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Manual Dexterity in Young and Healthy Older Adults. 1. Age- and Gender-Related Differences in Unimanual and Bimanual Performance

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Manual Dexterity in Young and Healthy Older Adults. 1. Age- and Gender-Related Differences in Unimanual and Bimanual Performance

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Running title: AGE AND GENDER DIFFERENCES IN DEXTERITY

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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, manual dexterity, kinematics, unimanual, bimanual, gender

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Manual Dexterity in Young and Healthy Older Adults. 1. Age- and Gender-Related Differences in Unimanual and Bimanual Performance

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, Hebert, 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, 2000). 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,

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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, Tigges, Schröter, Möller, & Hegerl, 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

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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

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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

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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, Hébert, Bravo, & Dutil, 1995; 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.

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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, 1996). Specifically, Gur et al. (1996) 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, Azcoitia, & DonCarlos, 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 & 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

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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.

Method

Participants

Forty-five young and 55 healthy, community-dwelling older adults participated in the study. Young adults (26 female, M_{age} = 22.8 years, range: 19-31 years) were recruited through flyers posted at the university campus. Older adults (25 female, M_{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, Steer, & Brown, 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-

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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.

Measures

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, under review.) 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 since 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

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unimanually with both the right and the left hand. The LI value of 0 is commonly used to indicate equal performance with either hand, i.e., no hand preference in the given task, whereas positive and negative LI values indicate better performance with the right and left hand, i.e., 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, i.e., 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.

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).

--- Insert Figure 1 about here ---

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

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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 one minute for the last subtest.

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., 1995). 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.

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

--- Insert Table 1 about here ---

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

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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.

--- Insert Figure 2 about here ---

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.

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 = .91, 95% CI

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[.89, .93]; for grasping, ICC = .97, 95% CI [.96, .98]; for transport, ICC = .92, 95% CI [.90, .94]; for inserting, ICC = .96, 95% CI [.95, .97]. Thus, the MT measures had a high degree of consistency (Rankin & Stokes, 1998).

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 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

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same angles, provided information about the speed of hand rotation during each movement. Larger 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.

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 minutes for young and 60 minutes for older participants.

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

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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 .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).

Results

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 = .102), MMSE ($M(SD)_{young}$ = 29.47(0.81), $M(SD)_{older}$ = 29.44(0.90), p = .861), or BDI scores ($M(SD)_{young}$ = 5.29(3.09), $M(SD)_{older}$ = 3.87(3.91), p = .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 = .004), but significantly lower Mental Health scores than the older ($M(SD)_{young}$ = 47.40(8.20), $M(SD)_{older}$ = 53.98(6.47), $p < .001$). 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

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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), $p < .001$), 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), $p < .001$). 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 nine older), 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.

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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.

Reaching. Mean values and *SD*s by Age and Gender are given in Table 2.

--- Insert Table 2 about here ---

There was a main effect of Age, $F(1, 96) = 19.54$, $p < .001$, $\eta^2_p = .169$, and an Age × Gender interaction, $F(1, 96) = 7.35$, $p = .008$, $\eta^2_p = .071$. 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), $p < .001$, $\eta^2_p = .202$. Older males were also slower than older females (M = 390.16, SD = 40.20), $p = .024$, $\eta^2_p = .052$. The Hand × Age interaction was significant, $F(1, 96) = 29.74$, $p < .001$, $\eta^2_p = .237$, 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), $p < .001$, $\eta^2_p = .286$)). Finally, the Task × Hand × Gender interaction was significant, $F(1, 96) = 16.85$, $p < .001$, $\eta^2_p = .149$. Simple effects of Gender showed that males were faster than females when reaching with the right hand in the unimanual task ($p = .048$, $\eta^2_p = .040$). (See Table 2 for mean values and *SD*s by Gender).

Grasping. Mean values and *SD*s by Age and Gender are given in Table 3.

--- Insert Table 3 about here ---

Time spent on grasping showed significant main effects of Age, $F(1, 96) = 74.33$, $p < .001$, $\eta^2_p = .436$, Gender, $F(1, 96) = 19.82$, $p < .001$, $\eta^2_p = .171$, and an Age × Gender interaction, $F(1, 96) = 12.90$, $p = .001$, $\eta^2_p = .118$. 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), $p < .001$, $\eta^2_p = .121$) and for males ($M(SD)_{young}$ = 676.05(175.10), $M(SD)_{older}$ = 1109.65(175.10), $p < .001$, $\eta^2_p = .426$). Additionally, older males were slower than older females, $p < .001$, $\eta^2_p = .274$. The Hand × Age interaction was also significant, $F(1, 96) = 8.42$, $p < .005$, $\eta^2_p = .081$. Pairwise comparisons showed that the older group was slower than the younger, both with the right ($M(SD)_{young}$ = 688.25(200.13), $M(SD)_{older}$ = 1038.28(198.52), $p < .001$, $\eta^2_p = .443$) and with the left hand ($M(SD)_{young}$ = 633.34(185.02), $M(SD)_{older}$ = 895.47(183.53), $p < .001$, $\eta^2_p = .343$). Finally, the Task × Gender interaction was significant, $F(1, 96) = 4.24$, $p = .042$, $\eta^2_p = .042$. Simple effects of Gender showed that males were slower than females in both unimanual ($M(SD)_{male}$ = 885.41(203.85), $p < .001$, $\eta^2_p = .189$) and bimanual grasping ($M(SD)_{male}$ = 900.30(189.46), $p = .001$, $\eta^2_p = .105$).

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Transport. Mean values and SDs by Age and Gender are given in Table 4.

--- Insert Table 4 about here ---

For transport times, there was a significant main effect of Age, $F(1, 96) = 23.34$, $p < .001$, $\eta^2_p = .196$, and an Age × Gender interaction, $F(1, 96) = 8.72$, $p = .004$, $\eta^2_p = .083$, which showed that older males were slower than younger males ($M(SD)_{young} = 384.66(55.53)$), $M(SD)_{older} = 472.28(55.52)$, $p < .001$, $\eta^2_p = .232$). Older males were also slower than older females ($M(SD)_{female} = 425.72(55.53)$, $p = .003$, $\eta^2_p = .091$). Moreover, the Hand × Age interaction was significant, $F(1, 96) = 37.32$, $p < .001$, $\eta^2_p = .280$, as well as the Task × Hand × Age interaction, $F(1, 96) = 6.25$, $p = .014$. 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 *p*s < .001, $\eta^2_p = .383$ and $\eta^2_p = .149$ for the unimanual and bimanual task, respectively).

Inserting. Mean values and SDs by Age and Gender are given in Table 5.

--- Insert Table 5 about here ---

For inserting time, there was a main effect of Age, $F(1, 96) = 33.40$, $p < .001$, $\eta^2_p = .258$, and three interactions involving Age were significant, Task × Age, $F(1, 96) = 5.22$, $p = .025$, $\eta^2_p = .052$, Hand × Age, $F(1, 96) = 5.37$, $p = .023$, $\eta^2_p = .053$, and Task × Hand × Age, $F(1, 96) = 4.51$, $p = .036$, $\eta^2_p = .045$. 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 *p*s < .01, $\eta^2_p = .235$ and $\eta^2_p = .117$ for the right and left hand, respectively, in the unimanual task; $\eta^2_p = .211$ and $\eta^2_p = .215$ for the right and left hand, respectively, in the bimanual task). A Task × Hand × Gender interaction was also significant, $F(1, 96) = 4.31$, $p = .041$, $\eta^2_p = .043$. Simple effect of Gender was only found in the unimanual task with the right hand, with females inserting faster than males, $p < .05$, $\eta^2_p = .066$.

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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.

Kinematic Results

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

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, $F(1, 96) = 17.37$, $p < .001$, $\eta^2_p = .153$, showing higher variability in the older group ($M(SD) = .68(.07)$) than the younger ($M(SD) = .62(.07)$). Significant main effects of Gender were found for angle, $F(1, 96) = 12.38$, $p = .001$, $\eta^2_p = .114$, and CV of angle, $F(1, 96) = 9.71$, $p = .002$, $\eta^2_p = .092$. 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 ($M(SD) = .19(.05)$) than males ($M(SD) = .15(.05)$).

Two-way interaction. A Hand × Age interaction was significant for linear velocity, $F(1, 96) = 11.14$, $p < .001$, $\eta^2_p = .104$. Pairwise comparisons revealed that the older group was slower than the young, but only with the left hand, ($M(SD)_{young} = 37.52(4.78)$, $M(SD)_{older} = 34.19(4.74)$, $p < .001$, $\eta^2_p = .112$).

Three-way interaction. A Task × Hand × Gender interaction was significant for linear velocity, $F(1, 96) = 7.97$, $p = .006$, $\eta^2_p = .077$, and path length, $F(1, 96) = 8.82$, $p = .004$, $\eta^2_p = .084$. Males had higher linear velocity than females when reaching with the right hand in the

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unimanual task (p = .045, η^2_p = .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.

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, $F(1, 96) = 18.97$, $p < .001$, $\eta^2_p = .166$, path length, $F(1, 96) = 48.70$, $p < .001$, $\eta^2_p = .339$, angle, $F(1, 96) = 12.85$, $p = .001$, $\eta^2_p = .119$, and CV of angle, $F(1, 96) = 7.90$, $p = .006$, $\eta^2_p = .077$. 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 ($M(SD)_{young}$ = .27(.10), $M(SD)_{older}$ = .21(.10)). Significant main effects of Gender were found for path length, $F(1, 96) = 32.03$, $p < .001$, $\eta^2_p = .252$, and angle, $F(1, 96) = 10.83$, $p = .001$, $\eta^2_p = .102$, 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 effect for linear velocity was found, $F(1, 96) = 7.77$, $p = .006$, $\eta^2_p = .076$. This effect is described below with the Age × Gender interaction.

Two-way interactions. An Age × Gender interaction was found for linear velocity, $F(1, 96) = 8.12$, $p = .006$, $\eta^2_p = .079$, showing that older males ($M(SD)$ = 6.54(0.99) were

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slower than younger males ($M(SD)$ = 7.56(0.99), p = .001, η^2_p = .115). Moreover, simple effect of Gender showed that younger males were faster than younger females ($M(SD)$ = 6.43(0.99)), p < .001, η^2_p = .132). A Hand × Age interaction was significant for path length, F(1, 96) = 8.04, p = .006, η^2_p = .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 < .001, η^2_p = .325 and η^2_p = .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 = .002, η^2_p = .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 < .05, η^2_p = .051 and η^2_p = .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 = .001, η^2_p = .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.

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 < .001, η^2_p = .148, angular velocity, F(1, 96) = 12.67, p = .001, η^2_p = .117, and CV of angular velocity, F(1, 96) = 14.21, p < .001, η^2_p = .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 = .001, η^2_p = .118, showing larger angles in males ($M(SD)$ = 54.13(6.54) than in females ($M(SD)$ = 49.52(6.37)), p = .001.

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Two-way interactions. A Task × Age interaction was significant for angular velocity, $F(1, 96) = 10.21$, $p = .002$, $\eta^2_p = .096$. 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 < .05, $\eta^2_p = .160$ and $\eta^2_p = .048$ for the unimanual and bimanual task, respectively. A Hand × Gender interaction was also found for angular velocity, $F(1, 96) = 9.29$, $p = .003$, $\eta^2_p = .088$. Angular velocity was lower in males, but only with the right hand ($M(SD)_{female} = 68.61(19.07)$, $M(SD)_{male} = 58.33(19.57)$, $p = .009$, $\eta^2_p = .069$). Furthermore, a Hand × Age interaction was significant for linear velocity, $F(1, 96) = 14.91$, $p < .001$, $\eta^2_p = .134$. 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 *p*s < .05, $\eta^2_p = .041$ and $\eta^2_p = .276$ for the right and left hand, respectively).

Three-way interactions. A Task × Hand × Age interaction was found for CV of linear velocity, $F(1, 96) = 52.24$, $p < .001$, $\eta^2_p = .352$, CV of angular velocity, $F(1, 96) = 9.25$, $p = .003$, $\eta^2_p = .088$, and path length, $F(1, 96) = 12.13$, $p < .001$, $\eta^2_p = .123$. 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 *p*s < .05, $\eta^2_p = .136$ and $\eta^2_p = .179$ 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, $p < .001$, $\eta^2_p = .203$. In contrast, the older group had higher variability than young in the unimanual task, $p = .049$, $\eta^2_p = .040$. 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, $p = .028$, $\eta^2_p = .049$.

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

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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.

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, $F(1, 96) = 17.71$, $p < .001$, $\eta^2_p = .156$, CV of angular velocity, $F(1, 96) = 26.22$, $p < .001$, $\eta^2_p = .215$, and path length, $F(1, 96) = 43.70$, $p < .001$, $\eta^2_p = .313$. Compared to the young group, the older group had higher CV of linear velocity ($M(SD)_{young} = .65(.06)$, $M(SD)_{older} = .70(.06)$, $p < .001$) and higher CV of angular velocity ($M(SD)_{young} = .85(.11)$, $M(SD)_{older} = .96(.11)$, $p < .001$). 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, $F(1, 96) = 8.78$, $p = .004$, $\eta^2_p = .084$, revealing larger angles in males ($M(SD) = 46.92(7.05)$) than in females ($M(SD) = 42.79(6.88)$), $p = .004$.

Two-way interaction. A significant Hand × Gender interaction was found for path length, $F(1, 96) = 8.38$, $p = .005$, $\eta^2_p = .080$. 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)), $p = .006$, $\eta^2_p = .076$.

Three-way interaction. A Task × Hand × Age interaction was significant for path length, $F(1, 96) = 14.26$, $p < .001$, $\eta^2_p = .129$. The older group had longer paths than the young across hands and tasks (all *p*s < .001, $\eta^2_p = .242$ and $\eta^2_p = .129$ for the right and left hand, respectively, in the unimanual task; $\eta^2_p = .244$ and $\eta^2_p = .347$ 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.

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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.

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

--- Insert Table 6 about here ---

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.

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

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hands, in unimanual and bimanual tasks. This approach expanded on our previous pilot study, since 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.

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., 2001; 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

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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.

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.

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 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 & 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

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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.

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

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al., 1995; 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, since 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 & 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.

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Effect Sizes

Significant effects of all sizes were obtained in the present study: small (i.e., η^2_p > .01), medium (i.e., η^2_p > .06), and large (i.e., η^2_p > .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.

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 and Nebes Handedness Inventory. However, the two performance tests of handedness did indicate no preference or left hand preference in nine participants. Even

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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, Pryde, & Roy, 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

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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.

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

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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.

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, i.e., 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.

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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

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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	.29(.05)	.29(.04)	.29(.04)	.30(.04)	.28(.05)	.31(.04)	.30(.04)	.30(.04)	.38(.05)	.44(.05)	.42(.07)	.40(.05)	.37(.04)	.38(.05)	.45(.06)	.42(.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	.34(.07)	.32(.07)	.32(.07)	.34(.07)	.32(.06)	.36(.07)	.32(.08)	.32(.06)	.45(.04)	.48(.07)	.46(.06)	.47(.06)	.44(.04)	.46(.04)	.48(.06)	.49(.08)
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	.64(.12)	.67(.13)	.67(.14)	.66(.12)	.66(.15)	.63(.11)	.67(.13)	.68(.12)	.60(.09)	.68(.11)	.64(.10)	.64(.12)	.61(.09)	.59(.09)	.67(.10)	.69(.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	.16(.07)	.14(.05)	.13(.05)	.16(.06)	.14(.06)	.17(.07)	.12(.05)	.15(.05)	.22(.07)	.19(.06)	.20(.07)	.22(.06)	.21(.08)	.23(.06)	.19(.07)	.19(.06)
	Bimanual task															
	Right hand								Left hand							
	Y	O	M	F	YM	YF	OM	OF	Y	O	M	F	YM	YF	OM	OF
MT	.40(.04)	.43(.07)	.43(.07)	.40(.05)	.40(.03)	.40(.05)	.45(.08)	.40(.05)	.40(.05)	.45(.05)	.43(.06)	.42(.06)	.38(.05)	.41(.05)	.46(.05)	.44(.06)
LinV	37.4(5.3)	35.3(5.2)	35.8(5.3)	36.6(5.35)	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	.43(.05)	.40(.05)	.41(.05)	.42(.05)	.42(.06)	.44(.04)	.40(.05)	.40(.06)	.43(.05)	.43(.04)	.42(.05)	.43(.05)	.43(.06)	.43(.05)	.43(.04)	.43(.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	.63(.10)	.69(.13)	.69(.11)	.63(.13)	.65(.09)	.61(.11)	.72(.12)	.66(.15)	.60(.09)	.67(.09)	.66(.10)	.62(.09)	.63(.09)	.57(.08)	.67(.10)	.67(.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	.16(.07)	.16(.08)	.14(.08)	.18(.07)	.12(.05)	.19(.08)	.15(.09)	.18(.07)	.18(.08)	.15(.05)	.15(.05)	.18(.07)	.16(.06)	.19(.09)	.14(.05)	.17(.05)

Note. 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.

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Table 3. *Movement Times and Kinematics during Grasping 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	0.69(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(.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	.66(.10)	.66(.08)	.66(.09)	.66(.08)	.66(.11)	.66(.09)	.67(.07)	.65(.08)	.58(.07)	.53(.07)	.54(.07)	.57(.07)	.57(.06)	.59(.07)	.53(.08)	.54(.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	.74(.13)	.77(.09)	.77(.09)	.75(.13)	.77(.08)	.72(.15)	.77(.10)	.79(.09)	.71(.09)	.74(.08)	.74(.09)	.71(.08)	.70(.10)	.72(.09)	.77(.08)	.70(.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	.28(.15)	.24(.13)	.24(.12)	.29(.16)	.24(.12)	.31(.17)	.23(.12)	.26(.14)	.28(.14)	.20(.09)	.23(.13)	.24(.12)	.27(.15)	.21(.11)	.21(.11)	.19(.07)
	Bimanual task															
	Right hand								Left hand							
	Y	O	M	F	YM	YF	OM	OF	Y	O	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	.61(.07)	.61(.09)	.60(.08)	.61(.08)	.60(.06)	.61(.07)	.60(.09)	.62(.10)	.58(.06)	.56(.07)	.56(.06)	.58(.07)	.57(.07)	.59(.05)	.55(.06)	.56(.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	.73(.08)	.75(.09)	.74(.07)	.74(.10)	.74(.06)	.72(.10)	.74(.07)	.75(.10)	.73(.10)	.75(.07)	.76(.07)	.73(.10)	.73(.08)	.73(.12)	.77(.06)	.73(.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	.24(.16)	.22(.12)	.20(.11)	.26(.16)	.18(.09)	.28(.18)	.21(.12)	.23(.13)	.28(.14)	.17(.08)	.19(.10)	.24(.12)	.24(.12)	.30(.15)	.16(.07)	.18(.10)

Note. 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.

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Table 4. *Movement Times and Kinematics during Transport 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	0.30(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	.35(.07)	.29(.07)	.31(.09)	.31(.06)	.34(.09)	.35(.06)	.29(.08)	.29(.06)	.40(.05)	.44(.05)	.42(.06)	.43(.05)	.39(.05)	.41(.05)	.44(.05)	.45(.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	.80(.10)	.76(.11)	.74(.09)	.82(.11)	.77(.09)	.83(.10)	.72(.08)	.80(.12)	.85(.11)	.82(.10)	.83(.10)	.84(.12)	.84(.10)	.86(.12)	.82(.09)	.81(.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	.13(.07)	.10(.04)	.09(.04)	.13(.06)	.10(.05)	.15(.07)	.09(.04)	.10(.03)	.17(.07)	.14(.06)	.15(.06)	.17(.07)	.15(.07)	.19(.07)	.14(.06)	.14(.06)
	Bimanual task															
	Right hand								Left hand							
	Y	O	M	F	YM	YF	OM	OF	Y	O	M	F	YM	YF	OM	OF
MT	0.44(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	.39(.04)	.40(.04)	.39(.04)	.39(.04)	.37(.04)	.40(.04)	.40(.04)	.39(.04)	.44(.05)	.42(.05)	.44(.05)	.43(.05)	.45(.06)	.44(.04)	.43(.05)	.41(.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	.81(.09)	.77(.10)	.77(.09)	.81(.10)	.78(.08)	.83(.09)	.76(.09)	.79(.10)	.96(.14)	.83(.10)	.86(.11)	.92(.15)	.94(.11)	.97(.15)	.81(.08)	.86(.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	.13(.06)	.12(.06)	.11(.06)	.14(.06)	.11(.05)	.15(.07)	.11(.07)	.13(.05)	.12(.05)	.12(.06)	.11(.05)	.12(.06)	.11(.05)	.13(.05)	.12(.05)	.12(.06)

Note. 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.

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Table 5. *Movement Times and Kinematics during Inserting by Age and Gender.*

	Right hand								Left hand							
	Y	O	M	F	YM	YF	OM	OF	Y	O	M	F	YM	YF	OM	OF
Unimanual task																
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	.71(.13)	.74(.09)	.75(.11)	.71(.11)	.73(.13)	.70(.13)	.75(.10)	.72(.09)	.59(.07)	.63(.08)	.63(.08)	.60(.08)	.59(.08)	.59(.07)	.65(.07)	.61(.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	.81(.14)	.92(.13)	.90(.15)	.85(.11)	.83(.14)	.80(.14)	.94(.14)	.90(.11)	.83(.14)	.93(.15)	.90(.15)	.87(.16)	.83(.14)	.82(.15)	.95(.14)	.91(.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	.18(.08)	.21(.08)	.19(.08)	.20(.09)	.16(.09)	.19(.08)	.20(.08)	.22(.09)	.19(.08)	.20(.09)	.18(.08)	.21(.09)	.17(.08)	.20(.08)	.19(.08)	.21(.09)
Bimanual task																
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(.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	.66(.11)	.74(.11)	.71(.12)	.70(.12)	.64(.09)	.67(.12)	.75(.11)	.73(.11)	.63(.08)	.68(.09)	.67(.09)	.65(.09)	.63(.07)	.64(.08)	.70(.09)	.66(.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	.87(.12)	.98(.16)	.96(.17)	.93(.15)	.86(.12)	.87(.13)	.97(.16)	.98(.16)	.88(.16)	.98(.14)	.94(.15)	.94(.17)	.87(.16)	.89(.16)	.98(.13)	.98(.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	.16(.07)	.20(.08)	.17(.07)	.19(.08)	.14(.07)	.17(.06)	.19(.07)	.20(.09)	.15(.08)	.17(.06)	.15(.06)	.18(.08)	.13(.06)	.17(.10)	.15(.05)	.19(.07)

Note. 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.

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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.
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							
		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.
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.

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Gender	F > M**	n.s.	n.s.	n.s.	F > M*	n.s.	n.s.	n.s.

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

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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)*	--

Note. 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. *** $p < .001$. ** $p < .01$. * $p < .05$. -- = effect not involved in the given interaction or has been reported as part of main text. n.s. = non-significant.

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Appendix B. *Multivariate Effects on Kinematics by Type of Movement*

Factor	Reaching		Grasping		Transport		Inserting	
	F	η^2_p	*F*	η^2_p	*F*	η^2_p	*F*	η^2_p
Task	58.86***	.821[a]	65.62***	.838	89.15***	.874	44.81***	.777
Hand	65.96***	.837	56.49***	.816	73.64***	.851	39.31***	.754
Age	5.38***	.295	14.61***	.535	5.67***	.306	10.70***	.454
Gender	2.98**	.188	5.67***	.308	3.80**	.228	3.48**	.213
Age × Gender	1.94	.131	3.23**	.203	1.88	.128	1.32	.093
Task × Hand	80.52***	.862	39.82***	.758	37.66***	.745	21.29***	.623
Task × Age	3.99**	.237	1.39	.099	3.17**	.198	0.53	.039
Task × Gender	3.03**	.191	1.42	.100	0.90	.066	0.57	.043
Hand × Age	5.75***	.309	4.60***	.266	6.38***	.332	0.96	.068
Hand × Gender	0.89	.064	1.35	.096	1.94	.131	0.85	.062
Task × Hand × Age	1.27	.090	2.18*	.146	9.53***	.426	4.13**	.243
Task × Hand × Gender	4.99***	.280	1.65	.115	3.47**	.213	2.34*	.154
Task × Hand × Age × Gender	0.89	.065	1.52	.107	0.43	.033	1.35	.095

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

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Figure caption

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

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.

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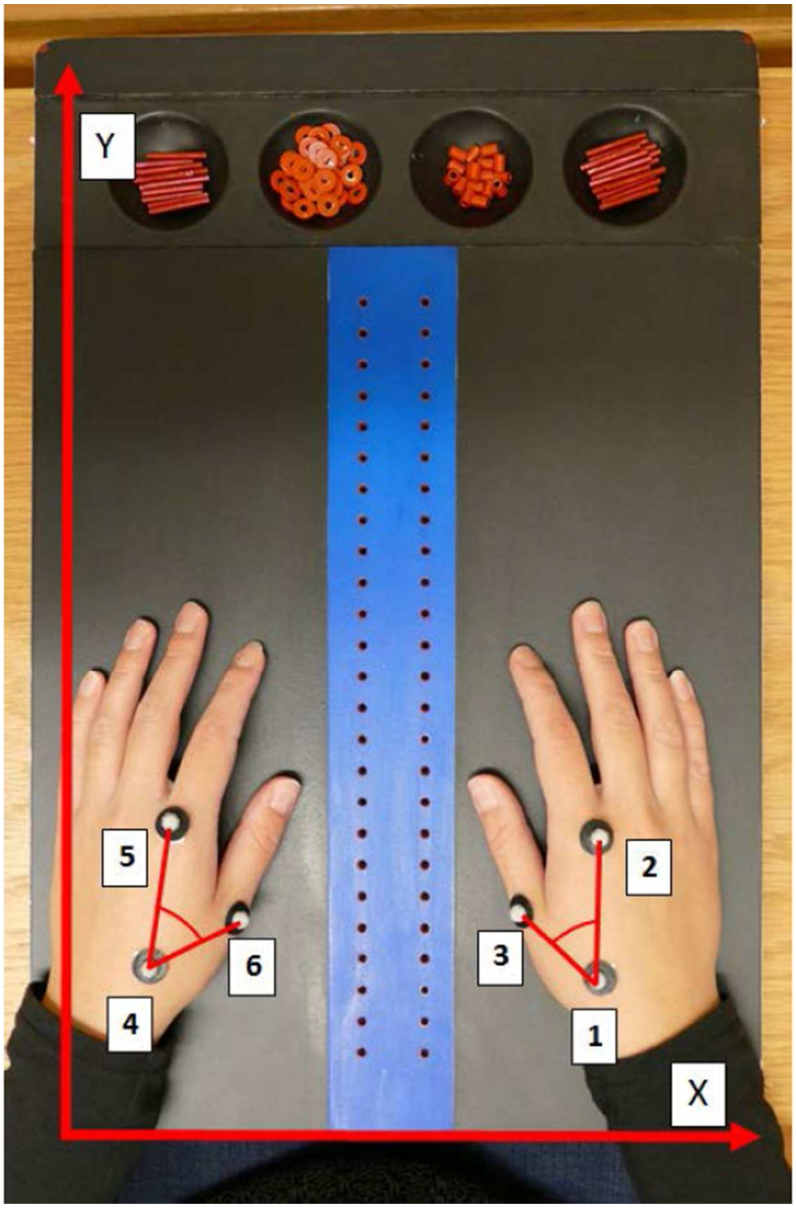

The Purdue Pegboard and marker arrangement, with angles used for kinematic analysis overlaid.

141x213mm (96 x 96 DPI)

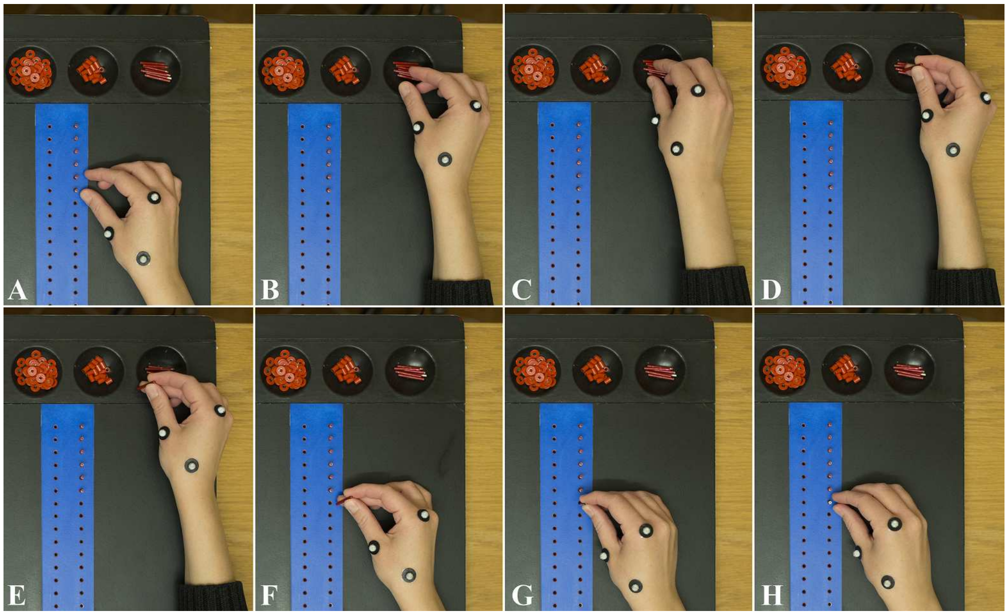

Figure 2. Onset and offset points for the different movement types during unimanual performance with right hand. A. Reaching onset. B. Reaching offset. C. Grasping onset. D. Grasping offset. E. Transport onset. F. Transport offset. G. Inserting onset. H. Inserting offset.

211x128mm (300 x 300 DPI)

Review