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Manual Dexterity in Young and Healthy Older Adults. 2. Association with Cognitive Abilities

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Running title: DEXTERITY AND COGNITIVE ABILITIES

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

Manual Dexterity in Young and Healthy Older Adults. 2. Association with Cognitive Abilities

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, 2000). 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, 2004), 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) 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). Secondly, 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, under review), 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., under review). 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., under review)), 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., under review). 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.

Method

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. (under review). 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. (under review). 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.

Measures

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., under review). 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. (under review) for a full description of dexterity assessment.

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).

Procedure

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

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., under review) 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).

Results

Demographics and Neuropsychological Results

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

--- Insert Table 1 about here ---

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.

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.

--- Insert Table 2 about here ---

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.

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., under review; 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.

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).

--- Insert Table 3 about here ---

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.

---- Insert Table 4 about here ----

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.

Prediction of kinematics.

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

--- Insert Table 5 about here ---

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 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.

--- Insert Table 6 about here ---

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.

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 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.

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.

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.

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., 1999; Lezak et al., 2012; Vasylenko et al., under review). 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.

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

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.

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., under review), 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.

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, 2010; Seidler, 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.

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. Psychological Corp. *San Antonio, TX.*

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,* glu025.

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.

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.

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.,* (pp. 568-617). New York, NY: Oxford University Press.

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.*

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, 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.

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.* 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., & Rodríguez-Aranda, C. (under review). Manual dexterity in young and healthy older adults. 1. Age- and gender-related differences in unimanual and bimanual performance.

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.

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, 2nd ed.,* (pp. 207-234). New York, NY: Oxford University Press.

Table 1

Demographics and Results of Neuropsychological Tests by Age Group

	Young (n = 45)	Older (n = 55)					
F/M Ratio	26/19	25/30			95% CI		
	M(SD)	*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

Note. CI=confidence intervals for the mean difference. *LL*=lower limit; *UL*=upper limit.

Table 2

Results of Principal Component Analysis of Neuropsychological Test Scores

Test	Factor loadings 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

Note. 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.		

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

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	.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

	U reaching	U inserting	B reaching	B inserting
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

	U reaching	U inserting	B reaching	B inserting
EF	n.s.	n.s.	n.s.	n.s.

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

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*	
	$\beta(SE)$ 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.	

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

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.
Memory						n.s.

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

Appendix

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