Article

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

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Abstract

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

Keywords

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

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Introduction

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

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

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

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

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

Method

Participants

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

Measures

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

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

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

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

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

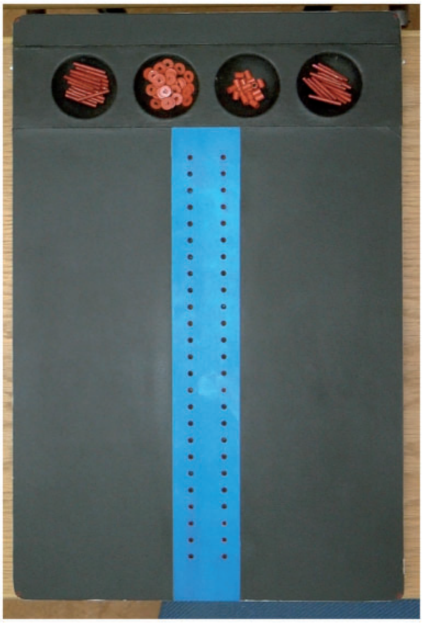


Figure 1. Purdue pegboard.

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

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

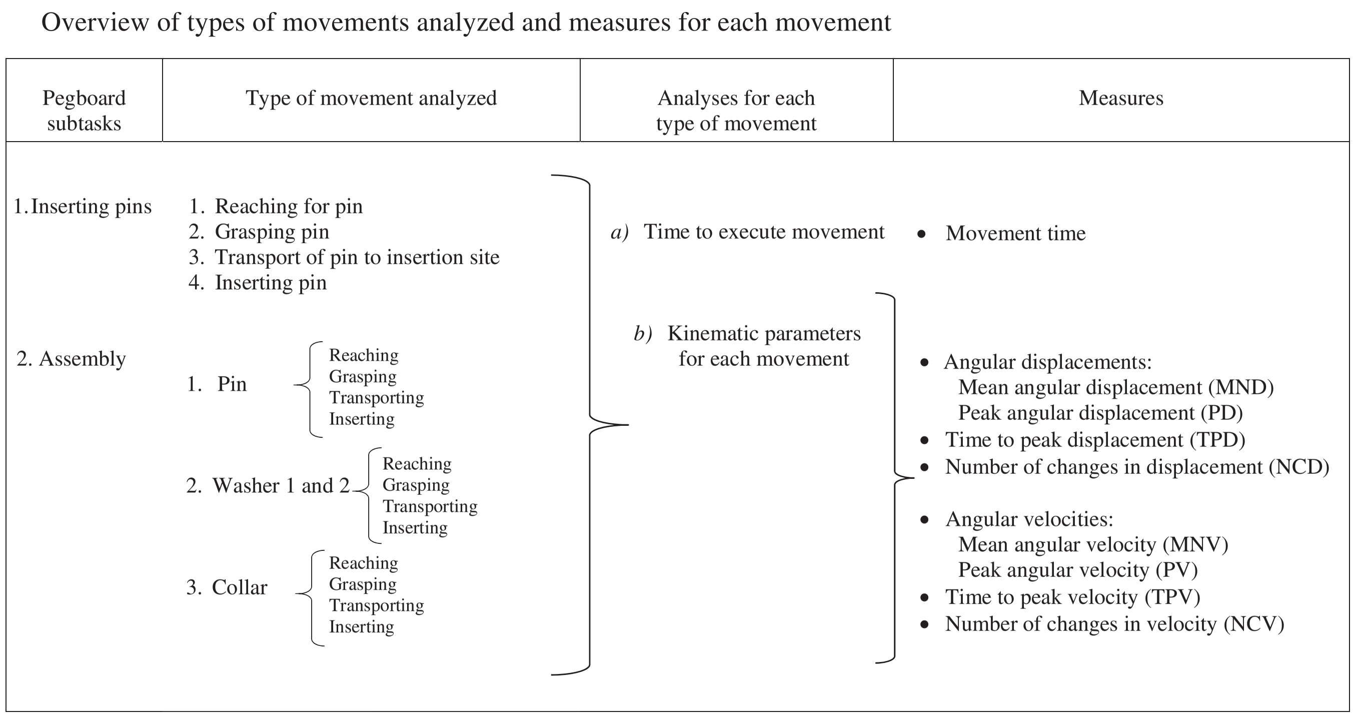
Temporal measures. Two-dimensional kinematic data were acquired during each subtask. Performance was video recorded with a Sony Handycam DCR-PC100E at the frequency of 25 Hz. The camera was attached on a rack above the pegboard, thus hand movements were recorded from a dorsal view.

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

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

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

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



Overview of types of movements analyzed and measures for each movement

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

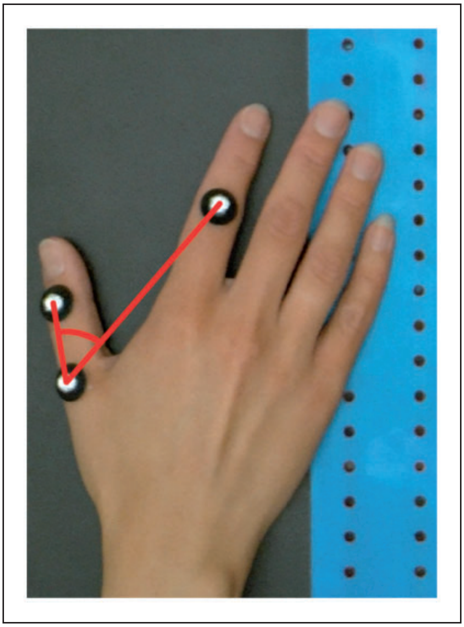


Figure 2. Positions of markers with the angle used in kinematic analysis overlaid.

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

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

Procedure

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

Statistical Method

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

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

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

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

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

Statistical Analysis

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

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

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

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

Results

Demographics and Neuropsychological Results

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

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

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

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

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

Overall Dexterity Performance

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

Movement Times

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

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

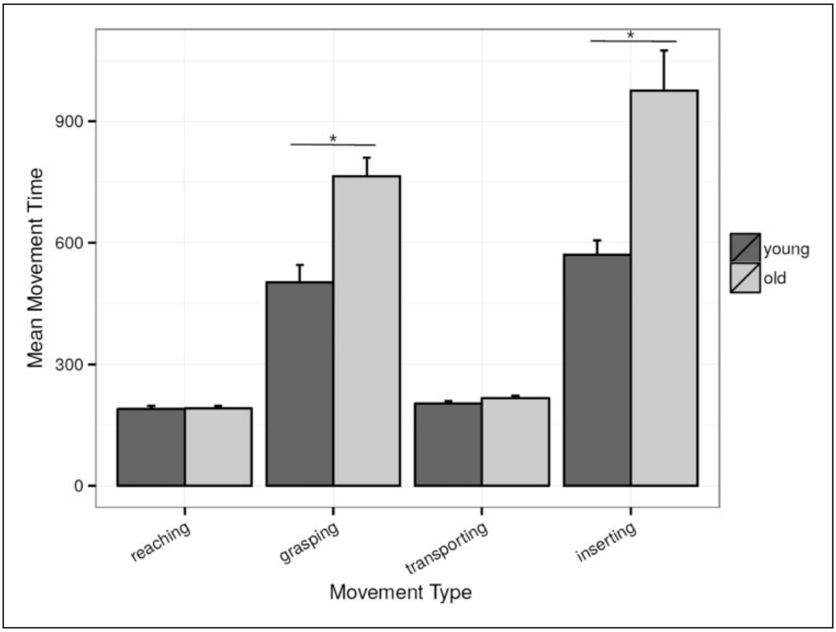


Figure 3. Movement times in the pins task. Asterisk indicates that the correponding posterior HDIs of the difference excluded zero.

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

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

Kinematic Results

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

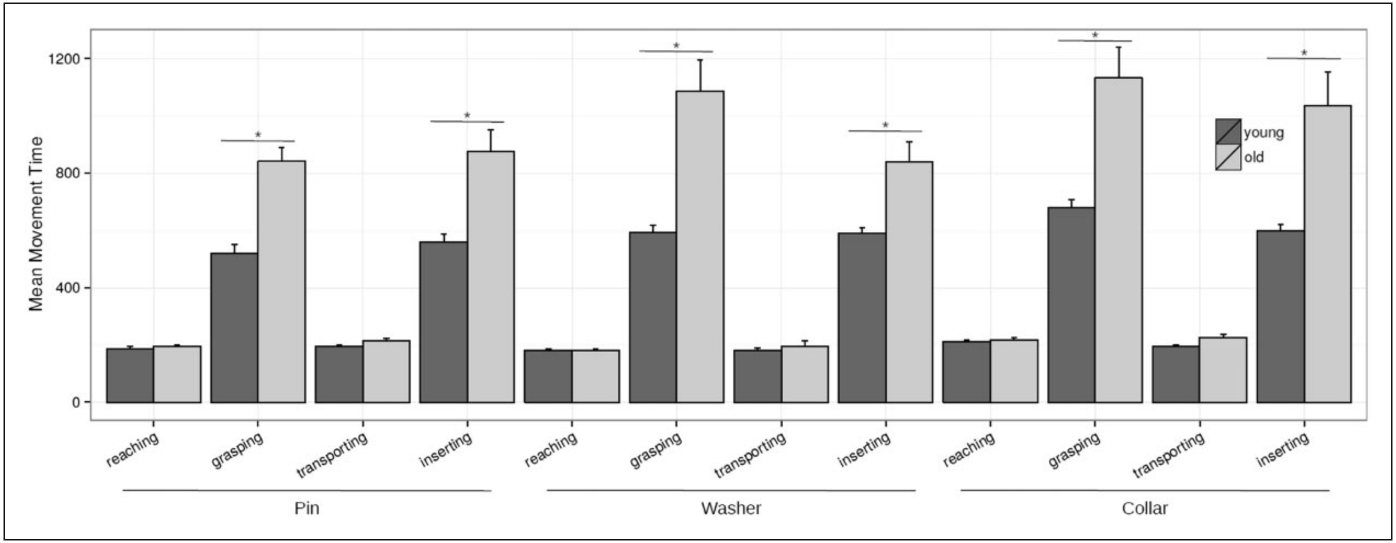


Figure 4. Movement times in the complex assembly task. Asterisk indicates that the correponding posterior HDIs of the difference excluded zero.

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

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

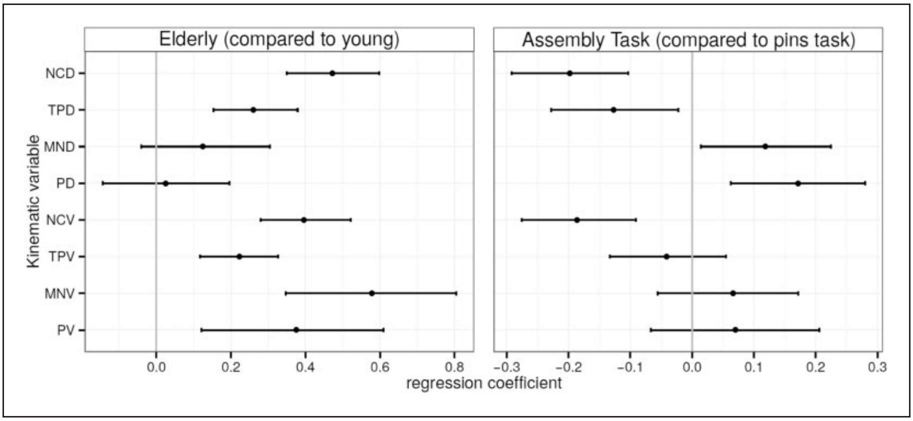


Figure 5. Regression coefficients for factors group and task. Coefficients code the difference between elderly and young subjects (left) and difference between simple and complex assembly task (right). Points signify the posterior mean, flanker are 95% posterior highest-density intervals (HDI). NCD =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

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

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

Association between kinematics and cognitive scores

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

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

Discussion

Dexterity Results

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

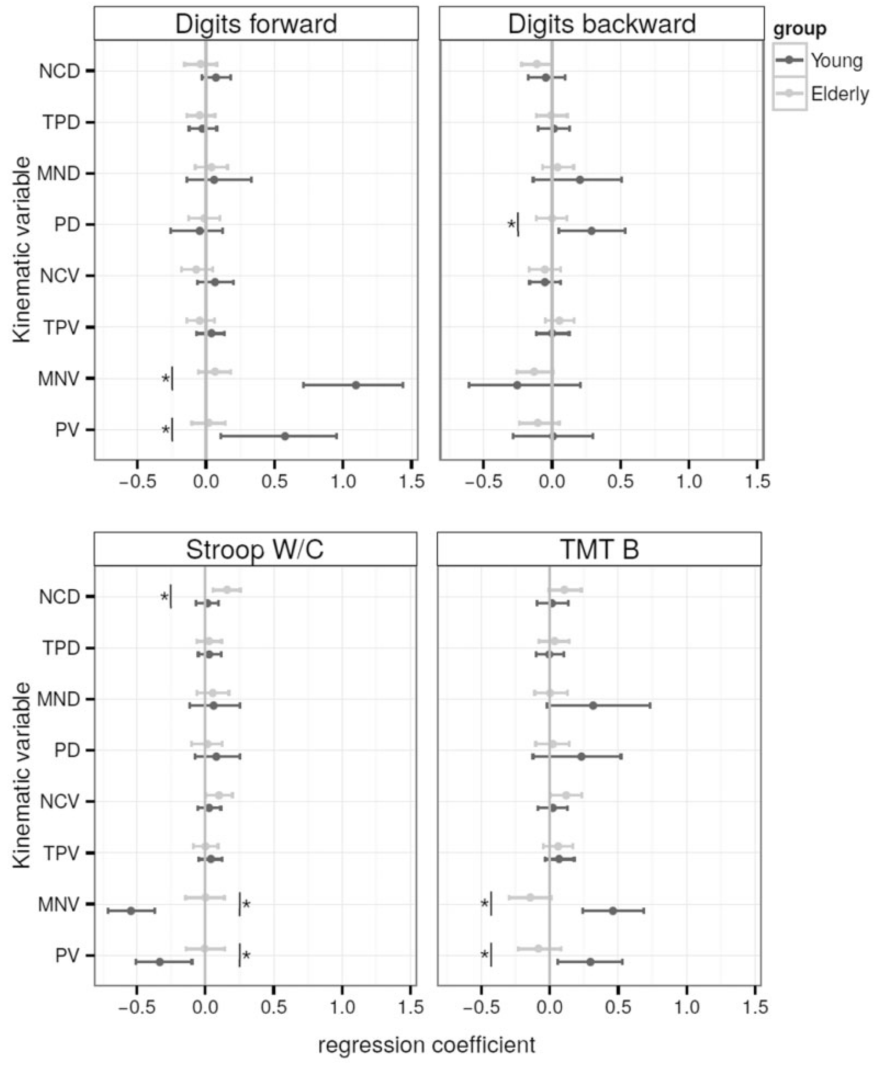


Figure 6. Regression coefficients for cognitive variables per group. Points signify the posterior mean, flankers are 95% posterior highest-density intervals (HDI). Asterisks indicate that the 95% HDI of the group × cognitive variable interaction coefficient excludes zero. NCD = number of changes in displacement,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

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

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

Cognitive Results

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

Association between Dexterity and Cognitive Results

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

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

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

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

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

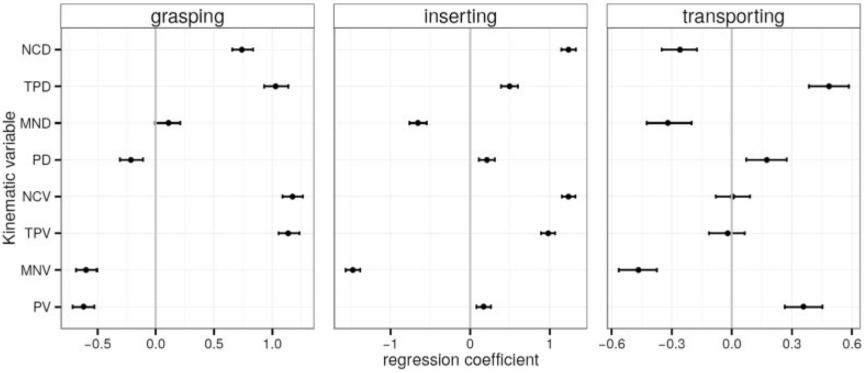
Limitations of the Study

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

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

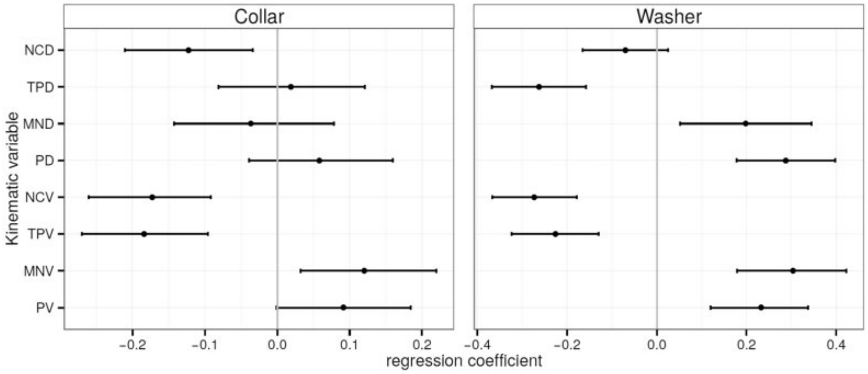
In conclusion, the present investigation contributes to the explorative analysis of the involvement of higher order cognitive functions in manual dexterity in healthy young and elderly adults. The detailed analysis of movements involved in the execution of two subtasks from the Purdue pegboard showed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

Appendix 1



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

Appendix 2



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

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Declaration of Conflicting Interests

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

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Author's note

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

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