Journal of Motor Behavior

ISSN: 0022-2895 (Print) 1940-1027 (Online) Journal homepage: https://www.tandfonline.com/loi/vjmb20

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To cite this article: Janine Vieweg, Peter Leinen, Willem B. Verwey, Charles H. Shea & Stefan Panzer (2019): The Cognitive Status of Older Adults: Do Reduced Time Constraints Enhance Sequence Learning?, Journal of Motor Behavior, DOI: 10.1080/00222895.2019.1654970

To link to this article: https://doi.org/10.1080/00222895.2019.1654970

Published online: 25 Aug 2019.

Journal of Motor Behavior, 2019

RESEARCH ARTICLE

The Cognitive Status of Older Adults: Do Reduced Time Constraints Enhance Sequence Learning?

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ABSTRACT. Research has indicated that older adults perform movement sequences more slowly than young adults. The purpose of the present experiment was to compare movement sequence learning in young and older adults when the time to perform the sequence was extended, and how the elderly's cognitive status (Montreal Cognitive Assessment [MoCA]) interacted with sequence learning. The task was to minimize the difference between a target sequence pattern and the sequence produced by elbow extension-flexion movements. On Day 1, participants (28 young adults; 28 older adults) practiced the sequence under two time windows: 1300 ms or 2000 ms. On Day 2, retention performance and the cognitive status were assessed. The results demonstrated that young adults performed superior compared to older adults. Additional time to perform the sequence did not improve retention performance for the older adults. The correlation between the error score and the MoCA score of $r = -.38$ ($p < .05$) in older adults indicated that a better cognitive status was associated with performance advantages in sequence learning.

Keywords: Sequence learning, aging, cognitive status

Age-related decline of motor learning has been demonstrated in a wide range of tasks (e.g. Bo, Borza, & Seidler, 2009; Panzer, Gruetzmacher, Ellenbürger, & Shea, 2014; Verwey, 2010; Voelcker-Rehage, 2008 for a review; Welsh, Higgins, & Elliott, 2007). For example, Voelcker-Rehage and Alberts (2005) used a force modulation task, in which young and older participants were instructed to produce isometric forces between the thumb and the index finger during 30 s to move a cursor on a target pattern presented on a screen. In the study of Verwey (2010) young adults and older adults practiced sequences of 3 and of 6 key presses. In this type of task, the participants were instructed to press spatial corresponding keys in a discrete manner to visual presented stimuli on the screen as quickly as possible. Shea, Park, and Braden (2006) used a continuous, dynamic movement sequence task in which older and young participants moved a lever to visual presented targets as quickly and smoothly as possible by an extension-flexion forearm movement. Regardless of the tasks in all cited experiments young adults outperformed older adults. The age-related regressive changes in motor performance and learning are reflected in movement slowing down, less reproducible motor responses, and less harmonic movements (Boyle, Kennedy, & Shea, 2015; Panzer, Gruetzmacher, Fries, Krueger, & Shea, 2011; Seidler, 2006; Shea, Panzer, & Kennedy, 2019; Verwey, 2010; Welford, 1984).

Although a number of physiological factors on the neuromuscular level contribute to the regression (e.g., sarcopenia, synaptic transmission delays, reduced excitability, reduced nerve conduction velocity, reduced muscle contractile speed, difficulty to adequately control agonist and antagonist), the mechanisms underlying behavioral slowing and the production of more variable motor responses are not well understood (Bo et al., 2009; Smits-Engelsman, van Galen, & Duysens, 2004). Numerous theorists in cognitive psychology (e.g., Verhaeghen & Salthouse, 1997 for a review) and motor learning (e.g., Cai, Chan, Yan, & Peng, 2014; Voelcker-Rehage, 2008 for reviews) have focused their attention on a possible decline resulting in behavioral slowing. Especially age-related decline in cognitive performance has received a good bit of experimental attention. The pattern of results, perhaps oversimplified, showed that age-related decline is determined more by central cognitive mechanisms than by peripheral processes (e.g., Chaput & Proteau, 1996; Welford, 1982). However, the amount of age-related changes is a controversial question. For example, in a longitudinal study Hayden et al. (2011) evaluated age-related changes during 15 years in a sample of priests, nuns and brothers. Their findings indicated that the cognitive decline in this subsample was relatively slow. Demonstrations and explanations of age-related differences in cognitive processes are provided by previous research in neuroscience and cognitive psychology. In the cognitive science literature working memory, discrimination, and recognition are associated with cognitive processing and they are often the object of contemplation in the research of age-related differences (Cai et al., 2014).

For example, the impact of aging on working memory and cognition was investigated in a study with positron emission tomography by Reuter-Lorenz et al. (2000). They showed age-related decline in the performance of the verbal and the spatial working memory, and this decline was reflected in a bilateral activation of both hemispheres (see also Bo et al., 2009). In a behavioral experiment to study cognitive functions, Starns and

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Ratcliff (2010) demonstrated with a letter discrimination task and a recognition memory task that older adults take more time to gather the required information before performing the tasks than young adults. As a result response time increases (see also Heitz, 2014 for a review of speed and accuracy idea). This led authors to conclude that older adults focus more on accuracy to avoid errors than on speed (Salthouse, 1979; Starns & Ratcliff, 2010).

These findings from cognitive psychology are accompanied by some results reported in the motor learning literature. Verneau, van der Kamp, Savelsbergh, and de Looze (2014) used a variant of a serial reaction time task to test the time effects on implicit and explicit movement sequence learning in older adults. Their results indicated that older adults benefit from a reduced time constraint to perform an explicit sequence learning task (see Cleeremans & Sarrazin, 2007 for a more general view). The aging research also shows a steady decline in motor sequence learning over age typically explained as result of reduced cognitive processing (Howard & Howard, 2001). The maintenance of working memory capacity (Maxwell, Masters, & Eves, 2003) or the ability to process different information about tasks simultaneously such as processing actual feedback information during sequence execution and information to use in advance to prepare/execute the next element or grouped elements of the sequence (de Kleine & van der Lubbe, 2011; Salthouse, 1996; Verwey, 2010) seem crucial for movement sequence learning.

Panzer et al. (2014) provided empirical evidence that older adults tend to rely on closed loop control in movement sequence learning. They conducted an experiment to test the development of a movement sequence representation. In an inter-manual practice design young and older participants performed a simple pre-planned spatial-temporal pattern with a sequence of three reversals, by extending and flexing the elbow in a given timeframe of 1300 ms across two days with the right and left limb. The results of the study indicated that older adults had problems in developing a specific movement sequence representation and they were actually less accurate in spatial performance than young adults. Note the spatial-temporal pattern disappeared after movement initiation. This led the authors to conclude that without the external visual feedback during sequence execution and the short duration of the sequence, older participants do not have the opportunity for a closed loop control to specify the movement plan (see also Adams, 1971; McNay & Willingham, 1998; Seidler & Stelmach, 1995). Extended time to execute a movement increases the likelihood that participants have enough time to utilize feedback based control loops to compare the visual or proprioceptive information with a movement plan or a 'blueprint of the movement' initiated prior to the movement to perform the task as accurate as possible (Potter & Grealy, 2008; Sarlegna, 2006; Verneau, van der Kamp, de Looze, & Savelsbergh, 2016). In other words, shorter duration movements rely predominantly on pre-planning, while longer duration movements have an initial pre-planned component after which movement control is gradually taken over by closed loop control (Glover, 2004). Pre-planning processes require the selection and programing of the appropriate information, including the timing and the velocity of the movement to reach the target. In short duration movements where the time to perform a task is constrained, planning and executing of the movement sequence, induces simultaneous processing operations. According to the limited time idea, it can be assumed that one of the relevant operations is executed to slow and reduces the amount of simultaneously present information that is needed to successfully process in the available time (Salthouse, 1996). In longer duration movements closed loop control can occur, because feedback loops to govern the movement have time to close, allows an updating of the commands to correct the movement (Bastian, 2006), and monitors the movement progress 'in flight' (Glover, 2004). This conclusion is also supported by the information-processing approach. According to the information-processing approach the human sensorimotor system has an inherent ability to correct errors during response execution using external visual information about the limb position relative to the movement goal and internal proprioceptive information arising from the muscles and other sensory systems within the performer. Recent research consistently demonstrated a general decline in information processing speed with increased aging (e.g., Keele & Posner, 1968; Shea et al. 2019).

Theories in cognitive psychology consider motor processes as a 'late' out-put related aspect in the information-processing approach which can be investigated independently from the 'central' cognitive processes. However, it has to be considered that motor processes represent a particularly important part of the task. Although there are several approaches in the cognitive psychology research and the motor control and learning research to explain age-related decline, 'it is no longer acceptable to think of a unitary cause' (Seidler & Stelmach, 1995, p. 387) of the regressive changes with advanced aging.

The purpose of the present experiment was twofold: (a) to investigate sequence learning when young and older adults were required to respond to a target sequence pattern as accurately as possible when the time for sequence production was systematically extended, and (b) to investigate how the cognitive status interacts with sequence learning. Note, the first purpose of the experiment was formulated, in part, based on previous results of the experiment conducted by Panzer et al. (2014) which indicated that extended time to perform the sequence may increase the likelihood for closed loop

TABLE 1. Characteristics of the Participants of the Different Groups (Mean, *SD*, for Age and Median and Interquartile Range for the MoCA Score).

Group	No. participants	Age (years)	Female/male	MoCA scores
YA 1300 ms	14	20.71 (1.77)	6/8	27.5 (2)
YA 2000 ms	14	21.71 (2.67)	6/8	28.0 (3)
OA 1300 ms	14	70.28 (4.63)	6/8	26.0 (5)
OA 2000 ms	14	70.31 (3.15)	8/6	27.0 (5)

control. Given the assumption that 'older adults prize accuracy more than speed' (Yu, 2012), can they increase sequence production accuracy when the time to produce the sequence is systematically extended (Verneau et al., 2014)? Note that additional time to perform a task increases the likelihood of closed loop control, retaining visual, spatial and proprioceptive information in working memory (Reuter-Lorenz et al., 2000; see also Adams, 1971). If older adults emphasize accuracy they should improve movement accuracy when more time is available.

Seidler and Stelmach (1995) argue for a more integrative research of cognitive science and motor control and learning. Therefore, another interesting question is to determine the extent to which the cognitive status of the older performers relates to movement sequence performance and learning. Due to the fact that cognitive processes, for example working memory processes, deteriorate with age (Verneau et al., 2014) we predict that the correlation between the cognitive status and sequence learning is higher in older adults compared to young adults.

METHOD

Participants

Young adults ($N = 28$; 23–29 years of age) and older adults ($N = 28$; 65–79 years of age) participated in the experiment. All participants had no history of neurologic disease, stroke, color blindness nor musculoskeletal dysfunctions and had normal or corrected-to-normal vision. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. All participants were right-hand dominant as determined by the Edinburgh Handedness Inventory (Oldfield, 1971) prior to the experiment. Informed consent was obtained prior to participation in the experiment. The young adults were undergraduate students and were given course credit for participation. All older adults were physically active and involved in the fitness program offered by the University for senior studies and they received compensation for travel expenses (7.50 € each) for their participation. The experiment was conducted in accordance with the revised version of the Declaration of Helsinki (2008). The characteristics of the young and older participants across the different groups are reported in Table 1.

Apparatus

The apparatus consisted of a horizontal lever, supported at the proximal end by a vertical axle that turned almost frictionless in a ball-bearing support. The lever was fixed on the right side of a table allowing the lever to move in the horizontal plane over the table. At the other end of the lever there was a vertical handle. The handles' position could be adjusted so that when grasping the handle the participant's elbow could be aligned with the axis of rotation. A potentiometer was attached to the lower end of the axis to record the position of the lever. The output was sampled at 1000 Hz and stored on a computer for later analysis. A wooden board was placed over the table to prevent participants from seeing the lever and their arm. A video projector (temporal resolution 100 Hz; spatial resolution 1152×854 pixel), located behind the participants, was used to display the target pattern and feedback on the wall facing the participant. Feedback was provided by superimposing the target sequence pattern over the actual pattern produced by the participant (see Figure 1). In addition, the root mean square error indicating the difference between the target trajectory and the actual produced trajectory by the lever/limb system was provided to the participant, and presented on top of the pattern. Participants were told to attempt to reduce this error value from trial to trial. Participants were seated at about 2 meters from the wall and a 2×2 m image was projected on the wall. The cursor and the target were generated with custom software.

Experimental Groups, Task, and Procedure

After entering the laboratory young and older participants were randomly assigned to one of two practice conditions that differed in terms of the time to produce the movement sequence. All participants were informed by written and verbal instructions how to perform the task. One practice condition allowed the participant to perform the movement sequence in 1300 ms while the

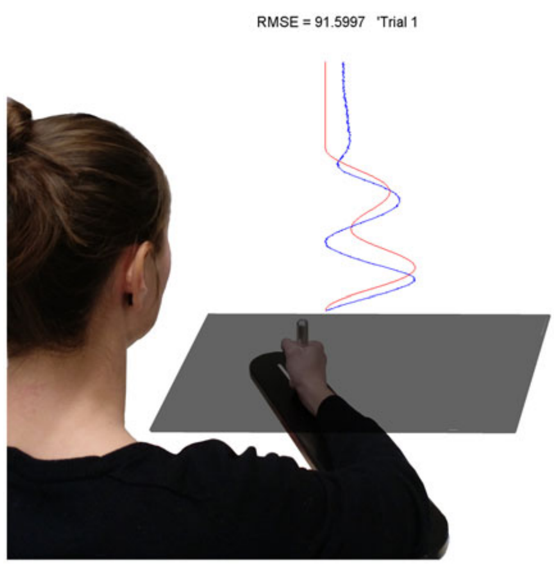

FIGURE 1. Schematic illustration of the apparatus with a participant sitting in front of the table, and the target sequence pattern, the produced sequence pattern and the RMSE displayed on the wall. Note, during the experiment the limb was covered symbolized by the transparent rectangle.

other condition permitted an additional 700 ms to perform the sequence (2000 ms). Participants were seated on a height-adjustable chair facing the wall and the apparatus was adjusted so that the participants had a comfortable position. At the starting position, the lower arm lever was positioned so that the upper-arm/lower-arm angle was approximately 85°. The participant's task was to move the lever through a sequence of elbow extension–flexion movements in the horizontal plane, in an attempt to produce the target spatial-temporal pattern displayed in front of them on the wall. The spatial-temporal sequence pattern was created by summing two sine waves with different amplitudes. The maximum amplitude in the target pattern was 45° from the start position (see Figure 1). One second after positioning the cursor in the start position (1° × 1° box), a tone indicated to the participant to begin his/her response when he/she was ready. Data collection was started by the movement of the lever. If the participant moved from the start position prior to presentation of the tone, the participant was required to return to the start position before the tone was presented again. This insured that participants started from the same position (85° elbow angle), but could initiate their response when they felt ready. As soon as the participant started moving the target pattern and the start position box disappeared from the screen and a cursor representing the current position of the lever/arm was displayed. The participants were instructed to move the lever with their dominant right arm through the sequential pattern of extension–flexion movements (3 reversals; changing the movement direction from extension to flexion and vice versa) in an attempt to produce the target spatial-temporal pattern as accurately as possible in a continuous manner. Note that the target pattern was displayed prior to the movement, but it was removed at movement onset. Approximately 10 s following the completion of the participants' response, feedback was provided for 5 s. For each trial the potentiometer output was recorded for 2000 ms for the 1300 ms condition and for 2500 ms for the 2000 ms condition. Practice of the target waveform consisted of 11 blocks of nine trials. Retention performance was assessed approximately 24 hours following practice. The retention test consisted of nine trials of the practiced sequence without feedback. Note that with the exception that feedback was not provided, all other conditions stayed the same as during the acquisition phase. Following the retention test the cognitive status for all participants was assessed by the Montreal Cognitive Assessment (MoCA) a cognitive screening tool with superior sensitivity indicating the cognitive decline in normal aging which also evaluated the participants working memory capacity (Nasreddine et al., 2005).

Data Analysis and Statistics

Data was analyzed using Matlab (Mathworks, Natick, MA). The individual trial time series was used to compute lever displacement. To reduce noise the angular displacement time series were filtered with a second-order dual-pass Butterworth filter with a cutoff frequency of 10 Hz. The primary overall error measure was the root mean square error (RMSE), computed between the angular elbow extension-flexion sequence and the target trajectory. RMSE captures errors in amplitude and time. Values of RMSE for individual trials were then averaged for each participant to yield a global estimate of RMSE for each block (9 trials). In addition, to assess whether practice improved the processing of temporal and spatial accuracy of the movement production, error measures in scaling the timing and amplitude were computed, using point estimates at the three peaks of the target pattern as a reference. The error measure was the absolute constant error (ACE). The ACE is an estimate of the accuracy with which the produced movement was scaled in time (ACE timing) and amplitude (ACE amplitude) as spatial accuracy. ACE was calculated as the absolute difference in time or amplitude at the Peaks 1 to 3 between the target and the produced sequence pattern. The values of each Peak for individual trials were then averaged for each participant to yield a global estimate of ACE timing and ACE amplitude for each block (9 trials). A supplementary measure was the index of harmonicity (H). This measure is based on the angular kinematics of the elbow acceleration obtained by the second derivation of the angular displacement of the elbow extension-flexion sequence. The *H*-value was computed as an indicator for cyclical, continuous or discrete movements and indicated the presence of goal-directedness of the continuous movement where a harmonic motion is required to achieve spatial-temporal accuracy (Guiard, 1993; Kovacs, Han, & Shea, 2009). Windows between a pair of zero crossings in the displacement trace are defined in order to compute an index of movement harmonicity (Guiard, 1993). Each non-overlapping time window comprises a single movement reversal. Within each time window, all deflections of the normalized acceleration trace are identified. When the acceleration trace is positive (negative displacement) within this window, *H* is computed as the ratio of minimum to maximum acceleration. Conversely, when the acceleration trace is negative (positive displacement) within this time window, *H* is computed as the absolute ratio of maximum to minimum acceleration. When a single peak (sinusoidal acceleration) occurs in the acceleration trace within this window the value of *H* is set to 1, indicating harmonic and continuous motion of the limb. If the acceleration trace crosses from positive to negative (or vice versa) within this window, the value of *H* is set to 0, indicating inharmonic and discrete motion. Finally, the individual *H*-values of each time window for a trial are averaged yielding a global estimate of *H*. Following this, the *H*-value for individual trials was then averaged for each participant to yield a mean *H*-value for each block (9 trials). In order to assess if the cognitive status is involved in the development and maintenance of sequence performance, the MoCA scores were correlated with the RMSE.

Statistical analyses were computed with SPSS for Windows version 22.0 (IBM Corp., Armonk, NY, USA). The analyses of variance (ANOVA) were computed using the Greenhouse-Geisser corrections when the epsilon value was smaller than 1 (Greenhouse & Geisser, 1959). The effect size partial eta square (η_p^2) was determined for all significant effects (Cohen, 1988). Significant main effects and interaction effects were followed by simple main effect analysis. The correlations were calculated by the Spearman Rho procedure. The mean RMSE and the *H*-value in acquisition were analyzed with a 2 (age: young adults, older adults) × 2 (acquisition condition: 1300 ms, 2000 ms) × 11 (block: 1–11) ANOVA with repeated measures on Block. Retention data were analyzed with a 2 (age: young adults, older adults) × 2 (acquisition condition: 1300 ms, 2000 ms) ANOVA. In addition, retention performance of the ACE timing and the ACE amplitude were analyzed in a 2 (age: young adults, older adults) × 2 (acquisition condition: 1300 ms, 2000 ms) × 3 (peak: 1–3) ANOVA with repeated measure on Peak. The analysis of the *H*-value was conducted to determine if there was evidence of participants performing the sequence with more inharmonic or harmonic motion. Note that lower values of *H* indicate the tendency to perform the sequence with an inharmonic motion. To determine that the MoCA scores between the 1300 ms and the 2000 ms condition did not differ for both age groups a Mann-Whitney *U* test was computed. On the retention test a separate correlation was computed across the young adults and the older adults between the MoCA scores and the RMSEs to determine the co-variation between the cognitive status and retention performance of the movement sequence.

RESULTS

Figure 2A and B displays the acquisition and retention results of the RMSE, and Figure 3A and B the corresponding *H*-values. Figure 4 shows the correlations between the RMSE and the MoCA score from the young and the older adults.

Acquisition

RMSE

The analysis of the RMSE detected main effects of block, $F(10,520) = 94.32$, $p < .0001$, $\eta_p^2 = .65$, acquisition condition, $F(1,52) = 8.67$, $p < .01$, $\eta_p^2 = .14$, and age, $F(1,52) = 21.47$, $p < .0001$, $\eta_p^2 = .29$. Duncan's new multiple range test indicated that the RMSE decreased through Block 7. No further differences were detected for Blocks 8–11. The main effect of acquisition condition indicated that RMSE was larger for the 1300 ms condition than for the 2000 ms condition. Older adults showed a larger RMSE compared to the young adults. The age × acquisition interaction, $F(1,52) = .79$, $p > .05$, and all other statistical analysis failed to reach significance.

H-Value

The analysis of the *H*-value indicated a block × acquisition condition interaction, $F(10,520) = 2.77$, $p < .05$, $\eta_p^2 = .05$. Simple main effect analysis for block across acquisition condition showed that the *H*-values were larger for the 1300 ms condition compared to the 2000 ms condition until Block 8. Then for both acquisition conditions the *H*-values did not differ. The analysis also indicated main effects of Block, $F(10,520) = 30.94$, $p < .0001$, $\eta_p^2 = .37$, Acquisition condition, $F(1,52) = 13.51$, $p < .01$, $\eta_p^2 = .21$, and age, $F(1,52) = 13.42$, $p < .01$, $\eta_p^2 = .20$. Older adults showed lower *H*-values than the young adults. All interactions failed to reach significance.

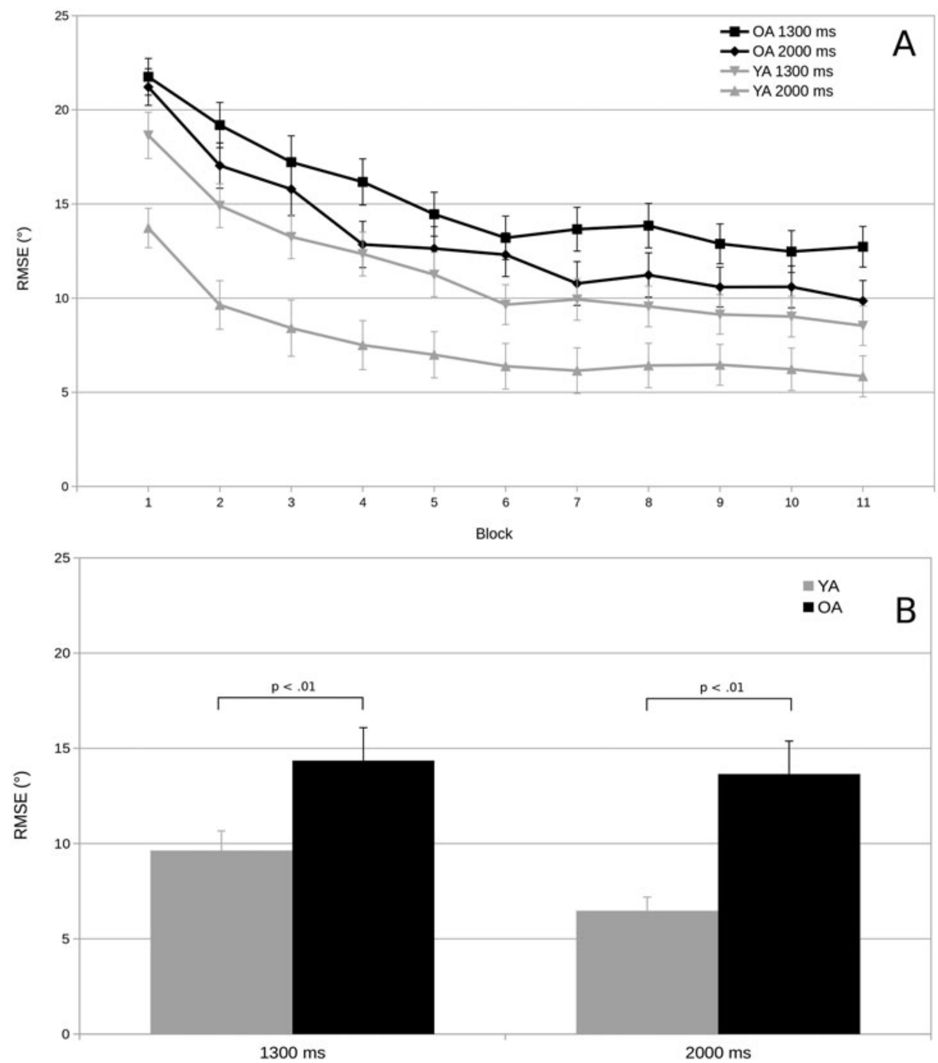

FIGURE 2. (A) Mean RMSEs and the standard error of the means (SEMs) of the acquisition phase for the older adults (OA) and the young adults (YA) at the 1300 ms and the 2000 ms conditions displayed. (B) Mean RMSEs and the SEMs of the retention tests for the older adults and the young adults at the 1300 ms and the 2000 ms conditions.

Retention Test

RMSE

The analysis detected only a main effect of age, $F(1,52) = 28.58$, $p < .0001$, $\eta_p^2 = .34$. The main effect of acquisition condition and the interaction age × acquisition condition failed to reach significance. The older adults produced a larger RMSE than the young adults.

H-Value

The analysis indicated a main effect of age, $F(1,52) = 10.59$, $p < .01$, $\eta_p^2 = .17$. The *H*-values were lower for the older adults compared to the young adults. All other statistical analysis failed to reach significance.

ACE Timing

The analysis revealed a peak × age interaction, $F(2,104) = 5.50$, $p < .01$, $\eta_p^2 = .10$. Simple main effect analysis for peak across age indicated that older adults perform Peak 3 with larger timing errors compared to the young adults. For Peaks 1 and 2 the ACE timing did not differ between the two age groups. In addition the main effects age, $F(1,52) = 4.20$, $p < .05$, $\eta_p^2 = .08$, and peak, $F(2,104) = 13.47$, $p < .0001$, $\eta_p^2 = .21$, reached significance.

ACE Amplitude

The analysis of the ACE amplitude indicated a Peak × Age interaction, $F(2,104) = 9.63$, $p < .0001$, $\eta_p^2 = .16$. Simple main effect analysis for Peak across

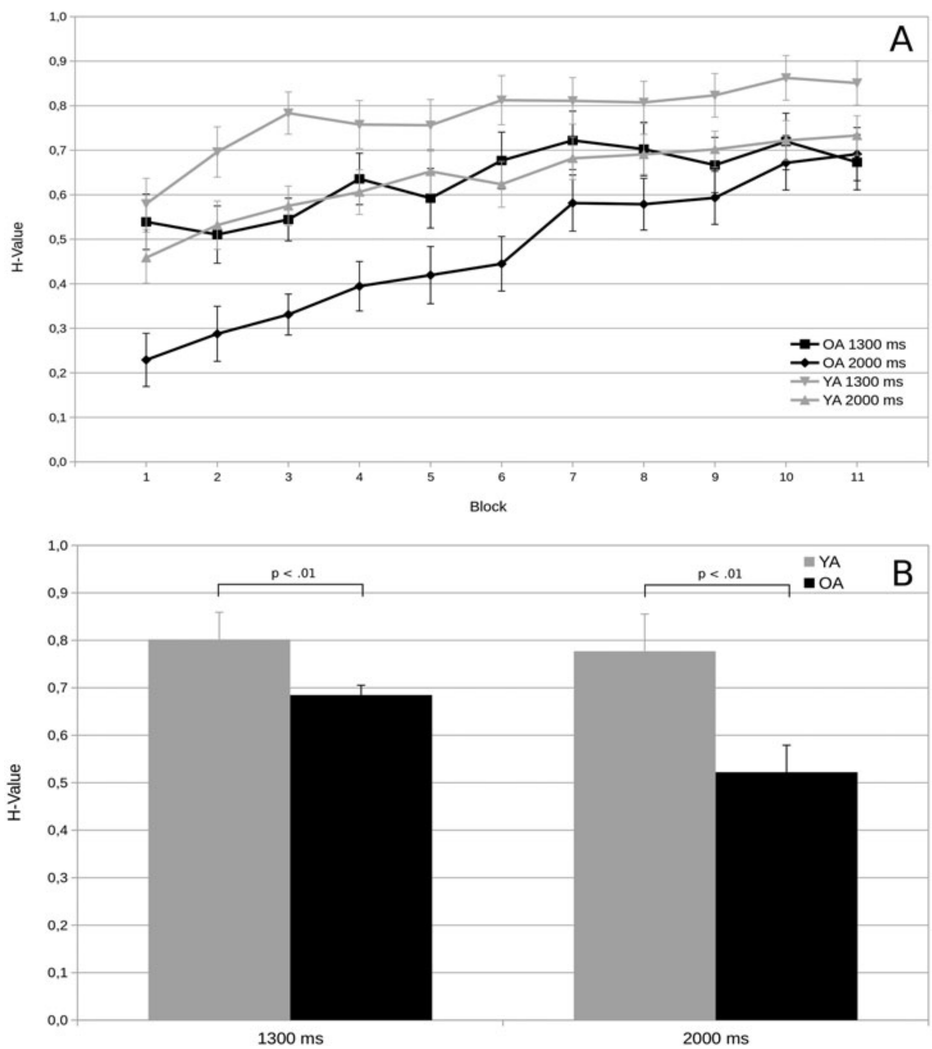

FIGURE 3. (A) Mean *H*-values and the SEMs of the acquisition phase for the older adults (OA) and the young adults (YA) at the 1300 ms and the 2000 ms conditions displayed. (B) Mean *H*-values and the SEMs of the retention tests for the older adults and the young adults at the 1300 ms and the 2000 ms conditions.

Age indicated that older adults perform Peaks 1 and 2 with larger amplitude errors compared to young adults. For Peak 3 the ACE amplitude did not differ between the two age groups. The main effects Age, $F(1,52) = 22.55$, $p < .0001$, $\eta_p^2 = .31$, and Peak, $F(2,104) = 6.61$, $p < .01$, $\eta_p^2 = .11$, also reached significance.

Correlations RMSE and MoCA Score

The MoCA scores between the 1300 ms and the 2000 ms conditions for the young participants, $U = -.21$, $p > .05$, and for the older participants, $U = -.62$, $p > .05$, indicated no significant differences. Note, one of the older participants refused to respond to the MoCA questionnaire. The RMSEs and the MoCA scores of the 1300 ms and the 2000 ms conditions were pooled before computing the correlations.

On the retention test the analysis showed a significant negative correlation between the RMSE and the MoCA score for the older adults, $r = -.38$, $p < .05$, $r^2 = .14$, but a near zero non-significant correlation for the young adults, $r = .03$, $p > .05$. This finding indicates that in older adults higher MoCA scores co-vary with lower RMSE.

DISCUSSION

In the present experiment we compared young and older adults performing an extension-flexion sequence in 1300 ms or 2000 ms. Seidler and Stelmach (1995) showed that self-paced movement has the potential to cause performers to focus more on accuracy and others more on speed. Therefore, to increase the likelihood that

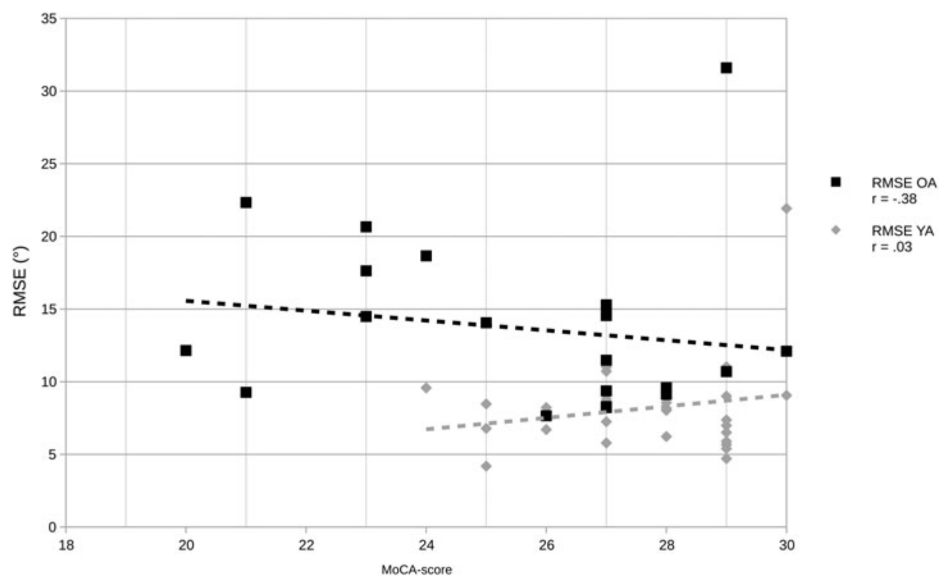

FIGURE 4. The scatter plot of the RMSEs and the MoCA scores of the older adults (black dots) and the young adults (gray dots). The black line represents the linear regression slope of the older adults, and the gray line the regression slope of the young adults.

performers emphasize accuracy, the task was predetermined in time to 1300 ms or 2000 ms. To determine the interaction between cognitive aging and motor learning, following the retention test the cognitive status of all participants was assessed by the MoCA. In terms of extended time to perform a movement sequence and aging we hypothesized that allowing additional time to produce the sequence of extension-flexion movements would facilitate movement accuracy especially for older adults and that sequence learning would be superior for older adults with a better cognitive status.

The acquisition results indicated that both age-groups reduced the RMSE during acquisition in both the 1300 ms and the 2000 ms conditions. This suggests that participants in both age-groups and Acquisition conditions improved during practice. However, both age-groups performed the 2000 ms condition with smaller errors, but older adults showed a larger RMSE compared to the young adults in both conditions. Considering the slowing down of the learning curve as a result of aging and that older adults started with larger RMSEs than young participants, the descriptive data for the young adults (mean decrease of –10.1°) and the older adults (mean decrease of –9.0°) from the beginning of acquisition (Block 1) to the end of acquisition (Block 11) for the 1300 ms condition, showed that both age groups decreased their errors on a similar level. For the 2000 ms Acquisition condition the decrease of the RMSE for the young adults was –7.9° and for the older adults –11.4°.

On the retention test young adults outperformed the older adults regardless of movement duration. This indicated that increasing response duration resulted in performance advantages for young and older adults during acquisition, but on the retention test performance differences between the 1300 ms and the 2000 ms conditions diminished for both age groups. The young adults performed the 1300 ms and 2000 ms sequences with less errors compared to the older adults. This finding is contrary to our initial extended time and accuracy hypothesis, but was consistent with a number of previous movement sequence learning experiments that found older adults produced larger errors in sequence execution and exhibited less learning of the movement sequence than young adults (e.g., Panzer et al., 2011; Shea et al., 2006; Verwey, 2010; Voelcker-Rehage, 2008). Solely, extending the time to increase the opportunity to use closed loop control processes to update the ongoing movement as indicated by Panzer et al. (2014), does not seem sufficient to improve sequence performance in older adults compared to young adults. The displayed visual information about the position of the cursor indicating the position of the limb during movement execution might not be sufficient sensory information for the older adults to perform a more accurate movement sequence. This result is also consistent with previous findings in the aging research that demonstrated a decline in perceptual abilities in older adults (Li, Lindenberger, Hommel, Aschersleben, Prinz, & Baltes, 2004; Seidler, 2010).

The task used in the present experiment required the participants to perform spatial temporal patterns of 1300 ms or 2000 ms by an elbow extension-flexion task, with three movement reversals. It is important to note that the simple movement sequence used in the present experiment required fewer reversals than the multi-element movement sequence used in previous studies by Panzer et al. (2011) or Shea et al. (2006). Therefore, chunking individual elements to subsequences to reduce information processing demands is not as important for the simple movement sequences as for more complex sequences (see Verwey, 2010). Furthermore, this task requires less time for continuous force control in the agonist and antagonist muscles during sequence execution compared to previous experiments where the multi-element task (Shea et al., 2006) or the force modulation task was used (Voelcker-Rehage & Alberts, 2005). Even though the number of reversals in the sequence and the information processing demands such as chunking were reduced, the older adults showed less sequence learning compared to the young adults.

The analysis of the *H*-values (harmonicity) provided some additional insights. As expected during acquisition, the *H*-values for the 2000 ms condition were lower than for the 1300 ms condition regardless of age. The lower *H*-values of the longer duration movement sequence indicated that participants attempted more online control while executing the movement pattern. Note that lower *H*-values were typically found in online controlled movements and higher *H*-values in pre-planned movements (Shea, Kovacs, & Panzer, 2011). This finding is in accordance with previous empirical findings including only young adults (Kovacs, Boyle, Grutmatcher, & Shea, 2010; Leinen, Shea, & Panzer, 2015), and it is consistent with the theoretical assumption of the planning and control framework proposed by Glover (2004). Therefore, pre-planning determines the initial movement parameters (kinematic characteristics of the movement) including timing and velocity, whereas the online control system monitors and if necessary adjusts movement progress 'in flight'. According to Glover (2004), online adjustments are limited to the spatial characteristics of the movement. With increasing movement time the initial pre-planned component is gradually taken over by the online control processes. Both age groups tended to an online control mode, when the response time was extended.

Similar to the RMSE the *H*-values on the retention test differed between the older adults and the young adults. This indicates that older adults performed the 1300 ms sequence and the 2000 ms sequence in a less harmonic and continuous motion compared to the young adults. According to the planning and control framework (Glover, 2004), and the empirical findings from Kovacs et al. (2010) it seems that older adults differ in the use of a pre-planning mode, where movement parameters including timing and velocity are set-up in advance, and in the online control mode (see Leinen et al., 2015; Seidler & Stelmach, 1995; Shea et al., 2011) compared to young adults. Especially the *H*-value for the older adults at the 2000 ms sequence tended to 0.5. This is typically the point at which movements change from continuous towards discrete movements (Buchanan, Park, & Shea, 2006). This indicated that older adults decelerate and accelerate the movement at some point during sequence execution, which results in movement instability rather than in reducing performance errors.

With regard to the ACE amplitude older adults showed less spatial accuracy at the retention test at Peak 1 and 2 for the 1300 ms and the 2000 ms sequence compared to young adults. At Peak 3 both age groups did not differ. This finding suggest that spatial accuracy suffered at the beginning of the sequence where the pre-planning mode is primarily responsible to control the sequence independent of the extended time to perform the movement. With this additional analysis we can more precisely discuss the previous mentioned point about the insufficient external visual information of the position of the limb during movement execution provided by the cursor in respect of time periods during sequence execution. It seems that external visual information about the position of the limb/lever provided by the cursor and intrinsic proprioceptive information in both Acquisition conditions are sufficient enough for the older adults to increase spatial accuracy at the end of sequence execution (Glover, 2004), but not at the beginning. Note the target template in the 1300 ms and the 2000 ms conditions was exactly the same except that the template was of a longer duration in the 2000 ms condition.

The results outlined above are consistent with two lines of previous research: research of pointing movements and research of advanced action planning and working memory. According to the research of pointing movements, Dounskaia, Wisleder, and Johnson (2005) reported that delays in the acceleration profiles in reciprocal movements (reversal pointing movements without dwelling on the targets) are associated with difficulty to adequately tune the muscle activation pattern (see also Dounskaia, 2005). Note that in the Dounskaia et al. (2005) experiment young participants had to control one or two degrees of freedom movements to reach the target. The present findings suggested that older adults have difficulties tuning in the neuromuscular system for spatial accuracy at the beginning of sequence production independent of the extended execution time, and when they have to control only one degree of freedom. However, later during sequence execution the spatial accuracy between young and older adults did not differ, while accuracy in timing increased between both age groups during response execution. This result is in agreement with the pre-planning online control idea from Glover (2004) who proposed that online adjustments are limited to the spatial characteristics of the movement.

However, the current results are also consistent with findings from Ketcham, Dounskaia, and Stelmach (2004) that older adults have problems to control simultaneously different mechanical/kinematic components of a movement.

As observed from advanced action planning and working memory research, older adults segment movements into shorter sub-movements to reduce the load of the working memory (see also Bo et al., 2009; Seidler & Stelmach, 1995). Theoretical discussions of the control processes in perceptual-motor tasks have suggested that the reliance on feedback is due to a 'play-it-safe' strategy (Welsh et al., 2007). This means that older adults know that their motor system is not as reliable as at a younger age, and therefore they try to divide the movement into shorter sub-movements in order to plan an action and then use sources of feedback for closed loop control to ensure spatial accuracy. The results of the *H*-values for the older adults at the 1300 ms and the 2000 ms sequence suggest that older adults have difficulties to concatenate sub-movements (Cooke, Brown, & Cunningham, 1989), because concatenation of sub-movements would suggest that delays and/or adjustments would be minimized (Guiard, 1993; Shea, Panzer, & Kennedy, 2019). Whereas, a decline in sequence learning is not uncommon when older participants have to develop longer chunk patterns (Panzer et al., 2011; Shea et al., 2006; Verwey, 2010), the current experiment indicated that a decline in sequence learning with aging also occurred when chunking processes are less important to perform the task. The MoCA data also support this notion.

The median MoCA score for the older adults was 27 and for the young adults 28 (see also Table 1 for more detailed information). This indicates that the average cognitive status for the older adults was above the threshold of 26 of normative data for cognitive impairment (Kenny, Coen, Frewen, Donoghue, Cronin, & Savva, 2013). The negative correlation for the older adults between the MoCA scores and the RMSE on the retention test that we observed, suggests that older adults with a better cognitive status showed superior performance in sequence execution. This finding is consistent with our initial hypothesis. While the MoCA is a relatively simple screening tool for the cognitive status including attention, working-memory, executive functioning and visual-spatial ability, the present results are in line with other findings that reported that a decline in cognitive functioning is associated with a decline in movement sequence learning (see Bo et al., 2009; Salthouse, 1996; Voelcker-Rehage, 2008), and that there is a close interaction between deficits in motor learning and cognitive aging (Cai et al., 2014).

In conclusion, slowing the movement by extending the time to produce a continuous movement sequence improved the acquisition performance, but did not facilitate sequence learning in older adults compared to young adults. With regard to the ACE amplitude, older adults exhibited less control in managing spatial accuracy of initial sequence execution (Rabbitt, 1979) independent of the extended time to perform the sequence. Furthermore, the negative correlation between the RMSE and the MoCA scores suggests that the cognitive status predicts sequence learning, and that cognitive aging is involved in some of the regressive processes in motor sequence learning of older adults.

In the current task participants have to control only one degree of freedom. However, the task requires some continuous proprioceptive and visual control for the 1300 ms and for the 2000 ms sequence. Although the duration of the control requirements were lower compared to the Shea et al. (2006) or Voelcker-Rehage and Alberts (2005) experiments, performance of the older adults suffers. In the current experiment proprioceptive information was not inhibited, but visual information was limited to a cursor indicating the position of the limb. Indeed, it seems possible that providing more visual feedback about the task is more important than proprioceptive feedback to improve performance (Nemanich & Earhart, 2015) in older adults. Future studies should focus their attention on systematically manipulating visual information such as providing concurrent visual information about the target and the position of the limb to increase closed loop control in older adults. If concurrent visual information improves performance of such simple one degree movements in older adults more complex movements where more degrees of freedom must be controlled should be tested.

ACKNOWLEDGMENT

We thank Julia Harenz to support data collection.

COMPLIANCE WITH ETHICAL STANDARDS

All procedures performed in the current experiment were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study. The authors report no conflicts of interest.

Funding

This study was funded by a grant from the German Research Foundation as a partner of the ORA Program (grant number: PA 774/12-1).

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Received September 28, 2018
Revised June 25, 2019
Accepted July 30, 2019