decline in normal aging. In the present study, the elderly group was particularly able to execute immediate recall of serial numbers forward while they were less proficient to perform the backwards part relying on higher levels of active manipulation of information. Overall, and compared to the younger subjects, the elderly showed preserved working memory abilities. In contrast, their performance on tests related to executive functions was poorer as compared to younger adults. These results support the age-related decline in planning, inhibition and monitoring of actions recurrently reported in the literature (Albinet, Boucard, Bouquet, & Audiffren, 2012).

Association between Dexterity and Cognitive Results

The main purpose of the present study was to explore possible associations between dexterity, working memory, and executive functions among healthy young and elderly adults. From an overall view, the Bayesian analysis demonstrated that attentional capacities were mainly associated with speed of rotational hand movements (i.e., mean angular velocity) and end-point of movement speed (i.e., peak velocity) in younger adults. All cognitive tasks, excepting the Digits Backwards showed this pattern of association also, in younger adults. Digits Backwards was actually associated positively with peak displacement, which is hard to interpret. The straightforward interpretation is that in spite of this single association, the type of working memory measured by Digits Span does not seem to be of importance for dexterity in our groups. In contrast, effective short time attentional demands measured by Digits forwards seems to be decisive for faster hand rotation in younger adults.

Regarding the involvement of executive functions in dexterity, the data showed interesting relationships. On one hand, higher inhibitory capacities measured in the Stroop task were associated with slower hand rotation (i.e., slower mean angular and peak velocities), in the young group. On the other hand, enlarged time in the Trail Making Test B was associated with faster rotational movements in the same group. In order to interpret these data it is necessary to highlight that although Stroop Word/Color and Trail Making Test B measure executive functions, including inhibition, planning and action monitoring, performance is scored in different ways. Stroop Test is time limited to 45 sec, and higher scores denote better performance. For part B of the Trail Making Test, performance is measured by the time employed to resolve tasks' demands, which means that higher scores give longer times and this is interpreted as deficient executive functioning. Thus, taken together results for the younger adults, the findings suggest that proficient executive functioning is associated with slower rotational hand movements. In other words, it seems that higher monitoring and cognitive flexibility is coupled with slower dexterity, which possibly denotes more carefulness in the control of hand speed. Hence, fast younger individuals performing the dexterity tasks on this study show lower executive control, maybe due to "careless behavior". This observation may also help to understand the obtained results for the elderly group.

In general, results in the older group did not show an evident association between executive functions and kinematics. However, one single measurement turned out to be associated with better executive functioning as measured with the Stroop test, namely, variability of movement displacement. The same association with the Trail

Making Tests B showed a similar trend. This relationship is in line with the fact that when an individual ages, movements become slower and also more variable (Ketcham & Stelmach, 2004; Christou, 2011). Nevertheless, the association found in this investigation is not easy to interpret. On one side, it suggests that older adults with higher executive functioning measured by the Stroop task show amplified movement variability in dexterity, while elderly with increased times in the Trail Making Test B, ergo lower executive functioning, also show increased variability. Both associations advocate for a real involvement of executive functioning and changes in movement variability among healthy elderly, though, the present data is inconclusive regarding the direction of this association.

Finally, it is worth mentioning that the lack of associations between working memory, executive functions and the rest of the kinematic variables in the elderly could be due to the fact that healthy older adults are more prone to adopt cautious strategies in the preplanning control of movement (Elliott et al., 2010). Indeed, elderly are known to be more conservative than younger adults concerning speed, and elderly might prefer accuracy rather than display a fast response (Ketcham & Stelmach, 2004). Nonetheless, in order to prove this statement, and to better understand the associations between executive functioning, working memory and hand dexterity, a future study should be carried out in which all participants perform dexterity tasks without time restrictions.

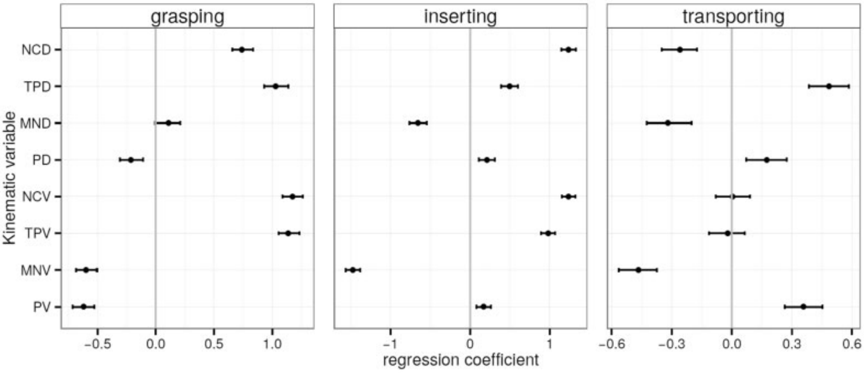
Limitations of the Study

A major limitation of the present study is the small sample size. The Bayesian analysis employed in this study partly remedies this problem by including all individual measurements and the major sources of variation in a comprehensive model. That way, the uncertainty induced by the low sample size will be reflected in broader posterior distributions (i.e., wide HDIs) such that uncertain estimates are more easily recognized as such. However, random influences resulting in seemingly systematic fluctuations are always possible in small datasets and the current study should therefore be regarded as exploratory. A replication of the main findings in a larger sample is therefore desirable and currently in preparation at the laboratory where this study took place. Another limitation exists regarding the possibility of a bias in our sample as all participants were volunteers and thus, the sample cannot be regarded as entirely representative. The use of different tasks tapping the same cognitive functions needs also to be implemented. Moreover, technical limitations existed. The 2D system employed for analysis of kinematic measures has some restrictions in capturing the exact movements of the fingertips during grasping. For this reason, a marker over the distal phalange of the index finger was not added and thus, the finest movements employed in grasping and inserting were not possible to analyze.

Regarding the methodology, movement errors or the frequency of dropped pegs during performance of the dexterity tasks were not measured. This might have given complementary information. Finally, it is necessary to keep in mind that the present study did not measure the cognitive demands on dexterity in the course of task execution. To obtain this information, it would be necessary to employ techniques registering brain function or other behavioral parameters such as eye-tracking. However, these approaches have the disadvantage of creating an unnatural testing environment and may induce additional stress and artificial demands on subjects (Woodruff-Pak, 2004).

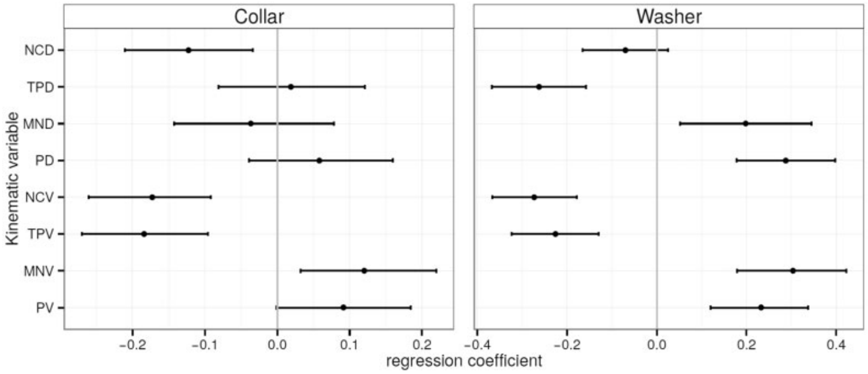
In conclusion, the present investigation contributes to the explorative analysis of the involvement of higher order cognitive functions in manual dexterity in healthy young and elderly adults. The detailed analysis of movements involved in the execution of two subtasks from the Purdue pegboard showed that the elderly differed from younger adults only on the grasping and inserting actions. There are two main findings from the present study: First, it was found that immediate attentional control and executive functions are related to rotational speed of hand movements (i.e., mean angular velocity) and to end-point movement speed (i.e., peak velocity) in younger individuals. Second, an association between executive functions and movement variability existed in the elderly, albeit the direction of the association was inconclusive. These data suggest that there are different patterns of attention-dexterity associations in younger and older adults. Further work is needed to understand the nature of these differences by deepening the study on the interaction between peripheral changes, motor and cognitive declines in the course of normal aging.

Appendix 1



Regression coefficients for movement type. Coefficients code the difference between reaching and each of the other movement types (grasping, inserting, transporting; left, middle right). Points signify the posterior mean, flankers are 95% posterior highest-density intervals (HDI). NCD = number of changes in displacement, TPD = time to peak displacement, MND = mean angular displacement, PD = peak displacement, NCV = number of changes in velocity, TPV = time to peak velocity, MNV = mean angular velocity, PV = peak velocity.

Appendix 2



Regression coefficients for object type. Coefficients code the difference between pin and each of the other objects (Collar and Washer). Points signify the posterior mean, flankers are 95% posterior highest-density intervals (HDI). NCD =number of changes in displacement, TPD = time to peak displacement, MND = mean angular displacement, PD = peak displacement, NCV = number of changes in velocity, TPV = time to peak velocity, MNV = mean angular velocity, PV = peak velocity.

Acknowledgments

We thank Mari Lise Eriksen for helping with data acquisition.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Financial support was received from the Faculty of Health Sciences, University of Tromsø. The study was also supported by a grant from Helse Nord funds.

Author's note

Annotated raw data and associated analyses scripts are available at http://github.com/ihrke/2016-executive-functions-manual-dexterity (DOI: 10.5281/zenodo.35402).

References

Albinet, C. T., Boucard, G., Bouquet, C. A., & Audiffren, M. (2012). Processing speed and executive functions in cognitive aging: How to disentangle their mutual relationship? *Brain and Cognition*, *79*, 1–11.

Andres, P., Guerrini, C., Phillips, L. H., & Perfect, T. J. (2008). Differential effects of aging on executive and automatic inhibition. *Developmental Neuropsychology*, *33*, 101–123.

Baldauf, D., & Deubel, H. (2010). Attentional landscapes in reaching and grasping. *Vision Research*, *50*, 999–1013.

Beck, A. T., Steer, R. A., & Garbin, M. G. (1988). Psychometric properties of the Beck Depression Inventory: twenty-five years of evaluation. *Clinical Psychology Review*, *8*, 77–100.

Bennett, K. M. B., & Castiello, U. (1994). Reach to grasp - changes with age. *Journals of Gerontology*, *49*, 1–7.

Bramell-Risberg, E., Jarnlo, G. B., & Elmstahl, S. (2010). Slowing of alternating forearm movements is associated with cognitive impairment in community-dwelling older people. *Dementia and geriatric cognitive disorders*, *29*, 457–466.

Briggs, G. G., & Nebes, R. D. (1975). Patterns of hand preference in a student population. *Cortex*, *11*, 230–238.

Buckingham, G., & Carey, D. P. (2015). Attentional asymmetries - cause or consequence of human right handedness? *Frontiers in Psychology*, *5*, 1587.

Cahn-Weiner, D. A., Malloy, P. F., Boyle, P. A., Marran, M., & Salloway, S. (2000). Prediction of functional status from neuropsychological tests in community-dwelling elderly individuals. *Clinical Neuropsychologist*, *14*, 187–195.

Carmeli, E., Patish, H., & Coleman, R. (2003). The aging hand. *Journals of Gerontology Series A-Biological Sciences and Medical Sciences*, *58*, 146–152.

Carpenter, B., Gelman, A., Hoffman, M., Lee, D., Goodrich, B., Betancourt, M. et al. Stan: A probabilistic programming language. *Journal of Statistical Software*, (in press).

Charlier, R., Mertens, E., Lefevre, J., & Thomis, M. (2015). Muscle mass and muscle function over the adult life span: A cross-sectional study in Flemish adults. *Archives of Gerontology and Geriatrics*, *61*, 161–167.

Christou, E. A. (2011). Aging and variability of voluntary contractions. *Exercise and Sport Sciences Reviews*, *39*, 77–84.

Cicerale, A., Ambron, E., Lingnau, A., & Rumiati, R. I. (2014). A kinematic analysis of age-related changes in grasping to use and grasping to move common objects. *Acta Psychologica*, *151*, 134–142.

Desrosiers, J., Hebert, R., Bravo, G., & Dutil, E. (1995). Upper extremity performance-test for the elderly (Tempa) - Normative data and correlates with sensorimotor parameters. *Archives of Physical Medicine and Rehabilitation*, *76*, 1125–1129.

Dienes, Z. (2011). Bayesian versus orthodox statistics: Which side are you on? *Perspectives on Psychological Science*, *6*, 274–290.

Diermayr, G., McIsaac, T. L., & Gordon, A. M. (2011). Finger force coordination underlying object manipulation in the elderly - A mini-review. *Gerontology*, *57*, 217–227.

Drag, L. L., & Bieliauskas, L. A. (2010). Contemporary review 2009: Cognitive aging. *Journal of Geriatric Psychiatry and Neurology*, *23*, 75–93.

Elliott, D., Hansen, S., Grierson, L. E. M., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: Two components but multiple processes. *Psychological Bulletin*, *136*, 1023–1044.

Folstein, M. F., Folstein, S. F., & McHugh, P. R. (1975). Mini Mental State: A practical method for grading the cognitive state of patients for the clinician. *Journal of psychiatric research*, *12*, 189–198.

Gelman, A., Carlin, J. B., Stern, H. S., & Rubin, D. B. (2014). *Bayesian data analysis* (Vols. 2). London: Chapman & Hall/CRC.

Gelman, A., & Rubin, D. B. (1992). Inference from iterative simulation using multiple sequences. *Statistical Science*, *7*, 457–472.

Gentilucci, M., Castiello, U., Corradini, M. L., Scarpa, M., Umilta, C., & Rizzolatti, G. (1991). Influence of different types of grasping on the transport component of prehension movements. *Neuropsychologia*, *29*, 361–378.

Golden, C. J. (1978). *Stroop color and word test. A manual for clinical and experimental uses*. Wood Dale, IL: Stoelting.

Grabowski, P. J., & Mason, A. H. (2014). Age differences in the control of a precision reach to grasp task within a desktop virtual environment. *International Journal of Human-Computer Studies*, *72*, 383–392.

Hackel, M. E., Wolfe, G. A., Bang, S. M., & Canfield, J. S. (1992). Changes in hand function in the aging adult as determined by the jebsen test of hand function. *Physical Therapy*, *72*, 373–377.

Halstead, W. C. (1947). *Brain and intelligence*. Chicago: University of Chicago Press.

Hardin, M. (2002). Assessment of hand function and fine motor coordination in the geriatric population. *Topics in Geriatric Rehabilitation*, *18*, 18–27.

Higgins, P. G., & Glasgow, A. (2012). Development of guidelines for designing appliances for older persons. *Work-A Journal of Prevention Assessment & Rehabilitation*, *41*, 333–339.

Hoekstra, R., Morey, R. D., Rouder, J. N., & Wagenmakers, E. J. (2014). Robust misinterpretation of confidence intervals. *Psychonomic Bulletin & Review*, *21*, 1157–1164.

Hoffman, M. D., & Gelman, A. (2014). The no-u-turn sampler: Adaptively setting path lengths in Hamiltonian Monte Carlo. *Journal of Machine Learning Research*, *15*, 1593–1623.

Jeffreys, H. (1998). *The theory of probability*. Oxford: OUP.

Ketcham, C. J., & Stelmach, G. E. (2001). Age-related declines in motor control. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (5th Edition ed., pp. 313–348). San Diego, CA: Academic Press.

Ketcham, C. J., & Stelmach, G. E. (2004). Movement control in the older adult. In R. W. Pew & S. B. Van Hemel (Eds.), *Technology for Adaptive Aging: Workshop Report and Papers* (pp. 64–92). Washington D.C.:USA: National Academies Press.

Kluger, A., Gianutsos, J. G., Golomb, J., Feris, S. H., George, A. E., & Franssen, E, et al. (1997). Patterns of motor impairment in normal aging, mild cognitive decline, and early Alzheimer's disease. *The Journals of Gerontology: Psychological Sciences*, *52B*, P28–P39.

Kruschke, J. K. (2010a). *Doing Bayesian data analysis: A tutorial introduction with R*. Oxford: Academic Press.

Kruschke, J. K. (2010b). What to believe: Bayesian methods for data analysis. *Trends in Cognitive Sciences*, *14*, 293–300.

Kruschke, J. K. (2013). Bayesian estimation supersedes the t test. *Journal of Experimental Psychology-General*, *142*, 573–603.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1996). Upright standing and gait: Are there changes in attentional requirements related to normal aging? *Experimental Aging Research*, *22*, 185–198.

Lezak, M. D. (1995). *Neuropsychological assessment* (3rd ed.). New York: Oxford University Press.

Lindstrom-Hazel, D. K., & Veenstra, N. V. (2015). Examining the Purdue Pegboard Test for occupational therapy practice. *The Open Journal of Occupational Therapy*, *3*, 1–13.

Love, J., Selker, R., Marsman, M., Jamil, T., Dropmann, D., Verhagen, A. J. et al. (2015). JASP (Version 0.75) [Computer software].

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163–203.

Martin, J. A., Ramsay, J., Hughes, C., Peters, D. M., & Edwards, M. G. (2015). Age and Grip Strength Predict Hand Dexterity in Adults. *Plos One*, *10*, e0117598.

Metter, E. J., Conwit, R., Metter, B., Pacheco, T., & Tobin, J. (1998). The relationship of peripheral motor nerve conduction velocity to age-associated loss of grip strength. *Aging-Clinical and Experimental Research*, *10*, 471–478.

Morey, R., Hoekstra, R., Rouder, J., Lee, M., & Wagenmakers, E. J. (2015). The fallacy of placing confidence in confidence intervals. *Psychonomic Bulletin & Review*, 1–21.

Morey, R. D. & Rouder, J. N. (2015). BayesFactor: Computation of Bayes Factors for common designs. R package version 0.9.12-2. https://cran.r-project.org/web/packages/BayesFactor/index.html [On-line]

Piau, A., Campo, E., Rumeau, P., Vellas, B., & Nourhashemi, F. (2014). Aging society and gerontechnology: A solution for an independent living? *Journal of Nutrition Health & Aging*, *18*, 97–112.

R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [Computer software].

Ranganathan, V. K., Siemionow, V., Sahgal, V., & Yue, G. H. (2001). Effects of aging on hand function. *Journal of the American Geriatrics Society*, *49*, 1478–1484.

Reitan, R. M., & Wolfson, D. (1993). *The Halstead- Reitan Neuropsychological Test Battery: theory and clinical interpretation*. Tucson, AZ: Neuropsychology Press.

Reuter-Lorenz, P. A., & Park, D. C. (2010). Human neuroscience and the aging mind: A new look at old problems. *Journals of Gerontology Series B-Psychological Sciences and Social Sciences*, *65*, 405–415.

Rodriguez-Aranda, C. (2003). Reduced writing and reading speed and age-related changes in verbal fluency tasks. *Clinical Neuropsychologist*, *17*, 203–215.

Scherder, E., Dekker, W., & Eggermont, L. (2008). Higher-level hand motor function in aging and (preclinical) dementia: Its relationship with (instrumental) activities of daily life - A mini-review. *Gerontology*, *54*, 333–341.

Scuteri, A., Palmieri, L., Lo Noce, C., & Giampaoli, S. (2005). Age-related changes in cognitive domains. A population-based study. *Aging Clinical and Experimental Research*, *17*, 367–373.

Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: Translating research into clinical practice* (3rd ed.). Philadelphia, PA: Lippincott, Williams & Wilkins.

Spector, W. D., & Fleishman, J. A. (1998). Combining activities of daily living with instrumental activities of daily living to measure functional disability. *Journals of Gerontology Series B-Psychological Sciences and Social Sciences*, *53*, S46–S57.

Strauss, E., Sherman, A. M., & Spreen, O. (2006). *A compendium of neuropsychological tests*. New York: Oxford university Press.

Strenge, H., Niederberger, U., & Seelhorst, U. (2002). Correlation between tests of attention and performance on grooved and purdue pegboards in normal subjects. *Perceptual and Motor Skills*, *95*, 507–514.

Tiffin, J. (1968). *Purdue Pegboard: Examiner manual*. Chicago: Science Research Associates.

Tombaugh, T. N. (2004). Trail Making Test A and B: Normative data stratified by age and education. *Archives of Clinical Neuropsychology*, *19*, 203–214.

Wagenmakers, E. J., Lodewyckx, T., Kuriyal, H., & Grasman, R. (2010). Bayesian hypothesis testing for psychologists: A tutorial on the Savage-Dickey method. *Cognitive Psychology*, *60*, 158–189.

Wechsler, D. (1981). *Manual for the Wechsler Adult intelligence Scale-Revised*. New York: Psychological Corporation.

Wetzels, R., Matzke, D., Lee, M. D., Rouder, J. N., Iverson, G. J., & Wagenmakers, E. J. (2011). Statistical evidence in experimental psychology: An empirical comparison using 855 t tests. *Perspectives on Psychological Science*, *6*, 291–298.

Willems, R. M., Van der Haegen, L., Fisher, S. E., & Francks, C. (2014). On the other hand: including left-handers in cognitive neuroscience and neurogenetics. *Nature Reviews Neuroscience*, *15*, 193–201.

Williams, M. E., Hadler, N. M., & Earp, J. A. L. (1982). Manual ability as a marker of dependency in geriatric women. *Journal of Chronic Diseases*, *35*, 115–122.

Wingfield, A., Stine, E. A. L., Lahar, C. J., & Aberdeen, J. S. (1988). Does the capacity of working memory change with age? *Experimental Aging Research*, *14*, 103–107.

Woodruff-Pak, D. S. (2004). *The neuropsychology of aging*. Oxford: Blackwell.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait & Posture*, *16*, 1–14.

Yancosek, K. E., & Howell, D. (2009). A narrative review of dexterity assessments. *Journal of Hand Therapy*, *22*, 258–269.

Author Biographies

Claudia Rodríguez-Aranda is Associate Professor in life-span developmental psychology at the department of Psychology at the University of Tromsø, Norway. She teaches courses in geropsychology, neuropsychology of aging and life-span developmental psychology. Her research interests include biological aspects related to normal cognitive aging and Alzheimer's disease; age-related slowing; attention and psychomotor functions in aging as well as association between cognitive decline and motor decline in normal aging and dementia.

Matthias Mittner holds a position as an Associate Professor of cognitive neuroscience at the department of Psychology, University of Tromsø, Norway. His research interests include model-based neuroscience, mind wandering, non-invasive brain stimulation and Bayesian data analysis.

Olena Vasylenko is a Ph.D. student in Psychology at the University of Tromsø. Her research topics are age-related differences in cognitive abilities and hand motor control.

Paper II

Vasylenko, O., Gorecka, M.M. & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 1. Age- and gender-related differences in unimanual and bimanual performance. *Developmental Psychobiology, 60*(4), 407-427

Received: 29 September 2017 | Accepted: 13 January 2018
DOI: 10.1002/dev.21619

RESEARCH ARTICLE

WILEY Developmental Psychobiology

Manual dexterity in young and healthy older adults. 1. Age- and gender-related differences in unimanual and bimanual performance

Olena Vasylenko[1] | **Marta M. Gorecka**[1,2] | **Claudia Rodríguez-Aranda**[1]

[1] Department of Psychology, University of Tromsø, Tromsø, Norway

[2] Department of Neurology, University Hospital of Northern Norway, Tromsø, Norway

Correspondence
Olena Vasylenko, Department of Psychology, Faculty of Health Sciences, University of Tromsø, Tromsø N-9037, Norway.
Email: olena.vasylenko@uit.no

Abstract

This study aimed to better characterize age-related differences in dexterity by using an integrative approach where movement times and kinematics were measured for both hands. Forty-five young (age 19–31) and 55 healthy older adults (age 60–88) were evaluated during unimanual and bimanual performance of the Purdue Pegboard Test. Gender effects were also assessed. From video-recorded data, movement times and kinematics were obtained for reaching, grasping, transport, and inserting. Results showed that older adults had longer movement times for grasping and inserting with the right hand, and across all movements with the left hand. Kinematic differences were found in path length, linear, and angular velocity. The patterns of slowing were similar in unimanual and bimanual tasks. Gender effects showed more slowing in older males than older females. Age differences in dexterity not only comprise slowing of movements but also kinematic alterations. The importance of gender in hand function was demonstrated.

KEYWORDS

aging, bimanual, gender, kinematics, manual dexterity, unimanual

1 | INTRODUCTION

Aging is associated with declines in cognitive and sensorimotor abilities. Whereas cognitive changes have been studied extensively, changes in motor performance have received less attention (Seidler et al., 2010). For instance, age-related decline in manual dexterity is a particularly important issue to address because most daily activities require efficient use of the hands. The most complete definition of manual dexterity has been formulated by Poirier (1987): "... a manual skill that requires rapid coordination of gross and fine voluntary movements based on a certain number of capacities, which are developed through learning, training, and experience." (pp. 71–72).

Age-related declines in dexterity have been observed in common daily activities such as dressing, writing, eating, and grooming (Desrosiers, Hébert, Bravo, & Rochette, 1999; Ranganathan, Siemionow, Sahgal, & Guang, 2001). These declines limit older adults' ability to live comfortably and independently, as poor hand function is a predictor of progressive impairment in instrumental activities of daily living and increased need for institutional care (Ostwald, Snowdon, Rysavy, Keenan, & Kane, 1989; Scherder, Dekker, & Eggermont, 2008). To prevent decline and prolong independent functioning in the steadily growing older population, researchers need a clear understanding of how and why dexterity declines occur with advanced age.

Evaluation of hand dexterity relies on two main approaches: the first one focuses on time measurements during performance of a task (i.e., movement time, MT). Studies using this approach have employed a variety of tasks to investigate movement slowing in older adults, such as aiming for targets or drawing lines with a hand-held stylus to connect targets on a digitizing tablet (Bellgrove, Phillips, Bradshaw, & Galucci, 1998; Yan, Thomas, & Stelmach, 1998). Manipulation of various objects has also been investigated. For example,

© 2018 Wiley Periodicals, Inc.

Smith et al. (1999) compared duration of movements involved in grasping cylinders placed on an even surface to movements involved in removing hollow cylinders placed on straight or curved rods. Object manipulation in daily activities has also been studied, such as picking up coins, writing, and tying a scarf (Desrosiers, Hébert, Bravo, & Dutil, 1995b). Finally, some studies have utilized standardized dexterity tests, such as the Purdue Pegboard Test, which involves manipulation of small pegs (Desrosiers, Hébert, Bravo, & Dutil, 1995a; Serbruyns et al., 2013). Depending on the type and complexity of the task, older adults show 10–70% longer MTs compared to younger adults (Ketcham & Stelmach, 2001). For example, Bellgrove et al. (1998) found about 15% slowing in older adults on a line-drawing task, whereas Smith et al. (1999) demonstrated almost 50% slower performance in older adults on a task that required removing hollow cylinders placed on a curved rod. Tasks that involve peg manipulation, such as the one employed in the present study, typically show that older adults manipulate about 20% fewer pegs than younger (e.g., Serbruyns et al., 2013).

Although MT gives a useful measure of overall performance, it does not provide detailed information about how dexterity changes with age. Accordingly, a second approach focuses on the measurement of kinematics of dexterity, including assessment of velocity, trajectory, and position of the hand. The advantage of kinematic analyses over MT measurements is their capacity to identify specific components of hand movement that decline with increasing age. Kinematic analyses have been conducted for specific actions, such as reaching, grasping, aiming, and line drawing (Bellgrove et al., 1998; Cooke, Brown, & Cunningham, 1989; Mergl et al., 1999; Morgan et al., 1994; Ketcham, Seidler, vanGemmert, & Stelmach, 2002). The main findings show that older adults present lower and more variable velocities as compared to younger adults, they spend more time in the deceleration phase of movement, and make more corrective submovements (Bellgrove et al., 1998; Cooke et al., 1989; Mergl et al., 1999; Morgan et al., 1994; Ketcham et al., 2002; Ketcham & Stelmach, 2001). Kinematic analyses have also shown that when older adults reach for a target, they have less accurate movements, as reflected by longer, more curved hand paths (daSilva & Bagesteiro, 2016; Wolpert & Ghahramani, 2000). As for grasping, it has been demonstrated that older adults use larger apertures (Grabowski & Mason, 2014; Cicerale, Ambron, Lingnau, & Rumiati, 2014), and their precision grasp patterns are less stable (Wong & Whishaw, 2004) and spatially misaligned (Parikh & Cole, 2012). Thus, the evaluation of kinematics has significantly contributed to better understanding the reasons behind age-related decline in dexterity.

The two approaches for measuring hand function (i.e., MTs and kinematics) are complementary as they together show that movements of older adults are not only slower, but also qualitatively different from those of younger adults. Therefore, it is beneficial to combine both approaches to thoroughly characterize possible age-related declines in hand function associated with daily activities. To date, very few studies have integrated detailed evaluations of MTs and kinematics for daily tasks. In a recent pilot study by our group (Rodríguez-Aranda, Mittner, & Vasylenko, 2016), dexterity was evaluated in healthy young and older adults by measuring both MTs and kinematics of reaching, grasping, transport, and inserting of pins in the unimanual Purdue Pegboard task. Results showed longer MTs and greater movement variability in the older group during grasping and inserting, but not during reaching and transport. One of the limitations of that study was that only two kinematic parameters were analyzed: hand position and the speed of hand rotation. To obtain a more detailed description of hand movement, additional parameters need to be included, such as linear speed and length of trajectory. Furthermore, the pilot study had a limited sample size (15 young and 15 older adults). Therefore, the obtained findings needed to be replicated in a larger sample. Additionally, in the pilot study dexterity analysis was restricted to unimanual movements of the right hand. To provide a thorough understanding of how dexterity declines in normal aging, we considered necessary to follow up this investigation by analyzing movements of both hands, especially since most daily activities require both hands for efficient performance. At present, there are limited investigations of bimanual object manipulation relevant for real life activities. A search in the literature shows that most studies of bimanual movements have used tasks like circle tracing or finger tapping (Maes, Gooijers, de Xivry, & Swinnen, 2017), which are of little relevance for daily actions that require manipulation of objects. However, a few exceptions exist: for example, Mason and Bryden (2007) investigated bimanual reaching and grasping of cubic objects in young adults and found that synchronous bimanual movements are performed in a manner similar to unimanual movements. A few studies have also compared bimanual object manipulation in young and older adults. Examples include Bernard and Seidler (2012) and Serbruyns et al. (2013), who compared young and older adults' performance on the bimanual tasks of the Purdue Pegboard Test (Tiffin, 1968; Tiffin & Asher, 1948) for reaching, grasping, transporting, and inserting pegs under different conditions. In both studies (Bernard & Seidler, 2012; Serbruyns et al., 2013), the older groups manipulated fewer pegs than younger adults, which provides evidence of age-related deficits in bimanual object manipulation. However, neither Bernard and Seidler (2012), nor Serbruyns et al. (2013) measured kinematics, and therefore, these studies could not provide detailed information about how bimanual object manipulation changes with advanced age. At present, there are no detailed descriptions of age-related dexterity changes that include both hands in unimanual and bimanual tasks and thus, a comprehensive assessment of performance on tasks that are relevant for daily living should be conducted.

Beside the importance of deepening the understanding of age effects on manual dexterity, other demographics with possible influence on hand function need to be addressed, such as gender. Gender is a complex biopsychosocial variable that influences many aspects of behavior, cognitive function, and brain organization (Cahill, 2006; Halpern, 2011). Research on motor skills in childhood and young to middle adulthood has demonstrated a clear pattern of gender differences (Junaid & Fellowes, 2006; Moser & Reikerås, 2016; Nicholson & Kimura, 1996; Ruff & Parker, 1993). Specifically, these studies have shown that males tend to perform better on tasks that require speed, such as finger tapping, whereas females tend to outperform males on tasks that require fine manipulation, such as the Purdue Pegboard Test (Junaid & Fellowes, 2006; Nicholson & Kimura, 1996; Ruff & Parker, 1993). This pattern of gender differences is supported by the finding that males and females employ different movement strategies in manual tasks, whereby males emphasize speed of performance, whereas females emphasize accuracy (Rohr, 2006).

Although gender differences in dexterity have been documented in childhood and young to middle adulthood, few studies have examined this issue in older adulthood. One important question to address is whether the pattern of differences obtained with children and adults also persists into older adulthood. Another important issue is whether there are gender differences in manual dexterity decline in older adults. Addressing these questions is important for a detailed understanding of how manual ability declines in the course of normal aging. To date, only a few studies have assessed gender differences in dexterity in older adults, and the findings have been inconsistent. One study (Haward & Griffin, 2002) found no gender differences in middle-aged adults, while others have reported gender differences after the 6th decade (Desrosiers et al., 1995a; Lezak, Howieson, Bigler, & Tranel, 2012; Ranganathan et al., 2001). In the latter studies, more decline has been found in older males, as shown by longer time needed to manipulate pegs in the Purdue Pegboard tasks. In contrast, recent findings by Sebastjan, Skrzek, Ignasiak, and Slawinska (2017) showed more decline in older females in tapping and peg inserting tasks. Although the mechanisms by which gender might influence age-related dexterity decline are far from understood, several factors may be relevant to account for the influence of gender on dexterity decline in aging. First, gender differences in the rate of brain atrophy and the age of its onset have been documented in multiple studies (Bellis & Wilber, 2001; Cowell, Allen, Zalatimo, & Denenberg, 1992; Gur et al., 1991). Specifically, Gur et al. (1991) found more cortical thinning in older males compared to females and Cowell et al. (1992) showed that the volume of the corpus callosum started to decrease in the perimenopausal years in females, whereas for males, this decrement seemed to start much earlier, in the third decade of life. The proposed mechanism for gender differences in brain aging is the protective effect of the female hormone estrogen on glia cells and neurons in the brain (see Garcia-Segura et al. [2001] for a review), and this effect may persist even after the reduction in estrogen levels occurring in menopause (Li, Cui, & Shen, 2014).

The second biological mechanism that is relevant to explain gender differences in dexterity decline is age-related reduction in muscle mass and strength. Recent research has shown that females are more vulnerable than males to substantial loss of muscle (Cruz-Jentoft et al., 2010) and that the prevalence of frailty is higher among females (Ruan et al., 2017). Therefore, females may experience an earlier decline in hand strength and function than males. The relevance of this factor is supported by research that has shown more functional limitations in daily tasks in older females compared to males (Merrill, Seeman, Kasl, & Berkman, 1997).

Another relevant mechanism relies on the amount of experience and expertise in performance of activities that require manual dexterity. Specifically, Merritt and Fisher (2003) suggested that females spend more time performing daily activities that involve fine manipulation and therefore may have more experience and expertise in this type of tasks, which may help delay age-related decline in manual dexterity.

It is important to note that the present study did not aim to examine the mechanisms of gender differences in age-related dexterity decline. Rather, the intention of conducting a detailed analysis of gender differences was to provide a comprehensive description of dexterity declines in aging.

To summarize, the purpose of the present study was three-fold. First, we aimed to replicate the results from our pilot study on right-hand manipulation of pegs in the Purdue Pegboard task in a larger sample of young and healthy older adults. The second aim was to extend earlier findings by conducting a detailed integrative assessment of MTs and kinematics of both hands during unimanual and bimanual manipulation of pegs. The third aim was to extend the existing evidence on the role of gender in dexterity by describing gender differences in both age groups.

2 | METHOD

2.1 | Participants

Forty-five young and 55 healthy, community-dwelling older adults participated in the study. Young adults (26 female, $M_{\text{age}} = 22.8$ years, range: 19–31 years) were recruited through flyers posted at the university campus. Older adults (25 female, $M_{\text{age}} = 70.6$ years, range: 60–88 years) were recruited from the local senior citizens' center and the general community through flyers and by word of mouth. Participants were briefed about the purpose of the study and signed informed consent before the procedure. All participants underwent screening, which included a short interview to obtain demographic and health information, followed by an assessment of visual acuity by Snellen charts (Snellen, 1862), cognitive status by Mini-Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975), hand preference by the Briggs-Nebes Handedness Inventory (Briggs & Nebes, 1975), and depression by Beck Depression Inventory (BDI), 2nd edition (Beck et al., 1996). The exclusion criteria were: previous stroke, head trauma, and injuries of the hands; currently taking medication affecting the central nervous system; current hand pain; impaired visual acuity (i.e., >20/40); signs of global cognitive deterioration (i.e., MMSE scores <27 [Petersen et al., 1999]); self-report of left-handedness (i.e., scores <+9 on the Briggs–Nebes Handedness Inventory); and depression. For young adults, the conventional BDI cut-off of 13 was used (Beck et al., 1996), but in one older participant, a mild level of depression (i.e., BDI score of 17) was accepted, as the BDI includes items concerning sleep and appetite, which naturally decline in healthy aging (Rodríguez-Aranda, 2003). All tests were administered and scored according to their respective administration manuals. The study was approved by the Regional Research Ethics Committee and carried out in accordance with the Helsinki guidelines.

2.2 | Measures

2.2.1 | Health, hand function, and handedness

To assess physical and mental health status, the RAND Short Form 36 (SF-36) was administered (Hays, Sherbourne, & Mazel, 1993). Physical hand function was evaluated with the Grip Strength Test and the Finger Tapping Test from the Halstead-Reitan neuropsychological battery, 2nd edition (Reitan & Wolfson, 1993). Age-related differences in hand function are discussed in the companion article (Vasylenko, Gorecka, & Rodríguez-Aranda, 2018). To define handedness, three tests were used. First, the Briggs-Nebes Handedness Inventory was administered, which comprises self-report of preferred hand in performing 12 daily activities (Briggs & Nebes, 1975). Secondly, the Finger Tapping Test and the MTs on the unimanual subtests of the modified Purdue Pegboard Test (see the next section for administration details) were used to compare performance with the right and left hand. Laterality indices (LIs) were calculated from the number of taps and MTs for the right (R) and left hand (L) with the formula LI = (R − L)/(R + L). We adopted this approach to defining handedness as it seems to be the most appropriate and it has been applied in earlier studies (e.g., Bernard, Taylor, & Seidler, 2011; Grosskopf & Kuhtz-Buschbeck, 2006). It is important to highlight that, currently, the optimal method to calculate LI remains unsettled. Notwithstanding, the LI describes hand preference based on performance differences between hands when the same task is performed unimanually with both the right and the left hand. The LI value of 0 is commonly used to indicate equal performance with either hand, that is, no hand preference in the given task, whereas positive and negative LI values indicate better performance with the right and left hand, that is, right- and left-hand preference, respectively (Annett, 2002; Bernard et al., 2011; Grosskopf & Kuhtz-Buschbeck, 2006). This criterion applies to tasks where performance is measured by the number of units completed, such as the number of taps in the Finger Tapping Test. However, in tasks where performance is measured by the amount of time spent, such as in the modified Purdue Pegboard Test used in the present study, shorter time indicates better performance. Therefore, positive and negative LI values indicate better performance with the left and right hand, that is, left- and right hand preference, respectively. Thus, in the present study, right hand preference was operationally defined as LI > 0 for the Finger Tapping Test scores and as LI < 0 for the MTs of the Purdue Pegboard tasks.

2.2.2 | Purdue Pegboard test and movement recording

The Purdue Pegboard Test (Lafayette Instrument Model 32020) is a standardized test of manual dexterity. It consists of a 22.7 × 44.9 cm board with four cups at the upper end and two parallel columns of holes running down the middle (Figure 1).

The cups contain, from left to right, pins, washers, collars, and pins. The Purdue Pegboard Test consists of four subtests. The first two subtests are unimanual tasks, which measure dexterity of the right and left hand, respectively. In the first subtest, right-handed participants are required to pick up pins one by one from the right-hand cup and insert them into the right column of holes, starting with the hole farthest away from the participant. In the second subtest, pins picked up from the left-hand cup with the left hand are inserted into the left column of holes. The third subtest is a synchronous bimanual task that requires simultaneous use of both hands to grasp pins from their corresponding cups (i.e., right hand-right cup, left hand-left cup) and place them in their corresponding columns of holes. The fourth subtest involves alternating movements of both hands to complete assemblies of different types of pegs including pins, washers, and collars, in the right column of holes. Standard scoring of the Purdue Pegboard Test is based on the number of pegs inserted in 30 s for the first three subtests, and in 1 min for the last subtest.

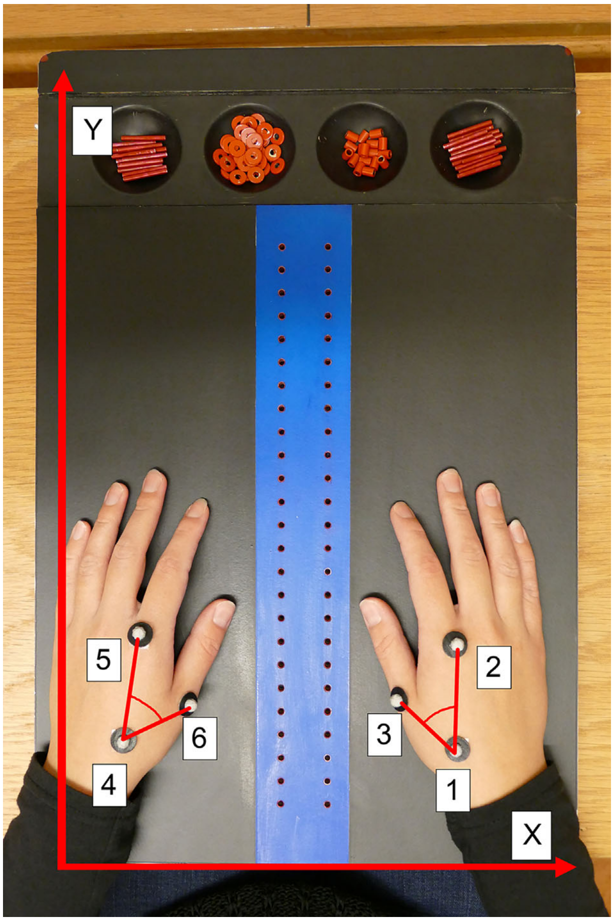


FIGURE 1 The Purdue Pegboard and marker arrangement, with angles used for kinematic analysis overlaid

For the present study, only the first three subtests were selected, because they allow to evaluate manual dexterity under different task requirements while controlling for type of object. The three subtests were administered in the specified order. To facilitate kinematic analysis, two adaptations were made to the test. First, to ensure sufficient image contrast between markers attached to the hand and the rest of the image, the pegboard was painted black and the pegs red (see Figure 1). Second, instead of inserting pins within 30 s, participants were required to insert 10 pins (pairs of pins in the third subtest) in each subtest, disregarding time employed. This modification was carried out to obtain equal amount of movement data from all participants for kinematic analysis. Ten trials were deemed sufficient as this is the average number of trials usually completed by healthy older adults in the standardized version of the Purdue Pegboard Test (Desrosiers et al., 1995a). Performance was recorded with a Vicon Motus 10.1 Motion Capture and Analysis System (Contemplas GmbH, Germany) with one camera capturing movement from a dorsal view at a sampling frequency of 50 Hz.

2.2.3 | Types of movements analyzed

An overview of tasks, temporal, and kinematic measures employed in this study is provided in Table 1.

Movement analysis was performed with Vicon Motus 10.1 Motion Capture and Analysis System in two steps. In the first step, all videos were manually subdivided into four actions: reaching for pin, grasping pin, transport of pin, and inserting pin. The onset and offset of each movement were operationally defined as follows. For reaching, onset was the first frame of movement toward the cup and offset was the frame where fingers were above the center of the cup; for grasping, onset was the first frame where fingers were lowered into the cup, and offset was the frame where the pin was just lifted out of the cup; for transport, onset was the first frame of movement toward the hole and offset was the frame where fingers just reached the hole; for inserting, onset was the first frame where pin was lowered into the hole and offset was the frame where fingers were just lifted off the pin. See Figure 2 for representative images of onset and offset points of the four movements during unimanual performance with the right hand.

Identification of onset and offset points was performed manually because the automatized Vicon Motus procedure was found to be inaccurate for this purpose. This procedure is based on a velocity criterion, but in the complex movements involved in the Purdue Pegboard tasks several velocity peaks often occur during a single action. After manual identification, onset and offset frames for each movement were manually entered into the Vicon Motus analysis software and the second step of analysis employed automatized algorithms to compute MTs and kinematics based on these intervals.

2.2.4 | Movement times

MTs for each of the actions were obtained for each trial of each task, computed as the time difference between the onset and offset of each movement. For the bimanual task, two sets of MTs were computed, one for each hand. Before entering statistical analysis, MTs for each type of movement were averaged across the 10 trials, thus providing, for each task and hand, mean MTs for reaching, grasping, transport, and inserting. To evaluate the reliability of MT measurement, intra-rater reliabilities were computed for each movement type, based on a random selection of 20% from each age group ($n_{young} = 9$, $n_{older} = 11$). The intraclass correlations coefficients (ICCs) were: for reaching, ICC = 0.91, 95%CI (0.89, 0.93); for grasping, ICC = 0.97, 95%CI (0.96, 0.98); for transport, ICC = 0.92, 95%CI (0.90, 0.94); for inserting, ICC = 0.96, 95%CI (0.95, 0.97). Thus, the MT measures had a high degree of consistency (Rankin & Stokes, 1998).

2.2.5 | Kinematic measures

The Vicon Motus 10.1 2D Motion Capture and Analysis system was used to perform kinematic analyses. To obtain kinematic data, three round reflective markers, 6 mm in diameter, were placed on each hand during dexterity tests (see Figure 1 for marker arrangement). After

TABLE 1 Overview of types of movement analyzed and measures for each movement

Purdue Pegboard subtasks	Types of movement analyzed for each task (and each hand of bimanual task)	Analyses for each movement	Measures (averaged across 10 trials)
a) Inserting pins unimanually	1. Reaching	a) Time to execute movement	- Movement time
1. With right hand (10 trials)	2. Grasping		- Linear velocity
2. With left hand (10 trials)	3. Transport		- CV of linear velocity
b) Inserting pins bimanually	4. Inserting		- Path length
3. With both hands simultaneously (10 trials)		b) Kinematic parameters	- Angular velocity
			- CV of angular velocity
			- Angle
			- CV of angle

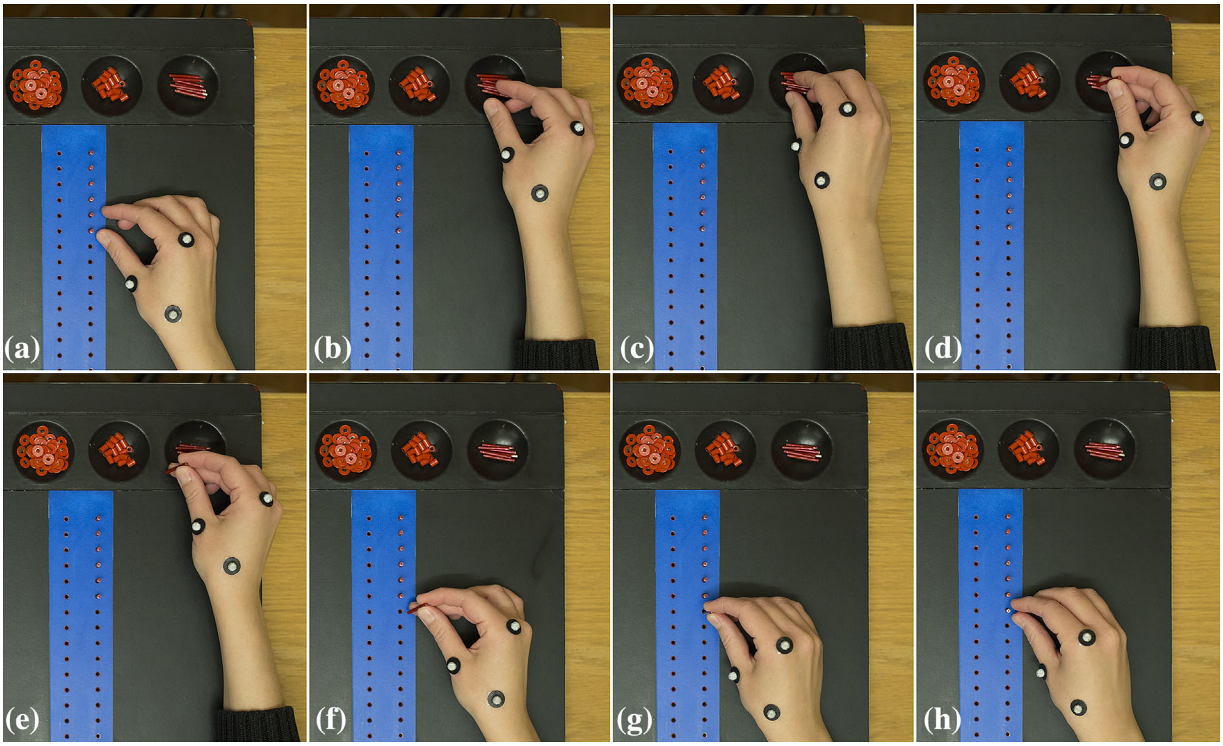


FIGURE 2 Onset and offset points for the different movement types during unimanual performance with right hand. (a) Reaching onset. (b) Reaching offset. (c) Grasping onset. (d) Grasping offset. (e) Transport onset. (f) Transport offset. (g) Inserting onset. (h) Inserting offset

recording, 2D coordinates were obtained for each marker through tracking. Raw coordinates of each marker were filtered with a low-pass Butterworth filter at the frequency of 7 Hz. Based on the manually defined onset and offset points, seven kinematic measures were computed from filtered coordinates for each movement (i.e., reaching, grasping, transport, and inserting). For the bimanual task, two sets of kinematic measures were computed, one for each hand. The kinematic measures were linear velocity, path length, angle, angular velocity, and coefficients of variation (CVs) in linear velocity, angle, and angular velocity. Marker numbers and the angles used for analysis are presented in Figure 1. Linear velocity for the right hand was computed from coordinates of marker 1, and for the left hand from marker 4. Higher linear velocity represents faster hand movement. Path length was also computed from coordinates of markers 1 and 4 for the right and left hand, respectively. This parameter gave information about the distance covered by the hand during each movement and thus served as an estimate of movement extent. Shorter paths represent more accurate movements, resulting from smoother and more direct trajectories to the target (Wolpert & Ghahramani, 2000). Angles were computed between markers 2-1-3 for the right hand and 6-4-5 for the left hand, with respect to the origin. This parameter provided information about the average position of the hand. In 2D images, larger angles represent a less pronated position of the hand, in which the palm is facing slightly away from the pegboard and the fingertips are clearly visible. Angular velocity, based on the same angles, provided information about the speed of hand rotation during each movement. Higher angular velocity represents faster rotation of the hand. All within-trial CVs were computed as *SD* to *M* ratios from their respective parameters. Higher variability in velocity and angle represents more adjustments to the speed and position of the hand, respectively. Thus, higher variability might indicate more extensive use of corrective movements (Ketcham & Stelmach, 2001). After all parameters were computed, each parameter was averaged across the 10 repetitions of each of the actions reaching, grasping, transport, and inserting. The mean values were entered into statistical analyses.

2.3 | Procedure

The study took place at the Department of Psychology, University of Tromsø. After obtaining informed consent, the interview was administered, followed by the screening measures. Next, assessment of dexterity with the modified Purdue Pegboard Test was carried out. Following demonstration of each task, participants were allowed to practice until they were able to correctly insert three pins (pairs of pins in the third subtest). After practice, they were asked to perform the task as quickly and accurately as possible at the experimenter's signal. Duration of the procedure was approximately 45 min for young and 60 min for older participants.

2.4 | Statistical analyses

Group differences in demographic variables and screening measures were assessed with independent *t* tests. To analyze MTs, we conducted separate four-factor repeated-measures ANOVAs for each type of movement (reaching, grasping, transport, inserting) with Task (unimanual, bimanual) and Hand (right, left) as within-subjects factors and Age (young, older) and Gender (male, female) as between-subjects factors. Significant main effects and interactions were followed up by pairwise comparisons with Sidak correction. To analyze kinematics, separate four-factor MANOVAs with repeated measures on within-subjects factors Task (unimanual, bimanual) and Hand (right, left), and with Age (young, older) and Gender (male, female) as between-subjects factor were conducted for each type of movement (reaching, grasping, transport, inserting). The dependent variables were the seven kinematic measures. In case of a significant omnibus test, univariate ANOVAs were performed for each kinematic measure. Significance levels for the univariate ANOVAs were adjusted with Bonferroni correction, thus only results at the alpha level below 0.007 were accepted as statistically significant. Greenhouse-Geisser corrections were used when the sphericity assumption was not met. Significant main effects and interactions were followed up by pairwise comparisons with Sidak correction. All statistical analyses were performed with IBM SPSS Statistics Version 23 (IBM Corp., 2014).

3 | RESULTS

3.1 | Demographics and handedness

The groups did not differ in the number of years of education (M $[SD]_{young} = 14.41$ [1.46], M $[SD]_{older} = 13.56$ [3.44], $p = 0.102$), MMSE (M $[SD]_{young} = 29.47$ [0.81], M $[SD]_{older} = 29.44$ [0.90], $p = 0.861$), or BDI scores (M $[SD]_{young} = 5.29$ [3.09], M $[SD]_{older} = 3.87$ (3.91), $p = 0.057$). The young group had significantly higher Physical Health scores than the older (M $[SD]_{young} = 53.54$ [6.20], M $[SD]_{older} = 49.16$ [6.78], $p = 0.004$), but significantly lower Mental Health scores than the older (M $[SD]_{young} = 47.40$ [8.20], M $[SD]_{older} = 53.98$ [6.47], $p < 0.001$). These results are in accordance with previous data on healthy older populations evaluated with the SF-36 (e.g., Sartor-Glittenberg et al., 2014).

Assessment of handedness showed that all participants scored +9 or above on the Briggs-Nebes Handedness Inventory, indicating right hand preference. Additionally, the two behavioral tests of handedness confirmed that performance was significantly better with the right hand than with the left. As stated in the Methods section, right hand preference (i.e., better performance with the right hand) is indicated by positive LI values for the Finger Tapping Test and negative LI values for the MTs of the Purdue Pegboard Test. Accordingly, LI for the Finger Tapping Test was M (SD) = 0.05 (0.05) and for MTs of the Purdue Pegboard M (SD) = −0.05 (0.04). Performance differences between hands were significant for both tests. On average, the number of finger taps was significantly larger with the right hand (M [SD] = 43.58 [7.80]) than with the left (M [SD] = 40.21 [7.87], $p < 0.001$), and MT was significantly shorter with the right hand (M [SD] = 23.06 [4.89]) than with the left (M [SD] = 25.38 [5.26], $p < 0.001$). However, examination of individual LI values showed LI ≤ 0 for Finger Tapping and/or LI ≥ 0 for the Purdue Pegboard tasks in nine participants (three young and six o*lder), indicating no hand preference or left hand preference in these participants. Due to this finding, all dexterity analyses were performed twice: one with the whole sample and one after exclusion of the nine participants that showed no preference or left hand preference. The results of the two analyses did not differ significantly, therefore, results for the whole sample are reported.

3.2 | Movement times

Due to numerous significant main effects and interactions and given that the goal of the present study was to explore age- and gender-related differences, we only report analyses that showed differences between age and/or gender groups. Regarding pairwise comparisons of interactions, we only report simple effects of Age and Gender in the main text. Simple effects of Task and Hand are summarized in Appendix A and are not mentioned further in the text. This applies for both MT and kinematic results.

3.2.1 | Reaching

Mean values and *SD*s by age and gender are given in Table 2.

There was a main effect of Age, F (1, 96) = 19.54, $p < 0.001$, $\eta^2_p = 0.169$, and an Age × Gender interaction, F (1, 96) = 7.35, $p = 0.008$, $\eta^2_p = 0.071$. The age difference was significant for males only, such that older males ($M = 415.08$, $SD = 40.20$) were slower than younger males ($M = 356.95$, $SD = 40.20$), $p < 0.001$, $\eta^2_p = 0.202$. Older males were also slower than older females ($M = 390.16$, $SD = 40.20$), $p = 0.024$, $\eta^2_p = 0.052$. The Hand × Age interaction was significant, F (1, 96) = 29.74, $p < 0.001$, $\eta^2_p = 0.237$, revealing that the older group was slower than the younger, but only with the left hand (M $[SD]_{young} = 385.86$ [46.50], M $[SD]_{older} = 443.58$ [39.40], $p < 0.001$, $\eta^2_p = 0.286$). Finally, the Task × Hand × Gender interaction was significant, F (1, 96) = 16.85, $p < 0.001$, $\eta^2_p = 0.149$. Simple effects of Gender showed that males were faster than females when reaching with the right hand in the unimanual task ($p = 0.048$, $\eta^2_p = 0.040$). (See Table 2 for mean values and *SD*s by Gender).

3.2.2 | Grasping

Mean values and *SD*s by age and gender are given in Table 3.

Time spent on grasping showed significant main effects of Age, F (1, 96) = 74.33, $p < 0.001$, $\eta^2_p = 0.436$, Gender, F (1, 96) = 19.82, $p < 0.001$, $\eta^2_p = 0.171$, and an Age × Gender interaction, F (1, 96) = 12.90, $p = 0.001$, $\eta^2_p = 0.118$. Slowing was observed in the older group as compared to the younger, both for females (M $[SD]_{young} = 645.54$ [175.10], M $[SD]_{older} = 824.10$ [175.10], $p < 0.001$, $\eta^2_p = 0.121$) and for males (M $[SD]_{young} = 676.05$ [175.10], M $[SD]_{older} = 1{,}109.65$ (175.10), $p < 0.001$, $\eta^2_p = 0.426$). Additionally, older males were slower than older females, $p < 0.001$, $\eta^2_p = 0.274$. The Hand × Age interaction was also significant, F (1, 96) = 8.42, $p < 0.005$, $\eta^2_p = 0.081$. Pairwise comparisons showed that the older group was slower than the younger, both with the right (M $[SD]_{young} = 688.25$ [200.13], M $[SD]_{older} = 1{,}038.28$ [198.52], $p < 0.001$, $\eta^2_p = 0.443$) and with the left hand (M $[SD]_{young} = 633.34$ [185.02], M $[SD]_{older} = 895.47$ [183.53], $p < 0.001$, $\eta^2_p = 0.343$). Finally, the Task × Gender interaction was significant, F (1, 96) = 4.24, $p = 0.042$,

TABLE 2 Movement times and kinematics during reaching by age and gender

	Unimanual task															
	Right hand								Left hand							
	Y	O	M	F	YM	YF	OM	OF	Y	O	M	F	YM	YF	OM	OF
MT	0.29 (0.05)	0.29 (0.04)	0.29 (0.04)	0.30 (0.04)	0.28 (0.05)	0.31 (0.04)	0.30 (0.04)	0.30 (0.04)	0.38 (0.05)	0.44 (0.05)	0.42 (0.07)	0.40 (0.05)	0.37 (0.04)	0.38 (0.05)	0.45 (0.06)	0.42 (0.05)
LinV	43.6 (6.7)	44.2 (7.3)	45.3 (7.2)	42.5 (6.6)	45.7 (7.8)	42.0 (5.4)	45.1 (6.9)	43.0 (7.6)	38.2 (5.2)	35.4 (4.9)	36.6 (5.4)	36.7 (5.1)	39.2 (5.5)	37.5 (4.9)	35.0 (4.7)	35.8 (5.2)
CV linV	0.34 (0.07)	0.32 (0.07)	0.32 (0.07)	0.34 (0.07)	0.32 (0.06)	0.36 (0.07)	0.32 (0.08)	0.32 (0.06)	0.45 (0.04)	0.48 (0.07)	0.46 (0.06)	0.47 (0.06)	0.44 (0.04)	0.46 (0.04)	0.48 (0.06)	0.49 (0.05)
PL	13.6 (1.7)	13.8 (1.7)	13.7 (1.8)	13.7 (1.6)	13.4 (1.9)	13.8 (1.5)	14.0 (1.6)	13.5 (1.7)	15.2 (1.5)	15.9 (1.7)	15.9 (1.7)	15.4 (1.5)	15.3 (1.5)	15.2 (1.5)	16.3 (1.7)	15.6 (1.6)
AngV	78.2 (26.5)	73.5 (23.7)	71.9 (25.7)	79.2 (24.0)	78.7 (29.3)	77.9 (24.8)	67.5 (22.7)	80.7 (23.4)	74.9 (24.0)	62.0 (13.8)	66.5 (21.8)	69.1 (18.4)	77.2 (26.1)	73.1 (22.8)	59.7 (15.4)	64.8 (11.3)
CV angV	0.64 (0.12)	0.67 (0.13)	0.67 (0.14)	0.66 (0.12)	0.66 (0.15)	0.63 (0.11)	0.67 (0.13)	0.68 (0.12)	0.60 (0.09)	0.68 (0.11)	0.64 (0.10)	0.64 (0.12)	0.61 (0.09)	0.59 (0.09)	0.67 (0.10)	0.69 (0.12)
Angle	40.0 (9.5)	42.2 (9.7)	44.0 (9.7)	38.6 (8.8)	44.1 (8.2)	37.0 (9.4)	43.8 (10.7)	40.2 (8.1)	35.5 (9.1)	35.7 (8.3)	36.9 (7.3)	32.7 (9.5)	38.3 (8.2)	30.0 (8.1)	36.0 (6.6)	35.5 (10.2)
CV angle	0.16 (0.07)	0.14 (0.05)	0.13 (0.05)	0.16 (0.06)	0.14 (0.06)	0.17 (0.07)	0.12 (0.05)	0.15 (0.05)	0.22 (0.07)	0.19 (0.06)	0.20 (0.07)	0.22 (0.06)	0.21 (0.08)	0.23 (0.06)	0.19 (0.07)	0.19 (0.06)
	Bimanual task															
	Right hand								Left hand							
	Y	O	M	F	YM	YF	OM	OF	Y	O	M	F	YM	YF	OM	OF
MT	0.40 (0.04)	0.43 (0.07)	0.43 (0.07)	0.40 (0.05)	0.40 (0.03)	0.40 (0.05)	0.45 (0.08)	0.40 (0.05)	0.40 (0.05)	0.45 (0.05)	0.43 (0.06)	0.42 (0.06)	0.38 (0.05)	0.41 (0.05)	0.46 (0.05)	0.44 (0.06)
LinV	37.4 (5.3)	35.3 (5.2)	35.8 (5.3)	36.6 (5.4)	38.1 (5.9)	36.8 (4.8)	34.4 (4.4)	36.5 (6.0)	36.6 (5.4)	32.9 (4.8)	34.4 (5.5)	34.7 (5.3)	37.6 (5.9)	35.8 (4.9)	32.3 (4.2)	33.6 (5.5)
CV linV	0.43 (0.05)	0.40 (0.05)	0.41 (0.05)	0.42 (0.05)	0.42 (0.06)	0.44 (0.04)	0.40 (0.05)	0.40 (0.06)	0.43 (0.05)	0.43 (0.04)	0.42 (0.05)	0.43 (0.05)	0.43 (0.06)	0.43 (0.05)	0.43 (0.04)	0.43 (0.05)
PL	15.6 (1.5)	15.4 (1.6)	15.8 (1.6)	15.3 (1.5)	15.9 (1.6)	15.4 (1.4)	15.7 (1.7)	15.1 (1.6)	15.2 (1.3)	15.5 (1.7)	15.3 (1.6)	15.4 (1.6)	15.0 (1.4)	15.3 (1.3)	15.4 (1.7)	15.5 (1.8)
AngV	62.5 (21.5)	63.9 (23.0)	56.5 (22.7)	69.8 (20.0)	56.8 (23.7)	66.7 (19.0)	56.4 (22.4)	72.9 (20.7)	65.2 (22.9)	57.1 (16.9)	56.6 (21.0)	64.7 (18.5)	66.1 (26.0)	64.6 (20.8)	50.6 (14.7)	64.9 (16.2)
CV angV	0.63 (0.10)	0.69 (0.13)	0.69 (0.11)	0.63 (0.13)	0.65 (0.09)	0.61 (0.11)	0.72 (0.12)	0.66 (0.15)	0.60 (0.09)	0.67 (0.09)	0.66 (0.10)	0.62 (0.09)	0.63 (0.09)	0.57 (0.08)	0.67 (0.10)	0.67 (0.08)
Angle	40.3 (8.6)	41.0 (9.4)	43.4 (8.7)	38.2 (8.6)	44.8 (6.5)	37.1 (8.7)	42.5 (9.9)	39.3 (8.6)	36.5 (8.8)	38.1 (7.3)	39.6 (7.2)	35.3 (8.2)	41.0 (8.6)	33.2 (7.5)	38.7 (6.2)	37.3 (8.6)
CV angle	0.16 (0.07)	0.16 (0.08)	0.14 (0.08)	0.18 (0.07)	0.12 (0.05)	0.19 (0.08)	0.15 (0.09)	0.18 (0.07)	0.18 (0.08)	0.15 (0.05)	0.15 (0.05)	0.18 (0.07)	0.16 (0.06)	0.19 (0.09)	0.14 (0.05)	0.17 (0.05)

Y, young; O, older; M, males; F, females; YM, young males; YF, young females; OM, older males; OF, older females; MT, movement time (s); LinV, linear velocity (cm/s); PL, path length (cm); AngV, angular velocity (°/s); CV, coefficient of variation.

TABLE 3 Movement times and kinematics during grasping by age and gender

	Unimanual task															
	Right hand								Left hand							
	Y	0	M	F	YM	YF	OM	OF	Y	0	M	F	YM	YF	OM	OF
MT	0.69 (0.14)	1.04 (0.36)	1.01 (0.36)	0.76 (0.24)	0.71 (0.11)	0.67 (0.16)	1.21 (0.33)	0.84 (0.28)	0.60 (0.12)	0.86 (0.30)	0.85 (0.29)	0.63 (0.20)	0.64 (0.11)	0.56 (0.13)	0.99 (0.28)	0.70 (0.24)
LinV	8.8 (1.9)	8.4 (1.6)	9.0 (1.9)	8.2 (1.4)	9.9 (2.0)	8.0 (1.5)	8.5 (1.7)	8.4 (1.4)	6.5 (1.3)	6.5 (1.2)	6.6 (1.2)	6.4 (1.1)	6.8 (1.4)	6.3 (0.9)	6.5 (1.1)	6.5 (1.3)
CV linV	0.66 (0.10)	0.66 (0.08)	0.66 (0.09)	0.66 (0.08)	0.66 (0.11)	0.66 (0.09)	0.67 (0.07)	0.65 (0.08)	0.58 (0.07)	0.053 (0.07)	0.54 (0.07)	0.57 (0.07)	0.57 (0.06)	0.59 (0.07)	0.53 (0.08)	0.54 (0.06)
PL	5.5 (1.5)	8.1 (2.7)	8.2 (2.8)	5.7 (1.8)	6.3 (1.3)	4.9 (1.4)	9.4 (2.8)	6.6 (1.8)	3.7 (1.0)	5.4 (2.0)	5.4 (2.0)	3.8 (1.3)	4.2 (1.1)	3.3 (0.8)	6.2 (2.0)	4.3 (1.5)
AngV	77.6 (39.7)	58.8 (23.5)	61.0 (23.9)	73.5 (39.4)	69.9 (28.7)	83.2 (45.8)	55.4 (18.6)	63.0 (28.4)	51.1 (19.0)	39.5 (12.0)	43.7 (16.7)	45.7 (16.4)	53.8 (18.6)	49.2 (19.3)	37.4 (11.7)	42.0 (11.8)
CV angV	0.74 (0.13)	0.77 (0.09)	0.77 (0.09)	0.75 (0.13)	0.77 (0.08)	0.72 (0.15)	0.77 (0.10)	0.79 (0.09)	0.71 (0.09)	0.74 (0.08)	0.74 (0.09)	0.71 (0.08)	0.70 (0.10)	0.72 (0.09)	0.77 (0.08)	0.70 (0.05)
Angle	30.6 (13.4)	38.6 (14.0)	40.0 (14.7)	30.1 (12.1)	36.1 (10.7)	26.5 (13.9)	42.3 (16.5)	34.0 (8.3)	22.0 (9.4)	31.7 (10.9)	29.3 (11.2)	25.4 (11.2)	26.2 (10.5)	19.0 (7.3)	31.2 (11.3)	32.3 (10.7)
CV angle	0.28 (0.15)	0.24 (0.13)	0.24 (0.12)	0.29 (0.16)	0.24 (0.12)	0.31 (0.17)	0.23 (0.12)	0.26 (0.14)	0.28 (0.14)	0.20 (0.09)	0.23 (0.13)	0.24 (0.12)	0.27 (0.15)	0.21 (0.11)	0.21 (0.11)	0.19 (0.07)
	Bimanual task															
	Right hand								Left hand							
	Y	0	M	F	YM	YF	OM	OF	Y	0	M	F	YM	YF	OM	OF
MT	0.69 (0.15)	1.06 (0.26)	0.98 (0.31)	0.81 (0.23)	0.69 (0.16)	0.69 (0.16)	1.16 (0.24)	0.94 (0.23)	0.66 (0.15)	0.96 (0.26)	0.92 (0.29)	0.73 (0.19)	0.67 (0.13)	0.66 (0.16)	1.08 (0.25)	0.81 (0.20)
LinV	6.1 (1.3)	5.7 (1.2)	6.1 (1.3)	5.6 (1.2)	6.9 (1.3)	5.5 (1.0)	5.7 (1.0)	5.7 (1.3)	6.2 (1.2)	5.6 (1.0)	6.0 (1.2)	5.8 (1.1)	6.7 (1.2)	6.0 (1.0)	5.6 (1.0)	5.6 (1.1)
CV linV	0.61 (0.07)	0.61 (0.09)	0.60 (0.08)	0.61 (0.08)	0.60 (0.06)	0.61 (0.07)	0.60 (0.09)	0.62 (0.10)	0.58 (0.06)	0.56 (0.07)	0.56 (0.06)	0.58 (0.07)	0.57 (0.07)	0.59 (0.05)	0.55 (0.06)	0.56 (0.08)
PL	3.9 (1.2)	5.8 (1.8)	5.7 (2.0)	4.3 (1.2)	4.5 (1.3)	3.5 (1.0)	6.4 (2.0)	5.0 (1.1)	3.9 (1.0)	5.1 (1.6)	5.1 (1.6)	4.0 (1.1)	4.2 (1.1)	3.6 (0.8)	5.7 (1.6)	4.4 (1.3)
AngV	51.8 (20.4)	40.2 (15.4)	42.3 (16.3)	48.6 (20.5)	42.2 (19.1)	53.6 (21.2)	38.0 (12.8)	43.1 (18.1)	49.3 (17.7)	31.3 (11.6)	34.6 (13.6)	44.2 (19.0)	46.6 (11.9)	51.2 (20.9)	27.0 (8.1)	36.6 (13.1)
CV angV	0.73 (0.08)	0.75 (0.09)	0.74 (0.07)	0.74 (0.10)	0.74 (0.06)	0.72 (0.10)	0.74 (0.07)	0.75 (0.10)	0.73 (0.10)	0.75 (0.07)	0.76 (0.07)	0.73 (0.10)	0.73 (0.08)	0.73 (0.12)	0.77 (0.06)	0.73 (0.08)
Angle	31.1 (12.7)	36.0 (14.8)	38.0 (14.2)	29.6 (12.6)	37.4 (10.2)	26.5 (12.5)	38.3 (16.4)	33.0 (12.1)	25.1 (10.7)	32.7 (9.4)	31.7 (9.7)	27.0 (11.2)	30.0 (11.2)	21.5 (9.0)	32.7 (8.7)	32.8 (10.5)
CV angle	0.24 (0.16)	0.22 (0.12)	0.20 (0.11)	0.26 (0.16)	0.18 (0.09)	0.28 (0.18)	0.21 (0.12)	0.23 (0.13)	0.28 (0.14)	0.17 (0.08)	0.19 (0.10)	0.24 (0.12)	0.24 (0.12)	0.30 (0.15)	0.16 (0.07)	0.18 (0.10)

Y, young; O, older; M, males; F, females; YM, young males; YF, young females; OM, older males; OF, older females; MT, movement time (s); LinV, linear velocity (cm/s); PL, path length (cm); AngV, angular velocity (°/s); CV, coefficient of variation.

$\eta^2_p = 0.042$. Simple effects of Gender showed that males were slower than females in both unimanual ($M\ [SD]_{male} = 885.41\ [203.85]$, $p < 0.001$, $\eta^2_p = 0.189$) and bimanual grasping ($M\ [SD]_{male} = 900.30\ [189.46]$, $p = 0.001$, $\eta^2_p = 0.105$).

3.2.3 | Transport

Mean values and SDs by age and gender are given in Table 4.

For transport times, there was a significant main effect of Age, $F\,(1, 96) = 23.34$, $p < 0.001$, $\eta^2_p = 0.196$, and an Age × Gender interaction, $F\,(1, 96) = 8.72$, $p = 0.004$, $\eta^2_p = 0.083$, which showed that older males were slower than younger males ($M\ [SD]_{young} = 384.66\ [55.53]$), $M\ [SD]_{older} = 472.28\ [55.52]$, $p < 0.001$, $\eta^2_p = 0.232$). Older males were also slower than older females ($M\ [SD]_{female} = 425.72\ [55.53]$, $p = 0.003$, $\eta^2_p = 0.091$). Moreover, the Hand × Age interaction was significant, $F\,(1, 96) = 37.32$, $p < 0.001$, $\eta^2_p = 0.280$, as well as the Task × Hand × Age interaction, $F\,(1, 96) = 6.25$, $p = 0.014$. Pairwise comparisons of the three-way interaction showed that older adults were slower than younger in both tasks, but only with the left hand (both ps < 0.001, $\eta^2_p = 0.383$, and $\eta^2_p = 0.149$ for the unimanual and bimanual task, respectively).

3.2.4 | Inserting

Mean values and SDs by age and gender are given in Table 5.

For inserting time, there was a main effect of Age, $F\,(1, 96) = 33.40$, $p < 0.001$, $\eta^2_p = 0.258$, and three interactions involving Age were significant, Task × Age, $F\,(1, 96) = 5.22$, $p = 0.025$, $\eta^2_p = 0.052$, Hand × Age, $F\,(1, 96) = 5.37$, $p = 0.023$, $\eta^2_p = 0.053$, and Task × Hand × Age, $F\,(1, 96) = 4.51$, $p = 0.036$, $\eta^2_p = 0.045$. The Task × Hand × Age interaction was further explored by pairwise comparisons, showing that older adults were slower than young across both hands and conditions (all ps < 0.01, $\eta^2_p = 0.235$, and $\eta^2_p = 0.117$ for the right and left hand, respectively, in the unimanual task; $\eta^2_p = 0.211$ and $\eta^2_p = 0.215$ for the right and left hand, respectively, in the bimanual task). A Task × Hand × Gender interaction was also significant, $F\,(1, 96) = 4.31$, $p = 0.041$, $\eta^2_p = 0.043$. Simple effect of Gender was only found in the unimanual task with the right hand, with females inserting faster than males, $p < 0.05$, $\eta^2_p = 0.066$.

Overall, MT results revealed slowing in all movements of older adults when performed with the left hand, but for the right hand, only grasping and inserting were slower. However, older males were slower than younger males during reaching with the right hand as well. Overall, males showed more age-related slowing than females in all movements except inserting.

3.3 | Kinematic results

Multivariate effects for kinematics of all four movement types are summarized in Appendix B and are not mentioned further in the text.

3.3.1 | Reaching

See Table 2 for mean values and *SD*s of reaching kinematics by age and gender.

Main effects of age and gender

A main effect of Age was found for CV of angular velocity, $F\,(1, 96) = 17.37$, $p < 0.001$, $\eta^2_p = 0.153$, showing higher variability in the older group ($M\ [SD] = 0.68\ [0.07]$) than the younger ($M\ [SD] = 0.62\ [0.07]$). Significant main effects of Gender were found for angle, $F\,(1, 96) = 12.38$, $p = 0.001$, $\eta^2_p = 0.114$, and CV of angle, $F\,(1, 96) = 9.71$, $p = 0.002$, $\eta^2_p = 0.092$. These effects showed that males had larger angles ($M\ [SD] = 41.15\ [7.14]$) than females ($M\ [SD] = 36.21\ [6.93]$) and that females had higher variability of angles ($M\ [SD] = 0.19\ [0.05]$) than males ($M\ [SD] = 0.15\ [0.05]$).

Two-way interaction

A Hand × Age interaction was significant for linear velocity, $F\,(1, 96) = 11.14$, $p < 0.001$, $\eta^2_p = 0.104$. Pairwise comparisons revealed that the older group was slower than the young, but only with the left hand, ($M\ [SD]_{young} = 37.52\ [4.78]$, $M\ [SD]_{older} = 34.19\ [4.74]$, $p < 0.001$, $\eta^2_p = 0.112$).

Three-way interaction

A Task × Hand × Gender interaction was significant for linear velocity, $F\,(1, 96) = 7.97$, $p = 0.006$, $\eta^2_p = 0.077$, and path length, $F\,(1, 96) = 8.82$, $p = 0.004$, $\eta^2_p = 0.084$. Males had higher linear velocity than females when reaching with the right hand in the unimanual task ($p = 0.045$, $\eta^2_p = 0.041$). Gender differences for path length did not reach significance.

Overall, these results indicate that reaching movements are slower and less stable when performed with the left hand, and this difference is more pronounced with advanced age. Moreover, males and females seem to use different hand positions during reaching (i.e., males have larger angles, which means they use a less pronated position in which the fingertips face slightly away from the pegboard), and males do not vary their hand position as much as females.

3.3.2 | Grasping

See Table 3 for mean values and *SD*s of grasping kinematics by age and gender.

Main effects of age and gender

Main effects of Age were significant for angular velocity, $F\,(1, 96) = 18.97$, $p < 0.001$, $\eta^2_p = 0.166$, path length, $F\,(1, 96) = 48.70$, $p < 0.001$, $\eta^2_p = 0.339$, angle, $F\,(1, 96) = 12.85$, $p = 0.001$, $\eta^2_p = 0.119$, and CV of angle, $F\,(1, 96) = 7.90$, $p = 0.006$, $\eta^2_p = 0.077$. The older group rotated their hands more slowly than the younger ($M\ [SD]_{young} = 57.09\ [16.10]$, $M\ [SD]_{older} = 42.81\ [15.57]$) and had longer paths ($M\ [SD]_{young} = 4.31\ [1.21]$, $M\ [SD]_{older} = 6.01\ [1.23]$). Moreover, older adults had larger angles ($M\ [SD]_{young} = 27.92\ [8.72]$, $M\ [SD]_{older} = 34.57\ [9.27]$) and lower variability of angles ($M\ [SD]_{young} = 0.27\ [0.10]$, $M\ [SD]_{older} = 0.21\ [0.10]$). Significant main effects of Gender were found for path length, $F\,(1, 96) = 32.03$, $p < 0.001$, $\eta^2_p = 0.252$, and angle, $F\,(1, 96) = 10.83$, $p = 0.001$, $\eta^2_p = 0.102$, showing that males had longer paths ($M\ [SD]_{female} = 4.47\ [1.20]$, $M\ [SD]_{male} = 5.85\ [1.23]$), and larger angles than females ($M\ [SD]_{female} = 28.19\ [9.21]$, $M\ [SD]_{male} = 34.30\ [9.10]$). Also, a significant main

TABLE 4 Movement times and kinematics during transport by age and gender

	Unimanual task															
	Right hand								Left hand							
	Y	0	M	F	YM	YF	OM	OF	Y	O	M	F	YM	YF	OM	OF
MT	0.30 (0.04)	0.31 (0.05)	0.31 (0.04)	0.30 (0.05)	0.29 (0.04)	0.31 (0.04)	0.32 (0.04)	0.29 (0.06)	0.37 (0.06)	0.47 (0.08)	0.45 (0.09)	0.40 (0.08)	0.37 (0.05)	0.36 (0.06)	0.50 (0.08)	0.45 (0.07)
LinV	36.1 (5.5)	34.7 (6.1)	35.1 (5.1)	35.6 (6.6)	36.6 (5.7)	35.8 (5.4)	34.2 (4.5)	35.4 (7.7)	32.4 (4.6)	27.1 (4.0)	28.8 (4.9)	30.2 (5.0)	32.7 (4.5)	32.2 (4.7)	26.2 (3.2)	28.2 (4.6)
CV linV	0.35 (0.07)	0.29 (0.07)	0.31 (0.09)	0.31 (0.06)	0.34 (0.09)	0.35 (0.06)	0.29 (0.08)	0.29 (0.06)	0.40 (0.05)	0.44 (0.05)	0.42 (0.06)	0.43 (0.05)	0.39 (0.05)	0.41 (0.05)	0.44 (0.05)	0.45 (0.04)
PL	11.3 (1.5)	10.7 (1.4)	11.0 (1.4)	10.9 (1.5)	11.2 (1.8)	11.4 (1.2)	11.0 (1.1)	10.5 (1.6)	12.2 (1.4)	12.9 (1.6)	12.9 (1.6)	12.3 (1.5)	12.5 (1.1)	11.9 (1.5)	13.2 (1.8)	12.7 (1.5)
AngV	77.3 (26.5)	63.6 (21.9)	62.2 (22.1)	77.0 (25.5)	68.2 (23.0)	83.9 (27.3)	58.4 (21.0)	69.9 (21.8)	67.1 (20.0)	50.2 (15.4)	57.3 (20.5)	58.3 (18.6)	66.5 (19.9)	67.5 (20.4)	51.5 (19.0)	48.6 (9.8)
CV angV	0.80 (0.10)	0.76 (0.11)	0.74 (0.09)	0.82 (0.11)	0.77 (0.09)	0.83 (0.10)	0.72 (0.08)	0.80 (0.12)	0.85 (0.11)	0.82 (0.10)	0.83 (0.10)	0.84 (0.12)	0.84 (0.10)	0.86 (0.12)	0.82 (0.09)	0.81 (0.12)
Angle	53.2 (11.0)	56.8 (8.3)	57.7 (10.2)	52.7 (8.6)	57.2 (11.6)	50.2 (9.6)	58.0 (9.4)	55.3 (6.5)	44.2 (8.8)	47.4 (7.6)	48.7 (6.5)	43.4 (9.0)	48.8 (7.5)	40.8 (8.2)	48.6 (5.8)	46.1 (9.2)
CV angle	0.13 (0.07)	0.10 (0.04)	0.09 (0.04)	0.13 (0.06)	0.10 (0.05)	0.15 (0.07)	0.09 (0.04)	0.10 (0.03)	0.17 (0.07)	0.14 (0.06)	0.15 (0.06)	0.17 (0.07)	0.15 (0.07)	0.19 (0.07)	0.14 (0.06)	0.14 (0.06)
	Bimanual task															
	Right hand								Left hand							
	Y	0	M	F	YM	YF	OM	OF	Y	O	M	F	YM	YF	OM	OF
MT	0.44 (0.07)	0.47 (0.09)	0.46 (0.09)	0.44 (0.08)	0.42 (0.06)	0.45 (0.07)	0.49 (0.09)	0.44 (0.08)	0.48 (0.06)	0.56 (0.12)	0.54 (0.12)	0.51 (0.09)	0.46 (0.05)	0.49 (0.07)	0.59 (0.13)	0.53 (0.10)
LinV	27.8 (5.2)	25.5 (4.7)	26.7 (5.4)	26.4 (9.7)	29.5 (4.7)	26.6 (4.6)	25.0 (4.7)	26.1 (4.8)	26.4 (4.7)	22.5 (4.4)	23.8 (5.3)	24.7 (4.6)	27.5 (4.7)	25.7 (4.6)	21.4 (4.2)	23.7 (4.4)
CV linV	0.39 (0.04)	0.40 (0.04)	0.39 (0.04)	0.39 (0.04)	0.37 (0.04)	0.40 (0.04)	0.40 (0.04)	0.39 (0.04)	0.44 (0.05)	0.42 (0.05)	0.44 (0.05)	0.43 (0.05)	0.45 (0.06)	0.44 (0.04)	0.43 (0.05)	0.41 (0.06)
PL	12.1 (1.9)	11.7 (1.4)	12.2 (1.5)	11.6 (1.8)	12.2 (1.7)	12.1 (2.1)	12.1 (1.5)	11.2 (1.1)	12.4 (1.7)	11.9 (1.5)	12.0 (1.6)	12.2 (1.6)	12.5 (1.6)	12.4 (1.9)	11.7 (1.5)	12.1 (1.4)
AngV	59.8 (18.8)	53.8 (18.7)	52.5 (18.5)	60.4 (18.6)	57.2 (19.0)	61.7 (18.8)	49.5 (17.8)	59.0 (18.8)	49.3 (16.8)	41.3 (14.9)	45.1 (17.6)	44.8 (14.9)	50.7 (18.5)	48.2 (15.8)	41.5 (16.4)	41.1 (13.3)
CV angV	0.81 (0.09)	0.77 (0.10)	0.77 (0.09)	0.81 (0.10)	0.78 (0.08)	0.83 (0.09)	0.76 (0.09)	0.79 (0.10)	0.96 (0.14)	0.83 (0.10)	0.86 (0.11)	0.92 (0.15)	0.94 (0.11)	0.97 (0.15)	0.81 (0.08)	0.86 (0.12)
Angle	55.4 (8.1)	56.7 (8.4)	58.4 (8.0)	53.8 (7.9)	58.7 (7.8)	52.9 (7.6)	58.2 (8.3)	54.8 (8.3)	49.3 (6.5)	50.0 (6.8)	51.5 (6.0)	48.0 (6.8)	52.8 (5.9)	46.8 (5.8)	50.7 (6.0)	49.2 (7.6)
CV angle	0.13 (0.06)	0.12 (0.06)	0.11 (0.06)	0.14 (0.06)	0.11 (0.05)	0.15 (0.07)	0.11 (0.07)	0.13 (0.05)	0.12 (0.05)	0.12 (0.06)	0.11 (0.05)	0.12 (0.06)	0.11 (0.05)	0.13 (0.05)	0.12 (0.05)	0.12 (0.06)

Y, young; O, older; M, males; F, females; YM, young males; YF, young females; OM, older males; OF, older females; MT, movement time (s); LinV, linear velocity (cm/s); PL, path length (cm); AngV, angular velocity (°/s); CV, coefficient of variation.

TABLE 5 Movement times and kinematics during inserting by age and gender

	Unimanual task															
	Right hand								Left hand							
	Y	0	M	F	YM	YF	OM	OF	Y	0	M	F	YM	YF	OM	OF
MT	0.75 (0.14)	0.99 (0.27)	0.96 (0.28)	0.81 (0.20)	0.75 (0.16)	0.75 (0.13)	1.09 (0.26)	0.87 (0.24)	0.82 (0.15)	0.96 (0.22)	0.93 (0.22)	0.87 (0.18)	0.81 (0.15)	0.83 (0.15)	1.0 (0.23)	0.91 (0.20)
LinV	6.4 (1.6)	7.2 (1.4)	7.2 (1.6)	6.5 (1.4)	6.9 (2.0)	6.0 (1.2)	7.3 (1.4)	7.0 (1.4)	5.7 (1.2)	6.1 (1.3)	6.0 (1.0)	6.0 (1.4)	6.1 (1.2)	5.5 (1.1)	5.9 (0.9)	6.5 (1.6)
CV linV	0.71 (0.13)	0.74 (0.09)	0.75 (0.11)	0.71 (0.11)	0.73 (0.13)	0.70 (0.13)	0.75 (0.10)	0.72 (0.09)	0.59 (0.07)	0.63 (0.08)	0.63 (0.08)	0.60 (0.08)	0.59 (0.08)	0.59 (0.07)	0.65 (0.07)	0.61 (0.09)
PL	4.4 (1.6)	6.8 (2.5)	6.6 (2.7)	5.0 (1.8)	4.8 (2.0)	4.2 (1.1)	7.7 (2.6)	5.8 (1.9)	4.5 (1.2)	5.7 (1.7)	5.3 (1.6)	5.0 (1.5)	4.7 (1.4)	4.3 (1.0)	5.1 (1.7)	5.6 (1.6)
AngV	45.1 (19.7)	48.5 (16.0)	46.1 (18.2)	47.8 (17.4)	45.2 (21.8)	44.9 (18.4)	46.6 (15.9)	50.7 (16.1)	33.1 (9.2)	35.7 (13.8)	33.8 (12.8)	35.2 (11.1)	34.2 (7.9)	32.3 (10.0)	33.6 (15.3)	38.3 (11.5)
CV angV	0.81 (0.14)	0.92 (0.13)	0.90 (0.15)	0.85 (0.11)	0.83 (0.14)	0.80 (0.14)	0.94 (0.14)	0.90 (0.11)	0.83 (0.14)	0.93 (0.15)	0.90 (0.15)	0.87 (0.16)	0.83 (0.14)	0.82 (0.15)	0.95 (0.14)	0.91 (0.15)
Angle	45.1 (10.0)	46.7 (9.9)	47.8 (10.1)	44.2 (9.6)	48.3 (9.9)	42.7 (9.6)	47.5 (10.4)	45.7 (9.5)	40.3 (8.1)	41.8 (9.2)	43.1 (6.9)	39.2 (9.9)	44.2 (7.0)	37.4 (7.8)	42.5 (6.8)	41.1 (11.6)
CV angle	0.18 (0.08)	0.21 (0.08)	0.19 (0.08)	0.20 (0.09)	0.16 (0.09)	0.19 (0.08)	0.20 (0.08)	0.22 (0.09)	0.19 (0.08)	0.20 (0.09)	0.18 (0.08)	0.21 (0.09)	0.17 (0.08)	0.20 (0.08)	0.19 (0.08)	0.21 (0.09)

	Bimanual task															
	Right hand								Left hand							
	Y	0	M	F	YM	YF	OM	OF	Y	0	M	F	YM	YF	OM	OF
MT	0.97 (0.20)	1.26 (0.33)	1.16 (0.33)	1.09 (0.30)	0.95 (0.22)	0.98 (0.18)	1.30 (0.31)	1.21 (0.036)	0.96 (0.20)	1.26 (0.33)	1.17 (0.32)	1.09 (0.30)	0.94 (0.21)	0.99 (0.19)	1.31 (0.30)	1.19 (0.36)
LinV	4.7 (1.1)	5.2 (1.4)	5.2 (1.4)	4.7 (1.1)	4.9 (1.1)	4.5 (1.1)	5.3 (1.6)	5.0 (1.1)	4.8 (1.1)	5.3 (1.1)	5.1 (1.0)	5.1 (1.2)	5.0 (0.9)	4.7 (1.2)	5.2 (1.1)	5.5 (1.2)
CV linV	0.66 (0.11)	0.74 (0.11)	0.71 (0.12)	0.70 (0.12)	0.64 (0.09)	0.67 (0.12)	0.75 (0.11)	0.73 (0.11)	0.63 (0.08)	0.68 (0.09)	0.67 (0.09)	0.65 (0.09)	0.63 (0.07)	0.64 (0.08)	0.70 (0.09)	0.66 (0.10)
PL	4.1 (1.0)	5.9 (1.9)	5.6 (2.1)	4.7 (1.4)	4.3 (1.3)	4.0 (0.8)	6.3 (2.1)	5.5 (1.5)	4.3 (1.0)	6.4 (1.6)	5.7 (1.7)	5.2 (1.6)	4.5 (1.2)	4.3 (0.9)	6.5 (1.5)	6.2 (1.7)
AngV	29.5 (9.1)	33.9 (12.3)	30.8 (12.5)	33.0 (9.7)	28.2 (9.0)	30.5 (9.2)	32.4 (14.2)	35.7 (9.7)	26.7 (10.7)	26.4 (7.8)	24.8 (8.1)	28.2 (9.9)	26.8 (9.3)	26.6 (11.8)	23.6 (7.0)	29.9 (7.4)
CV angV	0.87 (0.12)	0.98 (0.16)	0.96 (0.17)	0.93 (0.15)	0.86 (0.12)	0.87 (0.13)	0.97 (0.16)	0.98 (0.16)	0.88 (0.16)	0.98 (0.14)	0.94 (0.15)	0.94 (0.17)	0.87 (0.16)	0.89 (0.16)	0.98 (0.13)	0.98 (0.16)
Angle	47.3 (8.4)	47.4 (8.9)	49.7 (8.5)	45.1 (8.2)	50.7 (7.7)	44.8 (8.1)	48.9 (9.0)	45.5 (8.5)	43.5 (7.7)	45.1 (7.1)	46.4 (6.2)	42.5 (8.0)	47.5 (6.4)	40.5 (7.3)	45.7 (6.1)	44.5 (8.4)
CV angle	0.16 (0.07)	0.20 (0.08)	0.17 (0.07)	0.19 (0.08)	0.14 (0.07)	0.17 (0.06)	0.19 (0.07)	0.20 (0.09)	0.15 (0.08)	0.17 (0.06)	0.15 (0.06)	0.18 (0.08)	0.13 (0.06)	0.17 (0.10)	0.15 (0.05)	0.19 (0.07)

Y, young; O, older; M, males; F, females; YM, young males; YF, young females; OM, older males; OF, older females; MT, movement time (s); LinV, linear velocity (cm/s); PL, path length (cm); AngV, angular velocity (°/s); CV, coefficient of variation.

effect for linear velocity was found, $F(1, 96) = 7.77$, $p = 0.006$, $\eta^2_p = 0.076$. This effect is described below with the Age × Gender interaction.

Two-way interactions

An Age × Gender interaction was found for linear velocity, $F(1, 96) = 8.12$, $p = 0.006$, $\eta^2_p = 0.079$, showing that older males (M [SD] = 6.54 [0.99]) were slower than younger males (M [SD] = 7.56 [0.99], $p = 0.001$, $\eta^2_p = 0.115$). Moreover, simple effect of Gender showed that younger males were faster than younger females (M [SD] = 6.43 [0.99]), $p < 0.001$, $\eta^2_p = 0.132$). A Hand × Age interaction was significant for path length, $F(1, 96) = 8.04$, $p = 0.006$, $\eta^2_p = 0.078$. Simple effects of Age showed that the older group had longer paths than the younger, both with the right (M $[SD]_{young}$ = 4.79 [1.52], M $[SD]_{older}$ = 6.87 [1.52]), and with the left hand (M $[SD]_{young}$ = 3.82 [1.20], M $[SD]_{older}$ = 5.15 [1.22], both $ps < 0.001$, $\eta^2_p = 0.325$ and $\eta^2_p = 0.238$ for the right and left hand, respectively).

Three-way interaction

A Hand × Age × Gender interaction was significant for CV of angular velocity, $F(1, 96) = 10.43$, $p = 0.002$, $\eta^2_p = 0.099$. Age differences were found for the right hand in females and for the left hand in males, in both cases revealing higher variability in the older group (both $ps < 0.05$, $\eta^2_p = 0.051$ and $\eta^2_p = 0.095$ for females and males, respectively). Simple effect of Gender was significant only for the older group during grasping with the left hand, with males showing higher variability than females, $p = 0.001$, $\eta^2_p = 0.104$. Taken together, the results on grasping show less accurate movements and slower rotation of the hands in the older group. Moreover, these results suggest that age-related differences in grasping kinematics are more prominent for males than for females.

3.3.3 | Transport

See Table 4 for mean values and *SD*s of transport kinematics by Age and Gender.

Main effects of age and gender

Main effects of Age were significant for linear velocity, $F(1, 96) = 16.62$, $p < 0.001$, $\eta^2_p = 0.148$, angular velocity, $F(1, 96) = 12.67$, $p = 0.001$, $\eta^2_p = 0.117$, and CV of angular velocity, $F(1, 96) = 14.21$, $p < 0.001$, $\eta^2_p = 0.128$. These effects were also involved in interactions and are described below. A main effect of Gender was found for angle, $F(1, 96) = 12.78$, $p = 0.001$, $\eta^2_p = 0.118$, showing larger angles in males (M [SD] = 54.13 [6.54]) than in females (M [SD] = 49.52 [6.37]), $p = 0.001$.

Two-way interactions

A Task × Age interaction was significant for angular velocity, $F(1, 96) = 10.21$, $p = 0.002$, $\eta^2_p = 0.096$. Angular velocity was lower in the older group, both in the unimanual (M $[SD]_{young}$ = 71.52 [16.87], M $[SD]_{older}$ = 57.08 [16.74]), and the bimanual task (M $[SD]_{young}$ = 54.46 [15.08], M $[SD]_{older}$ = 47.79 [13.53]), both $ps < 0.05$, $\eta^2_p = 0.160$ and $\eta^2_p = 0.048$ for the unimanual and bimanual task, respectively. A Hand × Gender interaction was also found for angular velocity, $F(1, 96) = 9.29$, $p = 0.003$, $\eta^2_p = 0.088$. Angular velocity was lower in males, but only with the right hand (M $[SD]_{female}$ = 68.61 [19.07], M $[SD]_{male}$ = 58.33 [19.57], $p = 0.009$, $\eta^2_p = 0.069$). Furthermore, a Hand × Age interaction was significant for linear velocity, $F(1, 96) = 14.91$, $p < 0.001$, $\eta^2_p = 0.134$. Simple effects of Age showed that the older group was slower, both with the right (M $[SD]_{young}$ = 32.13 [4.88] M $[SD]_{older}$ = 30.16 [4.84] and with the left hand (M $[SD]_{young}$ = 29.51 [3.80], M $[SD]_{older}$ = 24.91 [3.77], both $ps < 0.05$, $\eta^2_p = 0.041$ and $\eta^2_p = 0.276$ for the right and left hand, respectively).

Three-way interactions

A Task × Hand × Age interaction was found for CV of linear velocity, $F(1, 96) = 52.24$, $p < 0.001$, $\eta^2_p = 0.352$, CV of angular velocity, $F(1, 96) = 9.25$, $p = 0.003$, $\eta^2_p = 0.088$, and path length, $F(1, 96) = 12.13$, $p < 0.001$, $\eta^2_p = 0.123$. Pairwise comparisons for CV of linear velocity revealed age differences in the unimanual task, in which the older group had higher variability than the young with the left hand, but lower with the right hand, both $ps < 0.05$, $\eta^2_p = 0.136$ and $\eta^2_p = 0.179$ for the left and right hand, respectively. For CV of angular velocity, the Task × Hand × Age interaction revealed lower variability for the older group in the bimanual task, but only with the left hand, $p < 0.001$, $\eta^2_p = 0.203$. In contrast, the older group had higher variability than young in the unimanual task, $p = 0.049$, $\eta^2_p = 0.040$. For path length, the Task × Hand × Age interaction showed that the older group had longer paths than younger in the unimanual task, but only with the left hand, $p = 0.028$, $\eta^2_p = 0.049$.

Overall, the results on kinematics of transport showed slower and less accurate movements in the older group, particularly with the left hand. Gender differences were similar to those found during grasping (i.e., males had larger angles than females), but these differences did not vary by age. Age differences in variability were somewhat inconsistent across hands and tasks.

3.3.4 | Inserting

See Table 5 for mean values and *SD*s of transport kinematics by Age and Gender.

Main effects of age and gender

Significant main effects of Age were found for CV of linear velocity, $F(1, 96) = 17.71$, $p < 0.001$, $\eta^2_p = 0.156$, CV of angular velocity, $F(1, 96) = 26.22$, $p < 0.001$, $\eta^2_p = 0.215$, and path length, $F(1, 96) = 43.70$, $p < 0.001$, $\eta^2_p = 0.313$. Compared to the young group, the older group had higher CV of linear velocity (M $[SD]_{young}$ = 0.65 [0.06], M $[SD]_{older}$ = 0.70 [0.06], $p < 0.001$) and higher CV of angular velocity (M $[SD]_{young}$ = 0.85 [0.11], M $[SD]_{older}$ = 0.96 [0.11], $p < 0.001$). The effect of Age on path length is described below with the Task × Hand × Age interaction. A main effect of Gender was significant for angle, $F(1, 96) = 8.78$, $p = 0.004$, $\eta^2_p = 0.084$, revealing larger angles in males (M [SD] = 46.92 [7.05]) than in females (M [SD] = 42.79 [6.88]), $p = 0.004$.

Two-way interaction

A significant Hand × Gender interaction was found for path length, $F(1, 96) = 8.38$, $p = 0.005$, $\eta^2_p = 0.080$. Simple effect of Gender was significant for the right hand only, showing that males had longer paths than females (M [SD] = 4.87 [1.61]), $p = 0.006$, $\eta^2_p = 0.076$.

Three-way interaction

A Task × Hand × Age interaction was significant for path length, F (1, 96) = 14.26, $p < 0.001$, $\eta^2_p = 0.129$. The older group had longer paths than the young across hands and tasks (all $ps < 0.001$, $\eta^2_p = 0.242$ and $\eta^2_p = 0.129$ for the right and left hand, respectively, in the unimanual task; $\eta^2_p = 0.244$ and $\eta^2_p = 0.347$ for the right and left hand, respectively, in the bimanual task). Overall, kinematics of inserting indicated more difficulty performing this action in the older group, as shown by higher variability and longer paths. Gender effects were similar to those observed during transport (i.e., larger angles and longer paths in males compared to females), but they did not vary by age.

3.3.5 | Summary of results

A summary of age- and gender-related differences in MTs and kinematics is provided in Table 6.

From this summary, three main findings can be identified. First, the extent of age-related slowing varied by hand. For the right hand, grasping and inserting showed evidence of slowing in the older group regardless of task, whereas transport only showed group differences in the unimanual task. In contrast, for the left hand, all four movement types showed evidence of slowing, regardless of task. Second, the parameters that most consistently differentiated the age groups varied depending on movement type: for reaching and transport (with the left hand), MT and linear velocity showed consistent group differences regardless of condition; for grasping (with both hands), MT, path length, and angular velocity consistently differentiated the groups; and for inserting, this was the case for MT, path length, and CV of angular velocity. Third, males showed more decline than females in MTs of reaching, grasping, and inserting, regardless of hand and task.

4 | DISCUSSION

The first aim of the present study was to replicate findings of our previous pilot investigation in a larger sample of young and healthy older adults. In the pilot study, we found that older adults had specific declines in the actions of grasping and inserting pins. Results obtained in the present study are partly consistent with our previous findings. In order to compare the present findings to the pilot study, it is appropriate to point to the second aim of the present study, which is closely related to replication of previous findings. The second aim was to employ an integrative methodological approach combining evaluation of MTs and kinematics to obtain a detailed description of age-related differences in dexterity of both hands, in unimanual and bimanual tasks. This approach expanded on our previous pilot study, as in that investigation we only explored dexterity of the right hand.

In the following discussion, we first address the age-related differences found in MTs and kinematics of the right hand, including a comparison of present results to our previous findings, then, the age-related differences found for the left hand and the bimanual condition, and finally, the effects of gender on MTs and kinematics.

4.1 | Age-related differences in dexterity of the right hand

The main finding regarding right hand performance was that the extent of age-related slowing varied by type of movement. Contrasting only age differences, it was evident that reaching showed less evidence of slowing than grasping and inserting. In the two latter movements, the older group was considerably slower and less accurate than the young group, as indicated by longer MTs, longer paths, lower and more variable angular velocities. This finding is consistent with previous reports of age-related declines in tasks that involve fine manipulation (e.g., Ketcham & Stelmach, 2001; Parikh & Cole, 2012). Moreover, the results on grasping and inserting are consistent with findings from our pilot study (Rodríguez-Aranda et al., 2016). The relative absence of age-related slowing in reaching and transport was also replicated and it may represent preservation of gross movements of the right hand with aging. Although several studies have reported poorer performance of gross movements in older adults (e.g., Ketcham et al., 2002; Ketcham & Stelmach, 2001), other research (Carnahan, Vandervoort, & Swanson, 1998; Cicerale et al., 2014; Grabowski & Mason, 2014) found similar MTs and velocities in young and older adults' reaching movements. Our results are consistent with these latter studies. An interesting finding was obtained for transport with the right hand. Previously, we reported no group differences in this type of movement (Rodríguez-Aranda et al., 2016), however, the present study showed group differences in angular velocity, as well as variability of angular and linear velocity. This difference might be due to a more sensitive analysis in the present study, resulting partly from measuring more kinematics (i.e., in the previous study, CVs of kinematics were not assessed), and partly from the larger sample size employed in the present investigation.

Overall, the findings obtained for the right hand mostly corroborate our previous findings, together indicating relative preservation of gross movements and decline in fine manipulation with the right hand in healthy aging.

4.2 | Age-related differences in dexterity of the left hand

In contrast to the right hand, group differences for the left hand were prominent across all four types of movements, in both unimanual and bimanual tasks. Actions that showed the most age-related differences were grasping, transport, and inserting, but also reaching showed differences in MTs, linear velocity, and CV of angular velocity. Thus, dexterity of the left hand appears to show a stronger and more uniform decline with advanced age. This is consistent with previous research that has suggested more decline in the left hand dexterity with aging (Desrosiers et al., 1999; Lezak et al., 2012), perhaps because it is the less practiced one for precise aiming and object manipulation.

4.3 | Age-related differences in the bimanual task

The pattern of group differences in bimanual performance was similar to that of the unimanual task: the right hand mainly showed evidence

TABLE 6 Summary of age- and gender-related differences in movement times and kinematics

	Unimanual task							
	Right hand				Left hand			
	Reaching	Grasping	Transport	Inserting	Reaching	Grasping	Transport	Inserting
MT								
Age	OM > YM*	O > Y***	n.s.	O > Y**	O > Y***	O > Y***	O > Y***	O > Y**
Gender	OM > OF*	OM > OF***	n.s.	M > F*	OM > OF*	OM > OF**	OM > OF**	n.s.
LinV								
Age	n.s.	YM > OM**	n.s.	n.s.	Y > O**	n.s.	Y > O***	n.s.
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CVLinV								
Age	n.s.	n.s.	Y > O*	n.s.	n.s.	n.s.	O > Y*	O > Y**
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
PL								
Age	n.s.	O > Y***	n.s.	O > Y***	n.s.	O > Y***	O > Y*	O > Y***
Gender	n.s.	M > F***	n.s.	M > F**	n.s.	M > F***	n.s.	n.s.
AngV								
Age	n.s.	Y > O**	Y > O*	n.s.	n.s.	Y > O***	Y > O*	n.s.
Gender	F > M**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CVAngV								
Age	n.s.	n.s.	Y > O*	O > Y***	O > Y***	n.s.	n.s.	0> Y**
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	OM > OF**	n.s.	n.s.
Angle								
Age	n.s.	O > Y*	n.s.	n.s.	n.s.	O > Y***	n.s.	n.s.
Gender	M > F**	M > F**	M > F*	n.s.	M > F*	M > F*	M > F**	M > F*
CV angle								
Age	n.s.	n.s.	n.s.	n.s.	n.s.	Y > O**	n.s.	n.s.
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Bimanual task							
	Right hand				Left hand			
	Reaching	Grasping	Transport	Inserting	Reaching	Grasping	Transport	Inserting
MT								
Age	OM > YM**	O > Y***	n.s.	O > Y**	O > Y***	O > Y***	O > Y***	O > Y**
Gender	OM > OF**	OM > OF***	OM > OF*	n.s.	n.s.	OM > OF***	OM > OF*	n.s.
LinV								
Age	n.s.	YM > OM**	n.s.	n.s.	Y > O***	YM > OM**	Y > O***	n.s.
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CVLinV								
Age	n.s.	n.s.	n.s.	O > Y***	n.s.	n.s.	n.s.	O > Y**
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
PL								
Age	n.s.	O > Y***	n.s.	O > Y***	n.s.	O > Y***	n.s.	O > Y***
Gender	n.s.	M > F***	n.s.	M > F*	n.s.	M > F***	n.s.	n.s.
AngV								
Age	n.s.	Y > O**	n.s.	n.s.	n.s.	Y > O***	Y > O*	n.s.
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

(Continues)

TABLE 6 (Continued)

	Bimanual task							
	Right hand				Left hand			
	Reaching	Grasping	Transport	Inserting	Reaching	Grasping	Transport	Inserting
CVAngV								
Age	O > Y*	n.s.	n.s.	O > Y***	O > Y***	n.s.	Y > O***	O > Y**
Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Angle								
Age	n.s.	n.s.	n.s.	n.s.	n.s.	O > Y**	n.s.	n.s.
Gender	M > F**	M > F**	M > F**	M > F**	M > F**	M > F**	M > F**	M > F*
CV angle								
Age	n.s.	n.s.	n.s.	n.s.	n.s.	Y > O***	n.s.	n.s.
Gender	F > M**	n.s.	n.s.	n.s.	F > M*	n.s.	n.s.	n.s.

MT, movement time; LinV, linear velocity; CV, coefficient of variation; PL, path length; AngV, angular velocity; n.s., non-significant; Y, young; O, older; M, male; F, female; YM, young male; OM, older male; OF, older female; Y > O, mean value is larger in the younger group. ***$p < .001$. ** $p < .01$. * $p < .05$.

of slowing during grasping and inserting, and the left hand was slower during all types of movements. Furthermore, the same dexterity measures as in the unimanual condition consistently differentiated the groups, thus, bimanual movements were not qualitatively different from unimanual. This is consistent with Mason and Bryden's (2007) finding in young adults that unimanual and synchronous bimanual movements are performed in the same manner.

In bimanual reaching, the right hand only showed age-related differences in CV of angular velocity. This finding is partly consistent with previous research that has found little age-related slowing in synchronous bimanual reaching movements (Maes et al., 2017). However, the left hand did show longer MT and lower linear velocity during reaching in the older group, which is inconsistent with the account that bimanual reaching is preserved in aging. Perhaps this may be due to the difference in tasks employed by earlier investigations and by the present study. While previous research on bimanual reaching has employed relatively simple reaching conditions (i.e., reaching for a single, clearly visible target), reaching in the Purdue Pegboard tasks is more complex, because the cup contains many pins, which may be aligned in different directions. Thus, reaching to grasp a pin in the Purdue Pegboard tasks may pose higher attentional demands, because it requires selecting one of many pins for grasping and planning hand position to match the direction of that pin during reaching. This may be more difficult for the left hand, because it is the less practiced one for precision aiming.

Bimanual grasping and inserting showed the same pattern of group differences as in the unimanual tasks: older adults were slower than young with either hand. This finding extends the existing evidence on bimanual coordination, demonstrating that whereas bimanual reaching may be relatively preserved, more complex actions that require object manipulation do show decline with increasing age. Overall, our findings regarding bimanual performance are consistent with previous analyses of bimanual Purdue Pegboard tasks (Bernard & Seidler, 2012; Serbruyns et al., 2013), which have shown poorer performance in older adults. Furthermore, our results extend these findings by documenting large MT and kinematic differences in fine manipulation and relative absence of differences in gross movements.

4.4 | Gender differences in MTs and kinematics

The main finding regarding gender was that older males had longer MTs compared to older females during reaching, grasping, and transport with either hand. This is consistent with previous research showing more age-related decline in dexterity in males (Desrosiers et al., 1995a; Lezak et al., 2012; Ranganathan et al., 2001). This gender difference can be explained in light of lifestyle factors such as females having more extensive practice in household activities, many of which involve fine manipulation of objects (Merritt & Fisher, 2003). However, this interpretation should be made with caution, as our study did not collect information about participants' involvement in this type of activities.

Several gender differences in kinematics were found, but these differences did not vary by age. For example, males had longer paths and less variable hand positions than females during grasping and inserting. These findings are consistent with the account that females and males use different movement strategies during dexterity tasks (Rohr, 2006) and suggest that the pattern of gender differences obtained in research with children and young adults, whereby females to a larger extent than males emphasize accuracy during fine motor performance (Rohr, 2006; Ruff & Parker, 1993) may persist into older adulthood. Moreover, these differences indicate less accurate movement strategies in males, which might help explain the larger age-related decline in males. This interpretation is consistent with the age-related differences found in the same kinematics, suggesting less efficient movement strategies employed by males. On the other hand, gender differences in kinematics might be due to differences in hand size, which was not controlled for in the present study. Hand size might be an important factor in explaining the mechanisms of gender differences in dexterity. For example, Peters and Campagnaro (1996) showed that the female advantage in a peg-manipulation task disappeared when hand size was controlled for. To explain this finding, Peters and Campagnaro (1996) argued that it may be more difficult to manipulate small pegs, such as those in the Purdue Pegboard Test, with large hands, and that gender difference in hand size may be the reason for gender differences in dexterity performance. Future assessments of the role of gender in dexterity should evaluate the role of hand size in relation to gender differences.

4.5 | Effect sizes

Significant effects of all sizes were obtained in the present study: small (i.e., $\eta^2_p > 0.01$), medium (i.e., $\eta^2_p > 0.06$), and large (i.e., $\eta^2_p > 0.14$) (Cohen, 1988). Significant effects of age on MTs were large for all four movement types. Effects of age on kinematics were of different sizes, depending on movement type and the type of kinematic measure. For reaching and transport, large effects of age were found for linear velocity and CV of angular velocity. For grasping and inserting, the effects of age were large for angular velocity and path length. The size of age-related gender effects on MTs and kinematics varied by movement type: large effects were obtained for grasping, medium for transport, small for reaching, and no significant effects for inserting. Significant gender effects that did not vary by age were also found. These effects were small to medium for reaching and inserting, medium for transport, and medium to large for grasping. Overall, effects of age were more numerous and larger than effects of gender.

4.6 | Hand preference

Only participants who identified themselves as right-handed were included in the present study. This is in agreement with most previous investigations of manual dexterity, which conventionally exclude left-handed participants. Inclusion of only right-handers in dexterity studies is based on the assumption that about 90% of the population are right-handers (Corballis, 1997) and therefore, results are assumed to generalize to most of the population. However, other research has shown that fine dexterity performance of right- and left-handers may not be directly comparable (Judge & Stirling, 2003). Therefore, future studies should aim to examine dexterity in self-defined left-handed participants.

All participants in the present study met the criterion for right-handedness according to the Briggs-Nebes Handedness Inventory. However, the two performance tests of handedness did indicate no preference or left hand preference in nine participants. Even though this did not affect the group-level dexterity analysis, this finding demonstrates that evaluation of hand preference based on performance tests may give more objective information about handedness (Bryden et al., 2000) than traditional handedness questionnaires. Therefore, performance measures should be used in future studies of dexterity. Another advantage of performance measures is that they allow to define handedness as a continuous variable, which may be more accurate than the right/left dichotomy (Annett, 2002). However, this is a complex issue that warrants further study before it is clear how assessment of handedness should best be performed in studies of aging. At present, a wide variety of performance measures is utilized and therefore, results of different measures are likely to vary between studies. Given that the choice of hand to perform an action may depend on the nature of the task (Provins, 1997), focused research is needed to identify which measures are the most appropriate to provide consistent assessment of hand preference across studies.

In the present study only the direction of handedness was analyzed, but not the strength of hand preference. According to Annett (2002), about 30% of the population may be characterized as mixed-handed, which means they sometimes choose one hand and sometimes the other to perform an action. Research with children has shown that the strength of hand preference (i.e., consistent vs. mixed) may influence cognitive and motor development in the first two years of life (Michel, Campbell, Marcinowski, Nelson, & Babik, 2016). In aging, the role of hand preference in cognitive or motor skills is still unclear. Furthermore, findings obtained with other age groups may not directly apply to older adults. For instance, it has been shown that brain asymmetries for several functions change in the course of aging (Bellis & Wilber, 2001), and dexterity may be one of them. One recent study (Bernard et al., 2011) showed that the relationship between the strength of hand preference and the distribution of motor cortical activity (i.e., ipsilateral vs. contralateral) during activation of hand muscles is opposite in young and older adults. This finding suggests that handedness is represented differently in the brains of young and older adults (Bernard et al., 2011), although it is still unclear how this relates to performance in dexterity tasks. Because evidence on the nature of this relationship in older adults is lacking, we did not analyze the strength of hand preference in relation to dexterity performance in the present study. Therefore, any interpretation in terms of hand dominance for the hand differences found in the present study should be made with caution. Future research is needed to address the question of how strength of hand preference may affect dexterity performance in older adults before it is clear how handedness should best be defined and measured in studies of aging.

4.7 | Limitations of the present study

There are some limitations that might have affected the validity and generalizability of the findings. The first limitation concerns the use of a complex factorial model for dexterity analyses. This might have led to overestimating effect sizes for the different groups. On the other hand, this analysis allowed to investigate the influence of age and gender on dexterity of both hands in different tasks. The second limitation concerns the administration order of the dexterity tasks. To adhere as closely as possible to the standardized procedure of the Purdue Pegboard Test, we administered the tasks in the same order for all participants rather than counterbalancing them. This order may have introduced practice effects, which may have led to an underestimation of the amount of slowing in the second and third task. However, the presence of such effects should be evaluated in future studies to clarify whether task order significantly influences dexterity performance. The third limitation concerns the 2D motion analysis system used in the present study. This system has some difficulty capturing movements of the fingertips, therefore we did not place markers on these sites and fine finger movements were not analyzed. 3D analyses should be applied in future studies to explore finger movements involved in object manipulation. Finally, we did not measure visuomotor processing, which has been shown to have a role in age-related dexterity decline (van Halewyck et al., 2014). Future studies should employ eye-tracking measurements to address the contribution of decline in visual attention and processing to age-related dexterity deficits.

5 | CONCLUSIONS

In conclusion, our findings replicate previous research, including part of our pilot data, and add to the existing evidence by a more comprehensive understanding of fine motor hand function. We showed that the extent of age-related slowing is not uniform, but varies by hand, with the left hand being the most affected. We also showed that the pattern of decline is similar in unimanual and bimanual performance and identified movement parameters that contribute to decline, that is, linear velocity for gross movements, angular velocity and path length for fine manipulation. Notably, we confirmed that the actions of reaching and transporting pins were relatively preserved in older adults in both unimanual and bimanual manipulation, whereas grasping and inserting showed substantial slowing. Finally, we showed that gender is an important factor underlying age-related differences in slowing of dexterity, whereby older males are particularly affected in both gross and fine movements.

The implications of our findings are, first, to highlight the fact that the process of normal aging not only causes slowing of movements, but that movements are qualitatively different in older adults. Additionally, the present findings might serve as an initial reference to understand dexterity deficits in elderly patients suffering pathological states that affect lateralized motor functions (e.g., stroke). Taken together, our findings extend and advance the current understanding of manual dexterity decline in healthy aging. Future studies should expand this line of research by addressing further factors affecting dexterity, such as global sensorimotor decline, cognitive decline, and brain changes in aging.

ORCID

Olena Vasylenko http://orcid.org/0000-0003-2300-2079

REFERENCES

Annett, M. (2002). *Handedness and brain asymmetry: The right shift theory [Kindle for Macintosh version]*. Retrieved from Amazon.com

Beck, A. J., Steer, R. A., & Brown, G. (1996). *BDI-II, beck depression inventory: Manual*. San Antonio, TX: Psychological Corp.

Bellgrove, M. A., Phillips, J. G., Bradshaw, J. L., & Galucci, R. M. (1998). Response (re-) programming in aging: A kinematic analysis. *Journal of Gerontology: Medical Sciences*, *53A*(3), 222–227.

Bellis, T. J., & Wilber, L. A. (2001). Effects of aging and gender on interhemispheric function. *Journal of Speech, Language, and Hearing Research*, *44*, 246–263.

Bernard, J. A., & Seidler, R. D. (2012). Hand dominance and age have interactive effects on motor cortical representations. *PLoS ONE*, *7*(9), e45443.

Bernard, J. A., Taylor, S. F., & Seidler, R. D. (2011). Handedness, dexterity, and motor cortical representations. *Journal of Neurophysiology*, *105*, 88–99.

Briggs, G. G., & Nebes, R. D. (1975). Patterns of hand preference in a student population. *Cortex*, *11*(3), 230–238.

Bryden, P. J., Pryde, K. M., & Roy, E. A. (2000). A performance measure of the degree of hand preference. *Brain and Cognition*, *44*(3), 402–414.

Cahill, L. (2006). Why sex matters for neuroscience. *Nature Reviews Neuroscience*, *7*(6), 477–484.

Carnahan, H., Vandervoort, A. A., & Swanson, L. R. (1998). The influence of aging and target motion on the control of prehension. *Experimental Aging Research*, *24*(3), 289–306.

Cicerale, A., Ambron, E., Lingnau, A., & Rumiati, R. (2014). A kinematic analysis of age-related changes in grasping to use and grasping to move common objects. *Acta Psychologica*, *151*, 134–142.

Cohen, R. J. (1988). *Statistical power analysis for the behavioral sciences*. (2nd ed.). Hillsdale, NJ: L. Erlbaum Associates.

Cooke, J. D., Brown, S. H., & Cunningham, D. A. (1989). Kinematics of arm movements in elderly humans. *Neurobiology of Aging*, *10*(2), 159–165.

Corballis, M. C. (1997). The genetics and evolution of handedness. *Psychological Review*, *104*(4), 714–727.

Cowell, P. E., Allen, L. S., Zalatimo, N. S., & Denenberg, V. H. (1992). A developmental study of sex and age interactions in the human corpus callosum. *Developmental Brain Research*, *2*(24), 187–192.

Cruz-Jentoft, A. J., Baeyens, J. P., Bauer, J. M., Boirie, Y., Cederholm, T., Landi, F., . . . Topinková, E (2010). Sarcopenia: European consensus on definition and diagnosis. *Report of the European Working Group on Sarcopenia in Older People. Age and Ageing*, *39*(4), 412–423.

daSilva, M. V., & Bagesteiro, L. B. (2016). Effects of aging on interjoint coordination during arm reaching. *Research on Biomedical Engineering*, *32*(3), 223–233.

Desrosiers, J., Hébert, R., Bravo, G., & Dutil, E. (1995a). The Purdue Pegboard test: Normative data for people aged 60 and over. *Disability and Rehabilitation*, *17*(5), 217–224.

Desrosiers, J., Hébert, R., Bravo, G., & Dutil, E. (1995b). Upper extremity performance test for the elderly (TEMPA): Normative data and correlates with sensorimotor parameters. *Archives of Physical Medicine and Rehabilitation*, *76*(2), 1125–1129.

Desrosiers, J., Hébert, R., Bravo, G., & Rochette, A. (1999). Age-related changes in upper extremity performance of elderly people: A longitudinal study. *Experimental Gerontology*, *34*, 393–405.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198.

Garcia-Segura, L. M., Azcoitia, I., & DonCarlos, L. L. (2001). *Progress in Neurobiology*, *63*, 29–60.

Grabowski, P. J., & Mason, A. H. (2014). Age differences in the control of a precision reach to grasp task within a desktop virtual environment. *International Journal of Human-Computer Studies*, *72*, 383–392.

Grosskopf, A., & Kuhtz-Buschbeck, J. P. (2006). Grasping with the left and right hand: A kinematic study. *Experimental Brain Research*, *168*, 230–240.

Gur, R. C., Mozley, P. D., Resnick, S. M., Gottlieb, G. L., Kohn, M., Zimmerman, R., . . . Beretta, D. (1991). Gender differences in age effect on brain atrophy measured by magnetic resonance imaging. *Proceedings of the National Academy of the United States of America*, *88*, 2845–2849.

Halpern, D. F (2011). *Sex differences in cognitive abilities* (4th ed.). [Kindle for Macintosh version]. Retrieved from Amazon.com.

Hays, R. D., Sherbourne, C. D., & Mazel, R. H. (1993). The RAND 36-Item Health Survey 1. 0. Health Economics. *2*, 217–227.

Haward, B. M., & Griffin, M. J. (2002). Repeatability of grip strength and dexterity tests and the effects of age and gender. *International Archives of Occupational and Environmental Health*, *75*, 111–119.

Judge, J., & Stirling, J. (2003). Fine motor skill performance in left- and right-handers: Evidence of an advantage for left-handers. *Laterality*, *8*(4), 297–306.

Junaid, K. A., & Fellowes, S. (2006). Gender differences in the attainment of motor skills on the Movement Assessment Battery for Children. *Physical and Occupational Therapy in Pediatrics*, *26*(1-2), 5–11.

Ketcham, C. J., Seidler, R. D., vanGemmert, A. W., & Stelmach, G. E (2002). Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *Journal of Gerontology: Psychological Sciences*, *57B*(1), 54–64.

Ketcham, C. J., & Stelmach, G. E., (2001). Age-related declines in motor control. In J. E. Birren, (Ed.), *Handbook of the psychology of aging* (pp. 313–348). San Diego, CA: Academic Press.

Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D (2012). Construction and motor performance. *Neuropsychological assessment* (5th ed.). New York, NY: Oxford University Press, (pp. 568–617).

Li, R., Cui, J., & Shen, Y. (2014). Brain sex matters: Estrogen in cognition and Alzheimer's disease. *Molecular and Cellular Endocrinology*, *389*, 13–21.

Maes, C., Gooijers, J., de Xivry, J.-J., & Swinnen, S. P. (2017). Two hands, one brain, and aging. *Neuroscience and Biobehavioral Reviews*, *75*, 234–256.

Mason, A. H., & Bryden, P. J. (2007). Coordination and concurrency in bimanual rotation tasks when moving away from and toward the body. *Experimental Brain Research*, *183*, 541–556.

Mergl, R., Tigges, P., Schröter, A., Möller, H.-J., & Hegerl, U. (1999). Digitized analysis of handwriting and drawing movements in healthy subjects: Methods, results, and perspectives. *Journal of Neuroscience Methods*, *90*, 157–169.

Merrill, S. S., Seeman, T. E., Kasl, S. V., & Berkman, L. F. (1997). Gender differences in the comparison of self-reported disability and performance measures. *Journal of Gerontology Series A: Biological and Medical Sciences*, *52*(1), 19–26.

Merritt, B., & Fisher, A. (2003). Gender differences in the performance of activities of daily living. *Archives of Physical Medicine and Rehabilitation*, *84*, 1872–1877.

Michel, G. F., Campbell, J. M., Marcinowski, E. C., Nelson, E. L., & Babik, I. (2016). Infant hand preference and the development of cognitive abilities. *Frontiers in Psychology*, *7*, 410.

Morgan, M., Bradshaw, J. L., Phillips, J. G., Mattingley, J. B., Iansek, R., & Bradshaw, J. (1994). Effects of hand and age upon abductive and adductive movements: A kinematic analysis. *Brain and Cognition*, *25*, 194–206.

Moser, T., & Reikerås, E. (2016). Motor-life-skills of toddlers—a comparative study of Norwegian and British boys and girls applying the Early Years Movement Skills Checklist. *European Early Childhood Education Research Journal*, *24*(1), 115–135.

Nicholson, K. G., & Kimura, D. (1996). Sex differences for speech and manual skill. *Perceptual and Motor Skills*, *82*(1), 3–13.

Ostwald, S. K., Snowdon, D. A., Rysavy, S. D., Keenan, N. L., & Kane, R. L. (1989). Manual dexterity as a correlate of dependency in the elderly. *Journal of the American Geriatrics Society*, *37*, 963–969.

Parikh, P. J., & Cole, K. J. (2012). Handling objects in old age: Forces and moments acting on the object. *Journal of Applied Physiology*, *112*, 1095–1104.

Petersen, R. C., Smith, G. E., Waring, S. C., Ivnik, R. J., Tangalos, E. J., & Kokmen, E. (1999). Mild cognitive impairment: Clinical characterization and outcome. *Archives of Neurology*, *56*(3), 303–308.

Poirier, F. (1987). Dexterity as a valid measure of hand function: A pilot study. *Occupational Therapy in Health Care*, *4*, 69–83.

Provins, K. A. (1997). The specificity of motor skill and manual asymmetry: A review of the evidence and its applications. *Journal of Motor Behavior*, *29*(2), 183–192.

Ranganathan, V. K., Siemionow, V., Sahgal, V., & Guang, H. Y. (2001). *Journal of the American Geriatrics Society*, *49*, 1478–1484.

Rankin, G., & Stokes, M. (1998). Reliability of assessment tools in rehabilitation: An illustration of appropriate statistical analyses. *Clinical Rehabilitation*, *12*(3), 187–199.

Reitan, R. M., & Wolfson, D. (1993). *The Halstead-Reitan neuropsychological test battery: Theory and clinical interpretation* (2nd ed.). Tucson, AZ: Neuropsychology Press.

Rodríguez-Aranda, C. (2003). Reduced writing and reading speed and age-related changes in verbal fluency tasks. *The Clinical Neuropsychologist*, *17*(2), 203–215.

Rodríguez-Aranda, C., Mittner, M., & Vasylenko, O. (2016). Association between executive functions, working memory, and manual dexterity in young and healthy older adults: An exploratory study. *Perceptual and Motor Skills*, *122*(1), 165–192.

Rohr, L. E. (2006). Gender-specific movement strategies using a computer-pointing task. *Journal of Motor Behavior*, *38*(6), 431–437.

Ruan, Q., D'Onofrio, G., Wu, T., Greco, A., Sancarlo, D., & Yu, Z. (2017). Sexual dimorphism of frailty and cognitive impairment: Potential underlying mechanisms (Review). *Molecular Medicine Reports*, *16*, 3023–3033.

Ruff, R. M., & Parker, S. B. (1993). Gender- and age-specific changes in motor speed and eye-hand coordination in adults: Normative values for the finger tapping and grooved pegboard tests. *Perceptual and Motor Skills*, *76*, 1219–1230.

Sartor-Glittenberg, C., Lehmann, S., Okada, M., Rosen, D., Brewer, K., & Bay, C. (2014). Variables explaining health-related quality of life in community-dwelling older adults. *Journal of Geriatric Physical Therapy*, *37*, 83–91.

Scherder, E., Dekker, W., & Eggermont, L. (2008). Higher-level hand motor function in aging and (preclinical) dementia: Its relationship with (instrumental) activities of daily life—a mini-review. *Gerontology*, *54*, 333–341.

Sebastjan, A., Skrzek, A., Ignasiak, S., & Slawinska, T. (2017). Age-related changes in hand dominance and functional asymmetry in older adults. *PLoS ONE*, *12*(5), e0177845.

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., . . . Lipps, D. B. (2010). Motor control and aging: Links to age-related structural, functional, and biochemical effects. *Neuroscience and Biobehavioral Reviews*, *34*, 721–733.

Serbruyns, L., Gooijers, J., Cayenberghs, K., Meesen, K. L., Cuypers, K., Sisti, H. M., . . . Swinnen, S. (2013). Bimanual motor deficits in older adults predicted by diffusion tensor imaging metrics of corpus callosum subregions. *Brain Structure and Function*, *220*, 273–290.

Smith, C. D., Umberger, G. H., Manning, E. L., Slevin, J. T., Wekstein, D. R., Schmitt, F. A.,, . . . Gash, D. M. (1999). Critical decline in fine motor hand movements in human aging. *Neurology*, *53*(7), 1458–1461.

Snellen, H. (1862). Probebuchstaben zur Bestimmung der Selschärfe [Sample Letters for the Determination of Visual Acuity]. Utrecht.

Tiffin, J. (1968). Purdue pegboard examiner manual. *Science Research Associate*.

Tiffin, J., & Asher, E. J. (1948). The Purdue Pegboard: Norms and studies of reliability and validity. *Journal of Applied Psychology*, *32*(3), 234–247.

van Halewyck, F., Lavrysen, A., Levin, O., Boisgontier, M. P., Elliott, D., & Helsen, W. F. (2014). Factors underlying age-related changes in discrete aiming. *Experimental Brain Research*, *233*, 1733–1744.

Vasylenko, O., Gorecka, M., & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 2. Association with cognitive abilities. *Developmental Psychobiology*.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience*, *3*, 1212–1217.

Wong, Y. J., & Whishaw, I. Q. (2004). Precision grasps of children and young and old adults: Individual differences in digit contact strategy, purchase pattern, and digit posture. *Behavioral Brain Research*, *154*, 113–123.

Yan, J. H., Thomas, J. R., & Stelmach, G. E. (1998). Aging and rapid aiming arm movement control. *Experimental Aging Research*, *24*(2), 155–168.

How to cite this article: Vasylenko O, Gorecka MM, Rodríguez-Aranda C. Manual dexterity in young and healthy older adults. 1. Age- and gender-related differences in unimanual and bimanual performance. *Developmental Psychobiology*. 2018;1–21. https://doi.org/10.1002/dev.21619

APPENDIX

APPENDIX A Simple effects of task and hand obtained from pairwise comparisons

		Age (Y, O)	Hand (R, L)	Gender (M, F)	Task (U, B)
Reaching					
MT	Hand × Age	L > R***	–	–	–
MT	Task × Hand × Gender	–	n.s.	B > U (F)**	L > R*
LinV	Hand × Age	R > L***	–	–	–
LinV	Task × Hand × Gender	–	U > B***	U > B***	R > L*
CV linV	Hand × Age	L > R***	–	–	–
Grasping					
MT	Hand × Age	R > L***	–	–	–
MT	Task × Gender	–	–	B > U (F)***	–
PL	Hand × Age	R > L***	–	–	–
CV angV	Hand × Age × Gender	R > L**	–	R > L**	–
Transport					
MT	Task × Hand × Age	B > U*	B > U*	–	n.s.
LinV	Hand × Age	R > L***	–	–	–
CV linV	Task × Hand × Age	L > R**	n.s.	–	L > R**
PL	Task × Hand × Age	L > R***	n.s.	–	n.s.
AngV	Task × Age	U > B***	–	–	–
AngV	Hand × Gender	–	–	R > L*	–
CV angV	Task × Hand × Age	L > R**	n.s.	–	L > R**
Inserting					
MT	Task × Hand × Age	B > U**	B > U***	–	n.s.
MT	Task × Hand × Gender	–	B > U (M)**	n.s.	n.s.
PL	Hand × Gender	–	–	R > L (M)*	–

Y, young; O, older; M, males; F, females; U, unimanual; B, bimanual; MT, movement time; LinV, linear velocity; CV, coefficient of variation; PL, path length; AngV, angular velocity; L > R, mean value is larger for the left hand than the right. ***$p < 0.001$. **$p < 0.01$. *$p < 0.05$. –, effect not involved in the given interaction or has been reported as part of main text; n.s., non-significant.

Appendix B Multivariate effects on kinematics by type of movement

	Reaching		Grasping		Transport		Inserting	
Factor	*F*	η^2_p	*F*	η^2_p	*F*	η^2_p	*F*	η^2_p
Task	58.86***	0.821[a]	65.62***	0.838	89.15***	0.874	44.81***	0.777
Hand	65.96***	0.837	56.49***	0.816	73.64***	0.851	39.31***	0.754
Age	5.38***	0.295	14.61***	0.535	5.67***	0.306	10.70***	0.454
Gender	2.98**	0.188	5.67***	0.308	3.80**	0.228	3.48**	0.213
Age × Gender	1.94	0.131	3.23**	0.203	1.88	0.128	1.32	0.093
Task × Hand	80.52***	0.862	39.82***	0.758	37.66***	0.745	21.29***	0.623
Task × Age	3.99**	0.237	1.39	0.099	3.17**	0.198	0.53	0.039
Task × Gender	3.03**	0.191	1.42	0.100	0.90	0.066	0.57	0.043
Hand × Age	5.75***	0.309	4.60***	0.266	6.38***	0.332	0.96	0.068

(Continues)

(Continued)

	Reaching		Grasping		Transport		Inserting	
Factor	***F***	**η^2_p**	***F***	**η^2_p**	***F***	**η^2_p**	***F***	**η^2_p**
Hand × Gender	0.89	0.064	1.35	0.096	1.94	0.131	0.85	0.062
Task × Hand × Age	1.27	0.090	2.18*	0.146	9.53***	0.426	4.13**	0.243
Task × Hand × Gender	4.99***	0.280	1.65	0.115	3.47**	0.213	2.34*	0.154
Task × Hand × Age × Gender	0.89	0.065	1.52	0.107	0.43	0.033	1.35	0.095

[a] η^2_p for multivariate effects is equal to Pillai's *V*.
df for all multivariate effects are 7, 90. ***$p < .001$. **$p < .01$. *$p < .05$.

Paper III

Vasylenko, O., Gorecka, M.M. & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 2. Association with cognitive abilities. *Developmental Psychobiology, 60*(4), 428-439.

Received: 29 September 2017 | Revised: 10 January 2018 | Accepted: 13 January 2018
DOI: 10.1002/dev.21618

RESEARCH ARTICLE

WILEY Developmental Psychobiology

Manual dexterity in young and healthy older adults. 2. Association with cognitive abilities

Olena Vasylenko[1] | **Marta M. Gorecka**[1,2] | **Claudia Rodríguez-Aranda**[1]

[1] Department of Psychology, University of Tromsø, Tromsø, Norway
[2] Department of Neurology, University Hospital of Northern Norway, Tromsø, Norway

Correspondence
Olena Vasylenko, Faculty of Health Sciences, Department of Psychology, University of Tromsø, N-9037 Tromsø, Norway.
Email: olena.vasylenko@uit.no

Abstract

Currently, little is known about the cognitive constraints underlying manual dexterity decline in aging. Here, we assessed the relationship between cognitive function and dexterity in 45 young and 55 healthy older adults. Effects of gender on the cognition-dexterity association were also explored. Cognitive assessment comprised neuropsychological tests of executive function, working memory, attention, and memory. Dexterity assessment included evaluation of movement times and kinematics during performance of unimanual and bimanual tasks of the Purdue Pegboard Test. Cognitive and dexterity group differences were established. Thereafter, regression analyses showed that executive function best predicted movement times and to some extent path lengths for the left hand in the older group. No gender differences were found in older participants. The findings confirm the involvement of executive function in manual dexterity in aging and suggest that movement times and path length may be useful parameters to assess the cognition-dexterity association in older adults.

KEYWORDS
aging, executive function, gender, kinematics, manual dexterity, movement time, path length

1 | INTRODUCTION

Manual dexterity is the ability to skillfully manipulate objects with the hands and it is required for most daily activities. Aging is associated with declines in manual dexterity, which limit older adults' ability to perform activities of daily living (Scherder, Dekker, & Eggermont, 2008). In order to prevent functional limitations in the older population, a detailed understanding of the factors that contribute to dexterity decline is necessary.

Substantial research has been carried out to explain the contribution of peripheral changes of the arm and hand to dexterity decline. Changes in skin, muscle, tactile sensitivity, grip, and pinch strength have been examined. Results have shown that skin of the fingers becomes more slippery with aging, which makes older adults more likely than young to drop grasped objects (Kinoshita & Francis, 1996). In addition, with advanced age, there is a decline in tactile sensitivity (Tremblay, Wong, Sanderson, & Coté, 2003), as well as reductions in muscle mass and in the number of motor units in the hand (Carmeli, Patish, & Coleman, 2003). These peripheral changes are thought to account for about 30% of the decline in pinch and grip strength (Ranganathan, Siemionow, Sahgal, & Guang, 2001). In turn, lower grip strength is associated with poorer hand function, particularly in aiming and finger tapping tasks (Martin, Ramsay, Hughes, Peters, & Edwards, 2015). Despite the decrease in grip and pinch strength, older adults consistently produce larger forces than necessary when manipulating objects (Diermayr, McIsaac, & Gordon, 2011; Parikh & Cole, 2012), which may result in fatigue and thus poorer dexterity performance.

Although the role of peripheral changes in dexterity has been established, these changes cannot consistently account for dexterity decline (Cole, Rotella, & Harper, 1998; Dayanidhi & Valero-Cuevas, 2014). For example, Cole et al. (1998) found no decline in older adults' performance on an object-lifting task when they were deprived of tactile information. Similarly, Dayanidhi and Valero-Cuevas (2014)

© 2018 Wiley Periodicals, Inc.

found no association between the ability to control fingertip force and performance in a peg-inserting task. These findings imply that other factors in addition to peripheral changes are involved in dexterity decline. For instance, cognitive abilities are important for planning and execution of complex actions (Rosenbaum, 2009), and therefore, age-related changes in cognitive function may also influence manual dexterity. Age-related decline has been well-documented for several cognitive abilities, including attention, working memory, executive functions, and memory. Attention is a multi-faceted ability that is closely related to other cognitive functions. Aging is associated with declines in selective and divided attention (Drag & Bieliauskas, 2010; Zanto & Gazzaley, 2017). Working memory (WM) is the ability concerned with active maintenance and manipulation of information that is used to guide ongoing and intended actions (Reuter-Lorenz & Lustig, 2017), and its capacity declines with aging, especially in tasks that also involve executive control (Reuter-Lorenz & Park, 2010). Executive functions (EF) are high-level cognitive abilities that regulate behavior by goal formation, planning, and carrying out goal-directed plans flexibly (Jurado & Rosselli, 2007). Difficulties with inhibition and switching are the first signs of decline in EF during the course of aging (Craik & Bialystok, 2006; Jurado & Rosselli, 2007). In the domain of memory, episodic memory (i.e., memory for events) is the ability most affected by aging (Reuter-Lorenz & Park, 2010; Wang & Cabeza, 2017). Because these cognitive abilities are necessary for efficient planning and execution of actions, researchers have begun to explore the role of cognitive decline and central nervous system changes in dexterity deficits. Important central changes include age-related volume reduction in gray and white matter in motor brain regions, such as the primary motor cortex (Salat et al., 2004), the corticospinal tract (Salat et al., 2005), and the cerebellum (Sullivan, Rohlfing, & Pfefferbaum, 2010), as well as in the corpus callosum, which is important for coordination of movement (Ota et al., 2006). Second, the prefrontal and parietal cortices, which are involved in action planning, working memory, and attention, also undergo substantial age-related atrophy (Salat et al., 2004). In addition, aging is also associated with degeneration of the dopaminergic neurotransmitter system, which particularly affects the basal ganglia, a structure that is essential for fine motor control (Emborg et al., 1998). Equally, age-related dopamine depletion has been critically implicated in higher-order cognitive functioning (Cropley, Fujita, Innis, & Nathan, 2006). Collectively, these central changes contribute to movement slowing and impaired coordination (Seidler et al., 2010). The role of brain changes in the regions involved in cognitive function is particularly important because, according to Seidler et al. (2010), control of skilled movements changes across the lifespan, from relying on relatively automatic processes in younger age to becoming more dependent on controlled mechanisms that involve cognitive abilities in older age. Therefore, the central changes that lead to cognitive decline, may also contribute to decline in manual ability (Seidler et al., 2010).

Support for the involvement of cognitive abilities in manual dexterity comes from several lines of research. First, several behavioral studies have assessed the role of cognitive functions in dexterity, both in young and older adults. Two studies with young adults (Steinberg & Bock, 2013; Strenge, Niederberger, & Seelhorst, 2002) found relationships between attention and dexterity. In Steinberg and Bock's (2013) study, focused attention was related to grasping performance with the right hand, and Strenge et al. (2002) found a relationship between focused attention and dexterity of the left hand, as well as between divided attention and performance on the bimanual task of the Purdue Pegboard Test (Tiffin, 1968; Tiffin & Asher, 1948). In a recent pilot study (Rodríguez-Aranda, Mittner, & Vasylenko, 2016), our group documented a relationship between EF and variability of unimanual right hand movements in a modified Purdue Pegboard task. In a study of bimanual coordination, Bangert, Reuter-Lorenz, Walsh, and Schachter (2010) showed that WM and EF scores were associated with asynchronous circle tracing and finger tapping performance, respectively. Second, experimental evidence by Fraser, Li, and Penhune (2010) confirmed the involvement of executive control in skilled hand movements. These researchers showed that increasing cognitive load by adding a dual task resulted in poorer performance of a sequential finger tapping task in older adults (Fraser et al., 2010). Finally, several neuroimaging studies have shown different patterns of brain activation during performance of motor coordination tasks in young and older adults (Coxon et al., 2010; Heinunckx, Wenderoth, Debaere, Peeters, & Swinnen, 2005). Specifically, in both studies older adults showed increased recruitment of parietal and prefrontal areas, which are thought to underlie attention and EF, respectively. Together, these behavioral, experimental, and neuroimaging studies provide evidence that older adults rely to a great extent on cognitive processes to control skilled hand movements. However, one limitation of the aforementioned studies is the lack of a comprehensive approach in which different cognitive capacities known to decline with aging are assessed alongside a detailed measurement of dexterity. Most of the previous investigations have restricted the evaluation of cognitive functions to attention and EF (Fraser et al., 2010; Steinberg & Bock, 2013; Strenge, Niederberger, & Seelhorst, 2002), although two studies also assessed WM (Bangert et al., 2010; Rodríguez-Aranda et al., 2016). However, to provide a complete understanding of the association between cognitive abilities and dexterity decline in aging, other cognitive functions that show substantial age-related decline, such as memory, should also be explored (Reuter-Lorenz & Park, 2010; Wang & Cabeza, 2017).

Moreover, current studies have limitations regarding the assessment of dexterity as most of them have used the number of errors or overall movement time (MT) to correlate with cognitive abilities (Fraser et al., 2010; Steinberg & Bock, 2013; Strenge, Niederberger, & Seelhorst, 2002). MT is the time participants require to complete the task and it gives a useful overall measure of performance. However, a dexterity task comprises different types of movements, such as aiming, reaching, grasping, and transport of objects, and these different movements may show varying degrees of decline in older adults. For example, in two studies performed by our group (Rodríguez-Aranda et al., 2016; Vasylenko, Gorecka, & Rodríguez-Aranda, 2018), older adults showed more slowing in grasping and inserting of pegs than in reaching for and transporting pegs in unimanual and bimanual tasks of the Purdue Pegboard test. Additionally, the extent of age-related slowing varied for different temporal and kinematic dexterity measures, with MTs and path lengths (i.e., the distance covered by the hand during a movement) being the most affected parameters (Vasylenko et al., 2018). These findings indicate that dexterity decline in older adults is a complex phenomenon, therefore, the use of only MT measures to assess the association of dexterity with cognition merely provides a generalized understanding of this relationship. If we aim to obtain precise information about the role of cognitive decline in dexterity deficits, it is more appropriate to employ detailed measures of separate types of movements involved in dexterity performance. Therefore, in the present study we aimed to extend the existing evidence on the involvement of cognitive function in dexterity by examining the relationships between MTs and kinematics of reaching, grasping, and manipulating objects in unimanual and bimanual tasks of the Purdue Pegboard Test (obtained in a recent study (Vasylenko et al., 2018)), and selected neuropsychological tests of cognitive function. For this aim, we expected to corroborate the roles of EF and attention in multiple measures of dexterity. Due to the limited existing evidence of the role of WM and memory, it is not possible to put forward any hypotheses concerning their association with dexterity, but we expected at least some contributions of these abilities to explaining dexterity performance.

The second aim of the present study was to examine the role of gender in the association between cognitive function and dexterity. Several studies have shown gender differences in dexterity performance of older adults (Desrosiers, Hébert, Bravo, & Dutil, 1995; Lezak, Howieson, Bigler, & Tranel, 2012; Ranganathan et al., 2001; Vasylenko et al., 2018). These studies have shown that older males experience more decline in dexterity than older females. Interestingly, a recent study (McCarrey et al., 2016) showed that older males also experienced more decline in global mental status, perceptual speed, and visuospatial ability than older females. A relevant hypothesis in this respect is that gender differences in cognition may contribute to gender differences in complex manual skill. Therefore, in the present study we evaluated whether associations between cognitive scores and dexterity measures differed by gender. To our knowledge, no study has yet investigated gender differences in the relationship between cognitive abilities and dexterity decline.

To summarize, the aims of the present study were (a) to assess the relationship between MT and kinematic measures of dexterity in unimanual and bimanual tasks of the Purdue Pegboard Test and selected neuropsychological measures of cognitive functions that decline with aging (i.e., attention, WM, EF, and memory) and (b) to evaluate gender differences in these relationships.

2 | METHOD

2.1 | Participants

Forty-five young (26 female, $M_{\text{age}} = 22.8$ years, range: 19–31 years) and 55 healthy, community-dwelling older adults (25 female, $M_{\text{age}} = 70.6$ years, range: 60–88 years) participated in the study. This sample is the same as the one reported in Vasylenko et al. (2018). None of the participants had cognitive dysfunction, depression or sarcopenia, none had experienced stroke or head trauma, had any injuries of the hands, or took any medications known to affect the central nervous system. All participants had normal or corrected-to-normal visual acuity and all were right-handed, as shown by scores of +9 or higher on the Briggs-Nebes Handedness Inventory (Briggs & Nebes, 1975). Mini-mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975) and Beck Depression Inventory (BDI), 2nd edition (Beck, Steer, & Brown, 1996) were used as screening measures for cognitive decline and depression, respectively. None of the participants were excluded on these grounds. For details on sampling and screening procedure, see Vasylenko et al. (2018). All neuropsychological tests were administered and scored in the standardized method, according to their respective manuals. All participants gave informed consent prior to participation. The study was approved by the Norwegian Regional Research Ethics Committee and conducted in accordance with the Helsinki guidelines.

2.2 | Measures

2.2.1 | Dexterity measures

Dexterity data used in the present study are the same as those reported in a recent study by our group and have been published separately (Vasylenko et al., 2018). Dexterity performance was assessed with the first three subtests of the Purdue Pegboard Test: inserting pins with the right hand, with the left hand, and bimanually. The kinematic measures were linear velocity (i.e., the speed of hand movement), angular velocity (i.e., the speed of hand rotation), path length (i.e., the distance covered by the hand), angle (i.e., the position of the hand with respect to the pegboard surface), as well as coefficients of variation (CVs) of these measures. See Vasylenko et al. (2018) for a full description of dexterity assessment.

2.2.2 | Neuropsychological and neuromuscular measures

EF was assessed with the Trail Making Test (Reitan & Wolfson, 1993) and the Stroop Color and Word Test (Golden, 1978). Attention and WM were measured with the Block Design Test and the Digit Span Test from the Wechsler Adult Intelligence Scale, 4th edition (Wechsler, 2014). Memory was assessed with the Logical Memory Test from the Wechsler Memory Scale, 3rd edition (Wechsler, 1997). Neuromuscular hand function was evaluated with the Grip Strength Test and the Finger Tapping Test from the Halstead-Reitan neuropsychological battery, 2nd edition (Reitan & Wolfson, 1993).

2.3 | Procedure

Neuropsychological assessment was carried out as part of a larger study, that also involved assessment of dexterity (see Vasylenko et al., 2018). Cognitive tests were administered following the dexterity assessment. Duration of neuropsychological assessment was about 45 min for young and about 1 hr for older participants.

2.4 | Statistical analyses

To investigate the association between neuropsychological scores and movement parameters, we conducted hierarchical multiple regression analyses for each task. Prior to these analyses, all neuropsychological measures were subjected to data reduction by Principal Component Analysis (PCA) with varimax rotation. The purpose of data reduction was to obtain composite scores representing cognitive and neuromuscular domains that could explain results previously obtained from the analyses of MTs and kinematics. The resulting component scores from the PCA were entered in the regression analyses as predictors, together with the control variables gender and education. Regression analyses were performed separately for each age group, to test whether the association between dexterity and cognitive abilities was stronger in older adults. Only MTs and kinematics that showed significant age-related differences in the separately published dexterity analysis (see Vasylenko et al., 2018) were selected as dependent variables for the regression analyses. First, to assess the relationship between cognitive abilities and dexterity for each age group independently of demographic variables, we controlled for gender and education. Thereafter, to test for gender differences in the obtained relationships, we compared the regression slopes of significant predictors from each significant model between genders. Slope comparisons were carried out by using the ANCOVA method (Andrade & Estévez-Pérez, 2014).

All statistical analyses were performed with IBM SPSS Statistics Version 23 (IBM Corp., 2014).

3 | RESULTS

3.1 | Demographics and neuropsychological results

Table 1 displays results for demographic variables and neuropsychological test scores by age group.

The groups did not differ in years of education, MMSE or BDI scores. As expected, the older group scored significantly lower on most cognitive tests. Only the Digits Backward test showed no age-related differences. Concerning the tests of neuromuscular function, grip strength did not differ significantly between groups, but finger tapping scores were lower in the older group.

3.2 | Dimension reduction of neuropsychological data

To ensure a good fit given our sample size, we relied on the cutoff of .60 when extracting factors (Tabachnik & Fidell, 2007). Four factors were identified, and labeled Grip/Tap, EF, Memory, and Attention/WM. See Table 2 for factor loadings, eigenvalues, and percentages of variance explained by each factor.

Combined, the four factors explained 79% of the variance in neuropsychological test scores. The Block Design test loaded on the same factor as the traditional tests of executive function, perhaps because of its spatial problem-solving component. Factor scores for each factor were computed and used as predictors in multiple regression analyses.

3.3 | Factor scores as predictors of dexterity

Results on age- and gender-related differences in MTs and kinematics of dexterity have been reported separately (Vasylenko et al., 2018; see Appendix for a summary of dexterity results obtained in that study). As mentioned in the Statistical Analyses, regression analyses were conducted separately for each group to evaluate whether the association between dexterity measures and cognitive abilities differed by age group. The demographic variables gender and education were entered in the first block of predictors. Thereafter, to assess the contribution of physical hand function, the Grip/Tap factor was entered in the second block. The third block contained scores from the three cognitive factors. All predictors of each block were entered in the regression model simultaneously by the Enter method.

3.3.1 | Prediction of MTs

In the young group, no MTs showed associations with any of the factors. However, in the older group, there were several significant relationships (see Tables 3 and 4).

For the right hand, significant regression models explained between 31% and 45% of the variance in inserting MTs in both unimanual and bimanual Purdue Pegboard tasks and reaching MT in the bimanual task (See upper part of Table 3). Although the first block accounted for 24% of the variance in unimanual inserting MT and 16% of the variance in bimanual reaching MT, the third block considerably improved the models by 17%, 25%, and 26%, respectively. The second block did not contribute significantly to any of the models. Among the cognitive predictors, EF scores were the most strongly related to MTs in all three models. All the significant associations for EF were negative, thus, higher EF scores were associated with shorter time spent on reaching and inserting movements. Additionally, Attention/WM showed significant relationship with unimanual inserting time, such that higher attention/WM scores were associated with shorter MTs.

For MTs of the left hand (see upper part of Table 4), the significant regression models explained between 28% and 35% of the variance in reaching and inserting MTs in the unimanual and bimanual conditions. Block 1 significantly accounted for 19% and 16% of the variance in unimanual inserting MT and bimanual reaching MT, respectively. Block 2 did not significantly contribute to any of the models. Block 3 significantly improved prediction for all the models, explaining between 14% and 25% of the variance. EF was the only significant predictor of this block, and it showed negative associations with reaching and inserting MTs, in both the unimanual and the bimanual conditions. Thus, higher EF scores were associated with shorter time spent on reaching and inserting. For the older group, none of the regression slopes differed significantly between the genders.

3.3.2 | Prediction of kinematics

Young group

Regression models that significantly predicted kinematics in the young group are summarized in Table 5.

TABLE 1 Demographics and results of neuropsychological tests by age group

	Young (*n* = 45)	**Older (*n* = 55)**			**95CI%**		
F/M ratio	**26/19** ***M(SD)***	**25/30** ***M(SD)***	***t***	***p***	***LL***	***UL***	**Cohen's *d***
Age	22.80 (2.76)	70.58 (6.20)					
Years of education	14.41 (1.46)	13.56 (3.44)	1.65	.102	−.17	1.87	0.32
Trail Making A	21.73 (5.35)	34.11 (10.68)	−7.52	**<.001**	−15.86	−8.91	−1.47
Trail Making B	55.28 (14.52)	87.33 (29.17)	−7.09	**<.001**	−41.54	−22.57	−1.39
Stroop Word	95.69 (10.66)	88.05 (14.28)	2.97	**.004**	2.54	12.73	0.61
Stroop Color	70.56 (10.94)	61.47 (10.05)	4.32	**<.001**	4.91	13.25	0.87
Stroop Color/Word	42.02 (8.55)	31.60 (7.70)	10.09	**<.001**	13.19	19.65	1.28
Digits Forward	9.76 (1.87)	8.82 (1.94)	2.44	**.017**	.17	1.70	0.49
Digits Backward	8.71 (1.93)	7.98 (1.95)	1.93	.057	−.02	1.48	0.38
Logical Memory I	29.18 (5.72)	24.13 (6.55)	4.03	**<.001**	2.57	7.54	0.82
Logical Memory II	14.52 (4.04)	10.73 (4.37)	4.44	**<.001**	2.10	5.49	0.90
Block Design	51.56 (8.93)	37.35 (9.03)	7.73	**<.001**	10.56	17.86	1.58
Grip Strength							
Right hand	41.50 (9.55)	38.25 (10.58)	1.60	.114	−.79	7.29	0.32
Left hand	37.79 (9.26)	36.93 (10.38)	0.43	.664	−3.08	4.81	0.09
Finger Tapping							
Right hand	46.01 (6.94)	41.14 (8.66)	3.05	**.003**	1.70	8.03	0.63
Left hand	42.39 (7.90)	38.03 (7.83)	2.76	**.007**	1.23	7.50	0.55

CI, confidence intervals for the mean difference; LL, lower limit; UL, upper limit.

In this set of analyses, two significant regression models were obtained, predicting path length during bimanual grasping with the right and left hand, respectively. The two models accounted for 40% and 33% of the variance, respectively. Neither the first nor the second block contributed significantly to any of the models, although gender was a significant predictor. In contrast, the third block containing the cognitive predictors explained 23% and 17% of the variance in path length during grasping with the right and the left hand, respectively. Attention/WM was the only significant predictor, and was negatively related to path length, such that better Attention/WM scores were

TABLE 2 Results of principal component analysis of neuropsychological test scores

	Factor loadings			
Test	**Grip/Tap**	**EF**	**Memory**	**Attention/WM**
Grip Strength right	**.92**	−.11	−.07	.08
Grip Strength left	**.90**	−.21	−.09	.04
Finger Tapping right	**.80**	.31	.14	−.15
Finger Tapping left	**.78**	.35	.09	.04
Trail Making A	.03	**−.87**	−.06	−.11
Trail Making B	.03	**−.81**	−.19	−.11
Stroop Color/Word	.14	**.77**	.15	.27
Digits Forward	−.02	.25	.06	**.85**
Digits Backward	.01	.21	.26	**.83**
Logical Memory I	.04	.21	**.91**	.17
Logical Memory II	−.03	.16	**.94**	.14
Block Design	.19	**.63**	.20	.38
Eigenvalues	4.20	2.83	1.31	1.08
% of variance	35.03	23.55	10.94	9.03

EF, Executive Function; WM, Working Memory. Factor loadings above .60 are given in bold.

TABLE 3 Hierarchical multiple regression analyses predicting movement times of the right hand from cognitive abilities in the older group

	U inserting		B reaching		B inserting	
Predictor	ΔR^2	β	ΔR^2	β	ΔR^2	β
Block 1[a]	.24**		.16*		.04	
Gender		−194.23***		−45.56*		−40.35
Education		−2.60		0.15		−16.41
Block 2	.04		.01		.01	
Grip/Tap		−85.05		−0.94		4.09
Block 3	.17**		.25**		.26**	
EF		−125.81**		−45.92***		−211.17***
Attention/WM		−73.21*		6.52		28.72
Memory		7.35		0.44		−69.45
Total R^2 change	.45***		.42***		.31**	
			β(SE) by gender			
Males						
EF	−150.45 (44.23)**		−45.33 (14.13)**		−171.15 (56.87)**	
Attention/WM	−62.00 (42.36)					
Females						
EF	−175.88 (76.19)*		−47.58 (14.86)**		−191.59 (55.21)*	
Attention/WM	−106.25 (52.83)					
			β difference by gender			
EF	n.s.		n.s.		n.s.	
Attention/WM	n.s.					

Only significant results are shown. [a]Control variables included gender and education. U, unimanual task; B, bimanual task; EF, executive function; WM, working memory.
$^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

associated with shorter paths. Comparison of slopes between the genders showed a significant difference in the association between path length of the right hand and Attention/WM, indicating that this association was stronger for males than for females.

Older group

Regression models that significantly predicted kinematics in the older group are summarized in Table 6. Significant results were found for the left hand only. The models accounted for 35%, 39%, and 25% of the variance in path lengths during unimanual grasping, bimanual grasping, and bimanual inserting, respectively. Block 1 significantly contributed to the first two models, explaining 22% and 23% of the variance in unimanual and bimanual path lengths during grasping. Block 2 accounted for 10% of the variance in path length during bimanual grasping. Block 3 significantly improved the first and third models, by 12% and 21%, respectively. EF was negatively related to unimanual path length during grasping and bimanual path length during inserting, thus, higher EF scores were associated with shorter paths. Additionally, path length during inserting was significantly predicted by Memory, such that higher memory scores were associated with shorter paths. No gender differences were found between the regression slopes.

In summary, multiple regression analyses revealed associations between cognitive abilities and dexterity for both groups, but the associations were more extensive for the older group, with cognitive abilities predicting both MTs and kinematics. EF was an important predictor of dexterity in the older group, whereas the other factors did not show consistent relationships with movement parameters. It is important to note that in several models, gender was an important predictor, explaining up to 24% of the variance in dexterity measures. However, gender differences in the relationship between cognitive function and dexterity were limited and were only found in the younger group. Moreover, education and physical hand function scores were practically irrelevant as predictors of dexterity.

4 | DISCUSSION

The first aim of the present study was to assess the relationship between cognitive abilities and dexterity in healthy young and older adults. The obtained results showed a significant involvement of cognitive abilities in dexterity, particularly for older adults. Thus, our findings are in agreement with the account that cognitive processes become more involved in the control of skilled hand movements in

TABLE 4 Hierarchical multiple regression analyses predicting movement times of the left hand from cognitive abilities in the older group

	U reaching		U inserting		B reaching		B inserting	
Predictor	**ΔR^2**	***β***	**ΔR^2**	***β***	**ΔR^2**	***β***	**ΔR^2**	***β***
Block 1[a]	.11		.19*		.16*		.08	
Gender		30.61		50.74		18.00		79.30
Education		0.18		−0.05		0.63		−20.80
Block 2	.01		.02		.02		.01	
Grip/Tap		−7.24		−48.64		−14.69		1.78
Block 3	.17*		.14*		.15*		.25**	
EF		−33.89**		−103.67**		−23.67*		−197.34***
Attention/WM		1.32		−18.73		11.99		2.73
Memory		−2.54		−8.52		−3.63		−67.49
Total R^2 change	.28*		.35**		.33**		.34**	
				β(SE) by gender				
Males								
EF	−40.40 (12.08)**		−122.56 (37.09)**		−28.41 (9.38)**		−156.23 (42.45)**	
Females								
EF	−15.94 (17.12)		−135.96 (62.71)*		−40.03 (19.91)*		−173.20 (59.32)*	
				β difference by gender				
EF	n.s.		n.s.		n.s.		n.s.	

Only significant results are shown. [a]Control variables included gender and education. U, unimanual task; B, bimanual task; EF, executive function; WM, working memory.
**p* < .05. ***p* < .01. ****p* < .001.

aging (Seidler et al., 2010). However, the significant associations were not observed to the same extent with the two types of dexterity measures, i.e., MTs and kinematics.

4.1 | Association between executive function and movement times

The main finding of the present study was that EF was related to MTs in the older group only. Specifically, MTs for reaching and inserting with either hand were predicted mainly by EF. For reaching, the involvement of EF seemed more important for the right hand than the left during bimanual performance, although the association was also found for the left hand to a lesser degree. For inserting, EF appeared more important in bimanual performance than unimanual, as shown by the higher portions of variance explained for either hand.

4.2 | Association between cognitive abilities and kinematics

Among the kinematic measures, only path length was predicted by cognitive abilities in both age groups. For the older group, significant relationships were found for the left hand only. Grasping and inserting were the actions related to cognitive abilities, although the former in unimanual and the latter in bimanual performance. EF and Memory were the significant predictors of path length during these actions. In contrast, for the young group, Attention/WM was the most consistent predictor of path lengths during bimanual grasping. This finding is consistent with the evidence that attention and WM are involved in normal control of dexterity (Baldauf & Deubel, 2010; Strenge et al., 2002). The present findings are somewhat in opposition to our pilot study (Rodríguez-Aranda et al., 2016), where EF was the ability most strongly related to dexterity measures in both young and older adults. However, it is important to note that in that study we did not conduct regression analyses separately for each age group, but instead, due to the limited sample size, common analyses for both age groups were employed.

Overall, our results concerning the relationship between cognitive abilities and dexterity in older adults show that EF was the cognitive function that best predicted dexterity measures. This finding is consistent with previous studies (Bangert et al., 2010; Fraser et al., 2010) that have showed the involvement of EF in dexterity of older adults.

Importantly, our results identified MT and path length as the dexterity parameters that were consistently predicted by EF. The direction of the relationships was negative in all the regression models, confirming that better EF scores were related both to shorter MTs and shorter paths. Whereas shorter MTs represent faster overall performance, shorter paths represent more precise movement trajectories to the target (Wolpert & Ghahramani, 2000). Thus, EF in older adults appears to be involved both in the control of speed of performance and, more specifically, in the control of the precision of movement in unimanual and bimanual object manipulation.

TABLE 5 Hierarchical multiple regression analyses predicting kinematics from cognitive abilities in the young group

	BR grasping PL		BL grasping PL	
Predictor	**ΔR^2**	**β**	**ΔR^2**	**β**
Block 1[a]	.17		.15	
Gender		0.93*		0.75*
Education		0.03		−0.12
Block 2	.01		.01	
Grip/Tap		−0.04		−0.02
Block 3	.23*		.17*	
EF		−0.56		−0.21
Attention/WM		−0.59**		−0.40*
Memory		−0.07		0.10
Total R^2 change	.40*		.33*	
		β(SE) by gender		
Males				
Attention/WM	−0.66 (0.24)*		−0.44 (0.25)	
Females				
Attention/WM	−0.11 (0.13)		−0.24 (0.19)	
		β difference by gender		
Attention/WM	M > F*		n.s.	

Only significant results are shown. [a]Control variables included gender and education. UR, unimanual task, right hand;. BR, bimanual task, right hand; BL, bimanual task, left hand; PL, path length; EF, executive function; WM, working memory.
*$p < .05$. **$p < .01$.

4.3 | The role of executive function in right and left hand dexterity

Another important finding was that although EF predicted MTs of both hands in the older group, it was involved in kinematics of the left hand only. This result is consistent with the finding that dexterity of the left hand shows more pronounced decline in aging (Desrosiers et al., 1995; Lezak et al., 2012; Vasylenko et al., 2018). A possible explanation of our findings is that because the left hand is less practiced for precise movements than the right, the involvement of cognitive abilities in its control is more extensive than for the right hand. Importantly, path length was the only kinematic measure predicted by EF in the older group. This suggests that control of precision during left-hand movements is sensitive to executive decline in aging. However, memory and neuromuscular hand function were also associated with path lengths, although to a lesser degree. Thus, multiple factors may affect this kinematic parameter in the elderly, and the contributions of cognitive and neuromuscular changes in age-related decline of movement precision should be further investigated in future studies.

Despite the obtained findings on the involvement of EF in dexterity, it is not possible to establish whether normal executive deterioration in older adults drives a decline in manual ability. Research with toddlers suggests that the direction of this relationship is opposite in infancy, since development of hand preference predicts development of language (Michel et al., 2016). However, in aging, it is not evident that decline in dexterity may have an impact on cognitive decline. It might be possible that dexterity changes precede cognitive deterioration, but the existing research on dexterity in aging does not allow to reach conclusions about the direction of this relationship.

4.4 | Other predictors of dexterity

Whereas EF was the most consistent predictor of MTs and path lengths in the older group, physical hand function, Attention/WM, and Memory showed few associations with movement parameters. However, this does not mean they are not important in explaining age-related decline in dexterity. In our study, neither grip strength nor WM showed declines in the older group, which may be the reason for their limited involvement in explaining dexterity measures. More research is needed to fully understand how age-related deficits in various cognitive domains affect manual dexterity as they start to show decline.

Among the demographic variables, education was not a significant predictor in any of the models. Although some earlier research has suggested that high level of education might delay declines in gait in older adults (Elbaz et al., 2013), little is known about the role of education in dexterity decline. Future studies should aim to assess the role of education in age-related deficits in hand function and fine motor skills. In contrast, gender was a significant predictor of path length during both unimanual and bimanual grasping with the left hand in the older group, and with both hands in the bimanual task in the young group. The direction of the relationship showed that males had

TABLE 6 Hierarchical multiple regression analyses predicting kinematics of left hand from cognitive abilities in the older group

	U grasping PL		B grasping PL		B inserting PL	
Predictor	**ΔR^2**	**β**	**ΔR^2**	**β**	**ΔR^2**	**β**
Block 1[a]	.22**		.23		.03	
Gender		1.90**		1.40**		0.17
Education		−0.05		−1.11		−0.07
Block 2	.01		.10*		.01	
Grip/Tap		−0.37		−0.87*		0.54
Block 3	.12*		.06		.21*	
EF		−0.90**		−0.36		−0.80**
Attention/WM		−0.26		−0.29		−0.16
Memory		0.16		−0.25		−0.72**
Total R^2 change	.35**		.39**		.25*	
β(SE) by gender						
Males						
Grip/Tap			−0.87(0.67)			
EF	−0.96 (0.44)*				−0.63 (0.24)*	
Memory					−0.94 (0.25)**	
Females						
Grip/Tap			−0.98 (0.40)*			
EF	−0.86 (0.55)				−0.75 (0.59)	
Memory					−0.27 (0.47)	
β difference by gender						
Grip/Tap			n.s.			
EF	n.s.					n.s.
Attention/WM						n.s.

Only significant results are shown. [a]Control variables included gender and education. U, unimanual task; B, bimanual task; PL, path length; EF, executive function; WM, working memory.
*p < .05. **p < .01.

longer paths than females in all models where gender was significant. This is consistent with our recent finding (Vasylenko et al., 2018) that males have longer paths than females during grasping, possibly indicating that males employ a less efficient strategy to perform this action.

4.5 | Effect of gender on the association between cognitive abilities and dexterity

The second aim of the present study was to assess gender differences in the relationship between cognitive abilities and dexterity. For the older group, no significant gender differences were found in the relationships between cognitive abilities, hand function, and dexterity parameters. None of the regression slopes for either MTs or kinematics were significantly different between the genders in the older group, indicating that cognitive abilities predicted dexterity equally well for both genders. However, it is important to note that performing regression analyses separately by age group and then further comparing the regression slopes between genders within each age group resulted in rather limited sample sizes. Performing separate analyses on relatively small subgroups might have been the reason for the lack of gender differences in the present study. Studies with larger sample sizes need to be conducted to further evaluate the role of gender in the relationship between cognitive function and dexterity in older adults.

Interestingly, in the young group, we found a gender difference in the relationship between Attention/WM and path length during grasping with the right hand. Comparison of regression slopes showed that Attention/WM was a better predictor of path length for males than for females. This finding was unexpected, and could perhaps indicate that some of the young males invested limited attentional resources in the task, whereas young females as a group invested more resources. This interpretation is consistent with research on gender differences in personality showing higher agreeableness in females compared to males (Weisberg, DeYoung, & Hirsh, 2011), which could lead to a stronger compliance to the study procedure.

4.6 | Limitations of the present study

The present study had some limitations. The first one concerns the nature of the sampling procedure. Specifically, we used convenience sampling rather than random selection from the population. This selection procedure might have resulted in an overrepresentation of physically and cognitively fit, as well as highly motivated, older adults, who volunteered for participation. These individuals might not be representative of the general population. Nevertheless, the obtained findings are valuable, because the proportion of older adults who are successful agers is increasing (Montross et al., 2006). The second limitation is closely related to the first, and concerns the lack of age difference in the Digits Backward Test. Because older adults had no deficits in working memory, they are less likely to show declines in dexterity due to reduced capacity in this cognitive ability. The role of working memory in manual ability should be further investigated in older adults with varying levels of cognitive decline. Furthermore, regarding the gender analysis, comparison of the regression slopes separately for each age group resulted in limited sample sizes within each group, which might have masked gender differences. On the other hand, gender difference was found in the young group, even given the small sample size. Future studies should employ larger samples of older adults to further explore the role of gender in dexterity decline. Finally, as mentioned in the companion article (Vasylenko et al., 2018), we evaluated handedness only in terms of the direction of hand preference., i.e., the tendency to choose one hand over the other to perform various actions, and not the strength of preference., i.e., how consistently one hand is preferred to the other. Thus, our sample likely contained participants with different degree of hand preference, such that some were consistent right-handers and some were mixed-handed with a self-reported preference for the right hand. Therefore, any interpretation of the findings in terms of hand dominance should be made with caution. However, all participants in the present study scored as right-handed on the Briggs-Nebes Handedness Inventory, which indicates a tendency toward right hand preference. Despite these limitations, our results provide a starting point and a reference for evaluation of the contribution of cognitive declines to dexterity performance in older adults.

5 | CONCLUSIONS

The present study is one of the first to explore the association of different cognitive abilities known to decline in aging with a comprehensive set of dexterity measures that included MTs and kinematics during unimanual and bimanual tasks. Furthermore, our investigation provides clear evidence of the involvement of EF in the control of dexterity in older adults. The main finding is that EF is related to MTs of both hands and path length of the left hand. The type of action assessed was not determinant for the associations as significant results were observed in reaching, grasping, and inserting. Thus, evaluation of the associations EF-MTs and EF-path lengths might be useful to assess dexterity decline in the elderly population. Also, in accordance with previous reports (Bangert et al., 2010; Seidler et al., 2010), we confirmed the existence of different association patterns between dexterity and cognitive abilities among young and older adults. These patterns of associations should be investigated in future studies with different elderly populations to understand whether the impact of cognitive function on dexterity depends only on deterioration in cognitive and motor resources, or whether other physiological factors (i.e., cardiovascular problems, arousal level, decline in muscle mass) may additionally affect this association in older adults developing pathological states.

ORCID

Olena Vasylenko http://orcid.org/0000-0003-2300-2079

REFERENCES

Andrade, J. M., & Estévez-Pérez, M. G. (2014). Statistical comparison of the slopes of two regression lines: A tutorial. *Analytica Chimica Acta*, *838*, 1–12.

Baldauf, D., & Deubel, H. (2010). Attentional landscapes in reaching and grasping. *Vision Research*, *50*, 999–1013.

Bangert, A. S., Reuter-Lorenz, P. A., Walsh, C. M., & Schachter, A. (2010). Bimanual coordination and aging: Neurobehavioral implications. *Neuropsychologia*, *48*, 1165–1170.

Beck, A. J., Steer, R. A., & Brown, G. (1996). *BDI-II, Beck depression inventory: Manual*. San Antonio, TX: Psychological Corp.

Briggs, G. G., & Nebes, R. D. (1975). Patterns of hand preference in a student population. *Cortex*, *11*(3), 230–238.

Carmeli, E., Patish, H., & Coleman, R. (2003). The aging hand. *Journal of Gerontology: Medical Sciences*, *58A*(2), 146–152.

Cole, K. J., Rotella, D. L., & Harper, J. G. (1998). Tactile impairments cannot explain the effect of age on a grasp and lift task. *Experimental Brain Research*, *121*(3), 263–269.

Coxon, J. P., Goble, D. J., Van Impe, A., De Vos, J., Wenderoth, N., & Swinnen, S. P. (2010). Reduced basal ganglia function when elderly switch between coordinated movement patterns. *Cerebral Cortex*, *20*, 2368–2379.

Craik, I. M., & Bialystok, E. (2006). Cognition through the lifespan: Mechanisms of change. *Trends in Cognitive Sciences*, *10*(3), 131–138.

Cropley, V. L., Fujita, M., Innis, R. B., & Nathan, P. J. (2006). Molecular imaging of the dopaminergic system and its association with human cognitive function. *Biological Psychiatry*, *59*, 898–907.

Dayanidhi, S., & Valero-Cuevas, J. (2014). Dexterous manipulation is poorer at older ages and is dissociated from decline of hand strength. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *69*(9), 1139–1145.

Desrosiers, J., Hebert, R., Bravo, G., & Dutil, E. (1995). The Purdue Pegboard Test: Normative data for people aged 60 and over. *Disability and Rehabilitation*, *17*(5), 217–224.

Diermayr, G., McIsaac, T. L., & Gordon, A. M. (2011). Finger force coordination underlying object manipulation in the elderly—a mini-review. *Gerontology*, *57*, 217–227.

Drag, L. L., & Bieliauskas, L. A. (2010). Contemporary review 2009: cognitive aging. *Journal of Geriatric Psychiatry and Neurology*, *23*(2), 75–93.

Elbaz, A., Vicente-Vytopilova, P., Tavernier, B., Sabia, B., Dumurgier, J., Mazoyer, B., . . . Tzourio, C. (2013). Motor function in the elderly: Evidence for the reserve hypothesis. *Neurology*, *81*, 417–426.

Emborg, M. E., Ma, S. Y., Mufson, E. J., Levey, A. I., Taylor, M. D., Brown, W. D., . . . Kordower, J. H (1998). Age-related declines in nigral neuronal function correlate with motor impairments in rhesus monkeys. *Journal of Computational Neurology*, *401*(2), 253–265.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). «Mini-mental state»: a practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198.

Fraser, S. A., Li, K. Z., & Penhune, V. B. (2010). Dual-task performance reveals increased involvement of executive control in fine motor sequencing in healthy aging. *Journal of Gerontology: Psychological Sciences*, *65B*(5), 526–535.

Golden, C. J. (1978). *Stroop color and word test: a manual for clinical and experimental uses*. Wood Dale, IL: Stoelting.

Heinunckx, S., Wenderoth, N., Debaere, F., Peeters, R., & Swinnen, S. P. (2005). Neural basis of aging: The penetration of cognition into action control. *Journal of Neuroscience*, *25*(29), 6787–6796.

Jurado, M. B., & Rosselli, M. (2007). The elusive nature of executive functions: A review of our current understanding. *Neuropsychologia Review Articles*, *17*, 213–233.

Kinoshita, H., & Francis, P. R. (1996). A comparison of prehension force control in young and elderly individuals. *European Journal of Applied Physiology and Occupational Physiology*, *74*(5), 450–460.

Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D. (2012). *Construction and motor performance. In Neuropsychological Assessment*. 5th ed. New York, NY: Oxford University Press, (pp. 568–617).

Martin, J. A., Ramsay, J., Hughes, C., Peters, D. M., & Edwards, M. G. (2015). Age and grip strength predict hand dexterity in adults. *PLoS ONE*, *10*(2), e0117598.

McCarrey, A. C., An, Y., Kitner-Triolo, M. H., Ferrucci, L., & Resnick, S. M. (2016). Sex differences in cognitive trajectories in clinically normal older adults. *Psychology and Aging*, *31*(2), 166–175.

Michel, G. F., Campbell, J. M., Marcinowski, E. C., Nelson, E. L., & Babik, I. (2016). Infant hand preference and the development of cognitive abilities. *Frontiers in Psychology*, *7*, 410.

Montross, L. P., Depp, C., Daly, J., Reichstadt, J., Golshan, S., Moore, D., . . . Jeste, D. V. (2006). Correlates of self-rated successful aging among community-dwelling older adults. *The American Journal of Geriatric Psychiatry*, *14*(1), 43–51.

Ota, M., Obata, T., Akine, Y., Ito, H., Ikehira, H., Asada, T., . . . Suhara, T. (2006). Age-related degeneration of corpus callosum measured with diffusion tensor imaging. *Neuroimage*, *31*(4), 1445–1452.

Parikh, P. J., & Cole, K. J. (2012). Handling objects in old age: Forces and moments acting on the object. *Journal of Applied Physiology*, *112*, 1095–1104.

Ranganathan, V. K., Siemionow, V., Sahgal, V., & Guang, H. Y. (2001). *Journal of the American Geriatrics Society*, *49*, 1478–1484.

Reitan, R. M., & Wolfson, D. (1993). *The Halstead-Reitan neuropsychological test battery: Theory and clinical interpretation*. 2nd ed. Tucson, AZ: Neuropsychology Press.

Reuter-Lorenz, P. A., & Lustig, C., (2017). Working memory and executive functions in the aging brain. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive neuroscience of aging* (pp. 235–258). New York, NY: Oxford University Press.

Reuter-Lorenz, P. A., & Park, D. C (2010). Human neuroscience and the aging mind: A new look at old problems. *Journals of Gerontology: Psychological Sciences*, *65B*(4), 405–415.

Rodríguez-Aranda, C., Mittner, M., & Vasylenko, O. (2016). Association between executive functions, working memory, and manual dexterity in young and healthy older adults: An exploratory study. *Perceptual and Motor Skills*, *122*(1), 165–192.

Rosenbaum, D. A. (2009). *Human motor control*. 2nd ed. Academic Press.

Salat, D. H., Buckner, R. L., Snyder, A. Z., Greve, D. N., Desikan, R. S., Busa, E., . . . Fischl, B. (2004). Thinning of the cerebral cortex in aging. *Cerebral Cortex*, *14*(7), 721–730.

Salat, D. H., Tuch, D. S., Greve, D. N., van der Kouwe, A. J., Hevelone, N. D., Zaleta, A. K., . . . Dale, A. M. (2005). Age-related alterations in white matter microstructure measured by diffusion tensor imaging. *Neurobiology of Aging*, *26*(8), 1215–1227.

Scherder, E., Dekker, W., & Eggermont, L. (2008). Higher-level hand motor function in aging and (preclinical) dementia: Its relationship with (instrumental) activities of daily life—a mini-review. *Gerontology*, *54*, 333–341.

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., . . . Lipps, D. B. (2010). Motor control and aging: Links to age-related structural, functional, and biochemical effects. *Neuroscience and Biobehavioral Reviews*, *34*, 721–733.

Steinberg, F., & Bock, O. (2013). Influence of cognitive functions and behavioral context on grasping kinematics. *Experimental Brain Research*, *225*, 387–397.

Strenge, H., Niederberger, U., & Seelhorst, U. (2002). Correlation between tests of attention and performance on grooved and purdue pegboards in normal subjects. *Perceptual and Motor Skills*, *95*, 507–514.

Sullivan, E. V., Rohlfing, T., & Pfefferbaum, A. (2010). Quantitative fiber tracking of lateral and interhemispheric white matter systems in normal aging: Relations to timed performance. *Neurobiology of Aging*, *31*(3), 464–481.

Tabachnik, B. G., & Fidell, L. S. (2007). *Using multivariate statistics*. Boston, MA: Pearson Education.

Tiffin, J. (1968). *Purdue pegboard examiner manual*. Chicago, IL: Science Research Associates.

Tiffin, J., & Asher, E. J. (1948). The Purdue Pegboard: Norms and studies of reliability and validity. *Journal of Applied Psychology*, *32*(3), 234–247.

Tremblay, F., Wong, K., Sanderson, R., & Coté, L. (2003). Tactile spatial acuity in elderly persons: Assessment with grating domes and relationship with manual dexterity. *Somatosensory & Motor Research*, *20*(2), 127–132.

Vasylenko, O., Gorecka, M. M., & Rodríguez-Aranda, C. (2018). Manual dexterity in young and healthy older adults. 1. Age- and gender-related differences in unimanual and bimanual performance. *Developmental Psychobiology*.

Wang, W.-C., & Cabeza, R., (2017). Episodic memory encoding and retrieval in the aging brain. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive neuroscience of aging* (pp. 301–335). New York, NY: Oxford University Press.

Wechsler, D. (1997). *WMS-III: Wechsler memory scale administration and scoring manual*. Psychological Corporation.

Wechsler, D. (2014). Wechsler adult intelligence scale—Fourth edition (WAIS-IV).

Weisberg, Y. J., DeYoung, C. G., & Hirsh, J. B. (2011). Gender differences in personality across the ten aspects of the big five. *Frontiers in Psychology*, *2*, 178.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience*, *3*, 1212–1217.

Zanto, T. P., & Gazzaley, A., (2017). Selective attention and inhibitory control in the aging brain. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive neuroscience of aging* (pp. 207–234). New York, NY: Oxford University Press.

How to cite this article: Vasylenko O, Gorecka MM, Rodríguez-Aranda C. Manual dexterity in young and healthy older adults. 2. Association with cognitive abilities. *Developmental Psychobiology*. 2018;60:428–439. https://doi.org/10.1002/dev.21618

APPENDIX

Summary of age- and gender-related differences in movement times and kinematics

		Right hand				Left hand			
Unimanual task		**Reaching**	**Grasping**	**Transport**	**Inserting**	**Reaching**	**Grasping**	**Transport**	**Inserting**
MT	Age	OM > YM*	O > Y***	n.s.	O > Y**	O > Y***	O > Y***	O > Y***	O > Y**
	Gender	OM > OF*	OM > OF***	n.s.	M > F*	OM > OF*	OM > OF**	OM > OF**	n.s.
LinV	Age	n.s.	YM > OM**	n.s.	n.s.	Y > O**	n.s.	Y > O***	n.s.
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CV LinV	Age	n.s.	n.s.	Y > O*	n.s.	n.s.	n.s.	O > Y*	O > Y**
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
PL	Age	n.s.	O > Y***	n.s.	O > Y***	n.s.	O > Y***	O > Y*	O > Y***
	Gender	n.s.	M > F***	n.s.	M > F**	n.s.	M > F***	n.s.	n.s.
AngV	Age	n.s.	Y > O**	Y > O*	n.s.	n.s.	Y > O***	Y > O*	n.s.
	Gender	F > M**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CV AngV	Age	n.s.	n.s.	Y > O*	O > Y***	O > Y***	n.s.	n.s.	O > Y**
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	OM > OF**	n.s.	n.s.
Angle	Age	n.s.	O > Y*	n.s.	n.s.	n.s.	O > Y***	n.s.	n.s.
	Gender	M > F**	M > F**	M > F*	n.s.	M > F*	M > F*	M > F**	M > F*
CV angle	Age	n.s.	n.s.	n.s.	n.s.	n.s.	Y > O**	n.s.	n.s.
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Bimanual task									
MT	Age	OM > YM**	O > Y***	n.s.	O > Y**	O > Y***	O > Y***	O > Y***	O > Y**
	Gender	OM > OF**	OM > OF***	OM > OF*	n.s.	n.s.	OM > OF***	OM > OF*	n.s.
LinV	Age	n.s.	YM > OM**	n.s.	n.s.	Y > O***	YM > OM**	Y > O***	n.s.
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CV LinV	Age	n.s.	n.s.	n.s.	O > Y***	n.s.	n.s.	n.s.	O > Y**
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
PL	Age	n.s.	O > Y***	n.s.	O > Y***	n.s.	O > Y***	n.s.	O > Y***
	Gender	n.s.	M > F***	n.s.	M > F*	n.s.	M > F***	n.s.	n.s.
AngV	Age	n.s.	Y > O**	n.s.	n.s.	n.s.	Y > O***	Y > O*	n.s.
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CV AngV	Age	O > Y*	n.s.	n.s.	O > Y***	O > Y***	n.s.	Y > O***	O > Y**
	Gender	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Angle	Age	n.s.	n.s.	n.s.	n.s.	n.s.	O > Y**	n.s.	n.s.
	Gender	M > F**	M > F**	M > F**	M > F**	M > F**	M > F**	M > F**	M > F*
CV angle	Age	n.s.	n.s.	n.s.	n.s.	n.s.	Y > O***	n.s.	n.s.
	Gender	F > M**	n.s.	n.s.	n.s.	F > M*	n.s.	n.s.	n.s.

MT, movement time; LinV, linear velocity; CV, coefficient of variation; PL, path length; AngV, angular velocity; n.s., non-significant; Y, young; O, older; M, male; F, female; YM, young male; OM, older male; OF, older female; Y > O, mean value is larger in the younger group.

***$p < .001$. **$p < .01$. *$p < .05$.