



Title	Association Between Physical Activity and Performance in Skill Learning Among Older Adults Based on Cognitive Function
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Association Between Physical Activity and Performance in Skill Learning Among Older Adults Based on Cognitive Function

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Free-Form Keywords:	habitual exercise, procedural memory, perceptual-motor learning, cognitive skill learning



Key Points

- This study investigated the association between physical activities (triaxial accelerometer and IPAQ) and skill learning based on cognitive function (the tower of Hanoi and mirror drawing tasks) in older adults.
- Skill acquisition was maintained in older adults but the ability to retain the acquired skills decreased significantly.
- Higher habitual exercise levels and more social or recreational participation may maintain and improve cognitive function and motor skill learning in older adults.

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- 1 **Association Between Physical Activity and Performance in Skill Learning Among Older**
- 2 **Adults Based on Cognitive Function**

1 **Abstract**

2 ***Background/Objectives***

3 Most older adults experience cognitive and physical functioning problems; however, they
4 require the ability to learn skills in response to age-related or social environmental changes
5 for independent living. This study aimed to clarify the associations between age-related
6 physical activity and performance in skill learning tasks based on cognitive function.

7 ***Methods***

8 Fifty-eight adults participated in this study and were divided into two groups: the control
9 group (aged under 65 years) and older adult group (aged over 65). All the participants
10 performed two-skill learning exercises based on cognitive function. Habitual exercise was
11 measured using an accelerometer and a self-reported questionnaire.

12 ***Results***

13 At baseline, the scores on skill tasks were lower in the older adult group than in the control
14 group and were associated with habitual exercise and motor performance. Skill acquisition,
15 observed in both groups, was associated with age and self-reported physical activity.
16 Retention of the acquired skill was not associated with habitual exercise, and it declined
17 significantly in the older group.

18 ***Conclusion***

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1 Skill acquisition was maintained regardless of age; however, the ability to retain the acquired
2 skills decreased among the older adults. Habitual physical activity was associated with skill
3 acquisition but not the retention of the acquired skill.

4 ***Significance/Implications***

5 The study findings highlight the association between habitual exercise and motor skill
6 learning in older adults, providing insight for practitioners in the rehabilitation and healthcare
7 fields.

8

9 **Keywords**

10 habitual exercise, procedural memory, accelerometer, perceptual-motor learning, cognitive
11 skill learning

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1 Physical and cognitive functions decrease in older adults, although these changes do not
2 occur simultaneously and their age-related effects or degrees vary among individuals. For
3 instance, compared with other cognitive functions, procedural memory, a subgroup of
4 implicit memory, and skill learning, which is dependent on procedural memory, are assumed
5 to be retained in older adults (Brosseau et al., 2007; Voelcker-Rehage, 2008). In reality,
6 however, there are serious social problems related to the deterioration of skills acquired in
7 these populations, especially, traffic accidents caused by careless driving (Gökçe et al.,
8 2022). Therefore, relearning skills to solve tasks in response to deterioration in physical and
9 cognitive functions due to aging and changes in the social environment is necessary for
10 independent living in older adults (Zwingmann et al., 2021).

11 Skill learning comprises motor, perceptual, and cognitive learning (Brosseau et al., 2007;
12 Taylor et al., 2024), which have often been assessed using the mirror tracing task (Bootsma et
13 al., 2021; Brosseau et al., 2007; De Wit et al., 2023; Rodrigue et al., 2005) and towers of
14 Hanoi (TOH) task (Córdova et al., 2009; Mitani et al., 2022). However, findings regarding
15 age-related effects on skill acquisition and its retention differ among studies. Previous studies
16 with cognitive skill learning tasks have reported that, although motor performance in the
17 older group was generally lower than that in the younger group, both groups showed similar
18 learning rates and retention of the acquired skill (Ballesteros et al., 2024; Carnahan et al.,
19 1996; Shea et al., 2006; Voelcker-Rehage, 2008). Nonetheless, some studies have reported

deficiencies in learning ability and retention that required the use of procedural memory in older adults (Brosseau et al., 2007; Gal et al., 2019; Müller et al., 2016; Rodrigue et al. 2005). For instance, the learning cost (i.e., learning rate) during a bimanual motor learning task has been reported to be lower in older adults than in young adults (Bhakuni & Mutha, 2015). Similarly, in the case of a mirror drawing (MD) task, older adults performed slower and made more errors than younger adults and the retention of acquired skills declined with age (Kennedy et al., 2008; Lemieux et al., 2014). Thus, older adults' skill learning appears to be inconsistent owing to methodological differences, such as the type and difficulty of the task (Brosseau et al., 2007; Martin et al., 2023; Voelcker-Rehage, 2008). Furthermore, another significant issue was the substantial variability in performance, especially in older participants (Córdova et al., 2009; Martin et al., 2023; Rodrigue et al. 2005), which could have complicated the understanding of older adults' learning abilities.

In general, skill learning is considered to gradually improve in accuracy and speed through exercise and experience (Brosseau et al., 2007; Taylor et al., 2024). Exercise is also recommended to improve the cognitive function underlying skill learning (Colcombe & Kramer, 2003; Taylor et al., 2024). Previous studies have focused on the intensity and frequency of exercise to enhance its effects (Brown et al., 2021; Northey et al., 2018; Young et al., 2015). More intensive exercise is believed to prevent decrease in cognitive function (Chang et al., 2012; Córdova et al., 2009; Northey et al., 2018), and even a single bout of

high intensity exercise was reported to have positive effects on motor learning (Roig et al., 2012). However, several recent studies have reported that exercise intensity or level does not affect motor learning (Hung et al., 2021; Ishihara et al., 2021; Pixa et al., 2021; Snow et al., 2016; Wanner et al., 2020). Furthermore, the cognitive benefit of fitness in cognitive tests (e.g., the flanker test) is considered to explain improvement in visual processing and motor response generation, rather than cognitive control as a direct effect of exercise (Brown et al., 2021; Fröhlich et al., 2024).

It is important for older adults to avoid possible adverse events, such as pain or soreness, dizziness, respiration or circulation problems, stomach pain, and fear of falling, when performing exercise or fitness at high-intensity levels (Littbrand et al., 2006). Most previous studies have not strictly reported the risk of exercise in older adults; one study reported that the attendance rate (i.e., dropouts) decreased to approximately 50% in high-intensity exercise for lower-limb strength (Littbrand et al., 2006). On the one hand, aerobic exercise at low-intensity levels is reasonably perceived to improve cognitive function while avoiding risks associated with exercise or fitness for older adults. However, the effects of low-intensity aerobic exercise on cognitive function are limited (Yang et al., 2020), and several recent studies have reported that exercise intensity or level does not affect motor learning (Hung et al., 2021; Ishihara et al., 2021; Sanders et al., 2020; Wanner et al., 2020). On the other hand, self-selected habitual exercises (e.g., walking), which can be continued effortlessly and

comfortably compared with resistance training, are considered to be beneficial for cognitive function in older adults (Etnier & Landers, 1998; Hübner & Voelcker-Rehage, 2017; O'Brien et al., 2024). According to a previous systematic review (Hübner & Voelcker-Rehage, 2017), the exercise type, motor task, and intensity and duration of exercise in chronic physical activity or habitual exercise have differed among studies, and the effect of recreational and habitual exercise on skill learning remains controversial.

Notably, evidence of the effect of physical exercise on cognitive function has been documented (Bloomberg et al., 2023; Kumar et al., 2022), whereas evidence of skill learning in older adults is rare and ambiguous (Hübner & Voelcker-Rehage, 2017; Yu et al., 2022).

This study aimed to clarify the association between age-related physical activity and performance in skill learning tasks based on cognitive function. As exercise can have a beneficial effect on hastened tasks for motor skill learning that rely heavily on executive control (Ballesteros et al., 2024; Smiley-Oyen et al., 2008), this study adopted perceptual motor (i.e., MD) and cognitive (i.e., TOH) tasks instead of a simple motor skill task. We hypothesized that the natural score in each task would decrease more in older adults and would be related to physical performance or activity. We further hypothesized that, although acquisition skill learning would be maintained in older adults, the retention of acquired skills will decline and skill learning will be affected by individual motor performance and physical activity.

Methods

Participants

Fifty-eight adults participated in this study and were divided into two groups: the control group (aged under 65) and older adult group (aged 65 and older). The initial sample size for analyzing the comparison and correlation between the two groups was confirmed to be 52 by G*Power (Faul et al., 2007; Hernández-Guillén et al., 2022).

Participants in the control group were recruited from among volunteers at our university, and those in the older adult group were randomly selected from among the university-dwelling older adults registered at an employment agency. The inclusion criteria for older adults included those who were able to walk without a cane or walking aid and able to independently perform daily living activities. The exclusion criteria included any neurological, cardiovascular, or musculoskeletal diseases within the past five years and a Mini Mental Status Examination (MMSE) score < 27 (Folstein et al., 1975). Data were collected at our laboratory from October 2021 to November 2022 and subsequently analyzed.

The right hand was dominant in all participants, and the tasks were performed using the right-hand side. The study was conducted according to the principles of the Declaration of Helsinki. Informed consent was obtained from all participants before enrolling them, and the task procedures were approved by the ethics committee of the (blinded for review).

After the explanations and interviews, for joint flexibility, the range of motion of ankle dorsiflexion in the ball kicking dominant leg was passively assessed by two clinicians. For motor performance, the muscle strength of the knee extensors during the maximum voluntary contraction in the dominant leg was assessed using a handheld dynamometer (Mobie, MT-100, SAKAI Co. Ltd., Chiba, Japan) (Martins et al., 2017). Participants were asked to walk approximately 5 m as fast as possible, and the maximum gait velocity was calculated (Kawasaki & Tozawa, 2020). For physical activity, gait steps were measured using a triaxial accelerometer (CaloriScan, HJA-405, OMRON Healthcare, Corp., Kyoto, Japan) for six days; subsequently, the number of steps for four days were averaged, except for the maximum and minimum steps. Additionally, regular physical activity was assessed through the self-reported International Physical Activity Questionnaire (IPAQ) score for six days (Hübner & Voelcker-Rehage, 2017; Kumar et al., 2022).

Skill Learning Tasks

Cognitive and sensory-motor skill learning were assessed using the TOH and MD tasks, respectively. These tasks are frequently used to assess the cognitive functions of procedural memory and executive function (Brosseau et al., 2007; Kiep & Spek, 2017; Viejo-Sobera et al., 2017; Voelcker-Rehage, 2008). The TOH task is a well-known cognitive skill or procedural learning task in cognitive science. This study used the five-disk version, and the

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1 minimum number of disk movements was 31 (Viejo-Sobera et al., 2017). The participants
2 were asked to move all the disks from the leftmost peg to the rightmost peg as fast as possible
3 by moving only one disk without placing the large disk on the small disk (Viejo-Sobera et al.,
4 2017). If the participants mistakenly determined the manner of the disk motion, the time
5 measurement stopped, and the participants restarted from the previous motion. A practice
6 session was performed using the three disks before the actual task. The completion time and
7 number of disk movements in the TOH task were measured, and the trial was aborted when
8 participants took more than 30 min to accomplish the task, according to a previous study
9 (Kiep & Spek, 2017).

10 The MD task is a classic visuomotor skill learning task performed using a computer software
11 via a mouse (MD software, Toyo Physical Co. Ltd., Fukuoka, Japan) (Figure 1). This
12 computerized MD task reversed the right-left and upward-downward movements of the
13 mouse on a 15.6-inch display, and the required figure was a double-lined star with five
14 spikes. The participants were required to draw a star counterclockwise without drawing out
15 the double line as fast as possible. A practice session was performed in a clockwise direction
16 before this task. No information or feedback on mouse motion was provided to the
17 participants. Errors were defined as the number of times the left or right boundary line was
18 crossed, and completion time was also measured. Similar to the TOH task, the trial was
19 aborted if it took 30 min to complete the MD task. Both tasks were performed in four trials

(Baseline, Trial 1, Trial 2, and Trial 3); to avoid fatigue, rest was allowed between trials. Skill acquisition ability was assessed by the rate of improvement in completion time for each task and by a moving number in the TOH task or an error number in the MD task between the baseline and the final trial.

To assess the retention of acquired skills, participants were asked to visit our laboratory for a retest after one week (Retest). Retention ability was assessed by the retention rate using the difference in scores between the final trial and retest after one week.

Statistical Analysis

All analyses were performed using SPSS version 18 (IBM Corp., Armonk, NY, USA). The Shapiro–Wilk test was performed to check for normality. If normality was not observed, the analysis was performed using a nonparametric approach. All data were shown as mean $\pm$ standard error. A two-tailed *t*-test or Mann–Whitney U test was used to compare demographic data and skill task scores at the baseline between the two groups. Spearman’s rank correlation analysis was performed to determine potential relationships between age, physical activity (average number of daily steps and IPAQ score), motor performance (muscle strength and gait speed), and scores in both skill learning tasks at the baseline. To determine the effect of age on skill acquisition, repeated-measures two-way ANOVAs were performed for scores on the TOH and MD tasks with the two groups (control vs. older

adults) and four trial times (baseline, Trials 1, 2, and 3). If there was a significant interaction, simple effects analysis was performed with Bonferroni adjustment. Similarly, to compare the retention of acquired skills between the groups, repeated-measures two-way ANOVAs were performed for scores on the TOH and MD tasks with the two groups (control vs. older adults) and two trials (Trial 3 and Retest). Furthermore, to investigate the association with skill learning, after confirming the absence of multicollinearity by using a variance inflation factor < 5 , multiple regression analysis was performed using backward stepwise selection based on the minimum Akaike information criterion. This was performed to identify whether habitual physical activity and motor performance (an independent variable) could explain skill learning scores (a dependent variable). Previous studies have suggested that demographic factors, especially age, may possibly influence the relationship between physical activity and cognitive function (Zheng et al., 2023; Kumar et al., 2022). Therefore, age was considered a confounder because it influences both habitual exercise and skill learning; in this study, thus, both the forced entry and stepwise method were performed. In addition, since there was a ceiling effect in range of motion (ROM) in both groups because all participants did not have orthopedic injuries, ROM was excluded from the independent variables in this analysis. The alpha significance level was set at .05 for all analyses.

Results

Table 1 shows the characteristics of the two groups. As three participants in the older adult group did not satisfy the inclusion criterion of the MMSE (< 27), they did not perform the tests and skill learning. Therefore, their data were not included in the older adult group. The older adult group were of lower height ($Z = -6.359, p = .018$), had lower muscle strength ($Z = -2.100, p = .036$), slower gait velocity ($Z = -2.768, p = 0.006$), and had fewer daily steps ($Z = -2.411, p = 0.016$) than the control group. There was no statistically significant difference in the IPAQ score between the groups ($Z = -0.539, p = .590$).

Comparison of Task Performance at Baseline

The older adult group had statistically significantly longer completion times ($Z = -3.641, p < .001$) and required more disk movements ($Z = -2.883, p = .004$) than the control group in the TOH task (Table 2). In the MD task, the older adult group had statistically significantly longer completion times ($Z = -4.796, p < .001$) and more errors ($Z = -4.520, p < .001$) than the control group (Table 3). In both tasks, the older adult group's performance was lower than that of the control group, and learning costs were higher.

There were statistically significant positive correlations between age and completion time ($r = .572, p < .001$) and between age and the number of disk movements ($r = .565, p < .001$) in the TOH task. In the MD task, there were statistically significant positive correlations between age and completion time ($r = .717, p < .001$) and between age and number of errors

($r = .683, p < .001$). These results revealed that skills decrease with increasing age. Muscle strength was statistically significantly negatively correlated with completion time ($r = -.311, p = .021$) and the number of disk movements ($r = -.350, p = .009$) in the TOH task and with completion time ($r = -.279, p = .039$) and the number of errors ($r = -.271, p = .045$) in the MD task (Figure 2 A–D). There were statistically significant negative correlations between gait velocity and completion time ($r = -.379, p = .004$) and between gait velocity and the number of errors ($r = -.324, p = .016$) in the MD task (Figure 2 E and F). These results on muscle strength and gait speed showed that physical performance was related to the cognitive and perceptual-motor task. There was a statistically significant negative correlation only between the average steps per day and number of disk movements ($r = -.281, p = .038$) in the TOH task (Figure 3). Self-reported IPAQ was also negatively but non-significantly correlated with the number of disk movements ($r = -.247, p = .069$) in the TOH task.

Comparison of Skill Acquisition in Each Task Between Groups

One older participant could not accomplish the TOH task within the allowed time; therefore, their data were excluded from the subsequent analysis of the TOH task. Two-way repeated-measures ANOVA revealed no statistically significant interaction effect of group $\times$ trial on the completion time in the TOH task ($F(2.308, 120.030) = 1.304, p = .276, \eta^2 = .024$). There was a statistically significant main effect of trial ($F(2.308, 120.030) = 13.987, p < .001, \eta^2$

= .212) and group ($F(1, 52) = 11.982, p = .001, \eta^2 = .187$) on the completion time in the TOH task. A post-hoc test showed that the completion time of the TOH task in the older adult group was statistically significantly greater than that in the control group ($p = .001$) (Figure 4A). Additionally, the completion time in all trials decreased significantly from the baseline (trial 1, $p = .028$; trial 2, $p = .005$; trial 3, $p < .001$). There was no statistically significant interaction effect of trial group $\times$ trial ($F(3, 156) = .550, p = .649, \eta^2 = .010$) for the number of disk movements. Although there was a statistically significant main effect of group for the number of disk movements ($F(1, 52) = 4.420, p = .04, \eta^2 = .078$), there was no statistically significant main effect of trial ($F(3, 156) = 1.688, p = .172, \eta^2 = .031$) for the number of disk movements, and the older adult group had more disk movements than the control group (Figure 4B).

Another older participant could not accomplish the MD task in the four trials on the first day; therefore, their data were excluded from subsequent analysis of the MD task. There was a statistically significant interaction effect of group $\times$ trial time ($F(2.002, 104.130) = 8.236, p < .001, \eta^2 = .137$) on completion time (Figure 4C). Moreover, there was a statistically significant main effect of group ($F(1, 52) = 27.312, p < .001, \eta^2 = .344$) and trial time ($F(2.002, 104.130) = 30.407, p < .001, \eta^2 = .369$) on the completion time in the MD task. A post hoc test showed that the completion time of the MD in the older adult group was statistically significantly longer than that in the control group in all trials (all $p < .001$).

Although there was no significant difference in the completion time of the MD between each trial in the control group, significant differences were observed among all trials in the older adult group (all $p < 0.05$) (Table 3). For the number of errors in the MD task, there was a statistically significant interaction effect of group $\times$ trial ($F(2.047, 106.457) = 5.081, p = .007, \eta^2 = 0.089$). A statistically significant main effect of group ($F(1, 52) = 31.831, p < .001, \eta^2 = .380$) and trial ($F(2.047, 106.457) = 21.501, p < .001, \eta^2 = .293$) was observed on the number of errors in the MD task (Figure 4D). A post hoc test showed that the number of errors in the MD in the older adult group was greater than that in the control group in all trials (all $p < .001$). There were significant differences in the number of errors between the baseline and all trials (all, $p < 0.01$) and between Trials 2 and 4 ($p = 0.001$) in the MD task. The older adult group improved in both time and errors in the MD task in Trial 4 compared with the baseline.

Comparison of Retest for the Retention of Acquired Skills in Tasks

In addition to the aforementioned older participants, as three additional older participants had practiced the TOH task many times approximately one week before the retest, their data were excluded from this analysis. Two-way repeated-measures ANOVA revealed no statistically significant interaction effect of group $\times$ trial on the completion time in the TOH task ($F(1, 49) = 0.329, p = 0.569, \eta^2 = .007$). Although there was a statistically significant main effect

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1 of group ($F(1, 49) = 10.064, p = .003, \eta^2 = .170$) on completion time in the TOH task, there
2 was no statistically significant main effect of trial on completion time in both groups (Figure
3 5A). There was no statistically significant interaction effect of group $\times$ trial ($F(1, 49) = .000,$
4 $p = .993, \eta^2 = .000$) and no statistically significant main effect of group ($F(1, 49) = 3.102, p$
5 $= .084, \eta^2 = .060$) and trial ($F(1, 49) = .854, p = .360, \eta^2 = .017$) on the number of disk
6 movements in the TOH task (Figure 5B). These findings showed that performance of the
7 TOH task did not change in both groups compared with the performance on the previous trial.
8 For retention in the MD task, there was a statistically significant interaction effect of group $\times$
9 trial on the completion time ($F(1, 52) = 5.010, p = .030, \eta^2 = .088$). There were statistically
10 significant main effects of the group ($F(1, 52) = 22.419, p < .001, \eta^2 = .301$) and trial ($F(1,$
11 $52) = 11.666, p = .001, \eta^2 = .183$) on the completion time in the MD task. A post hoc test
12 showed that the completion time of the MD task at retest (i.e., the second day after one week)
13 increased statistically significantly more than that during the final trial on the first day in the
14 older group ($p < .001$) (Figure 5C). There was no statistically significant difference between
15 the final trial and retest in the completion time of the MD task at retest in the control group (p
16 $= 0.391$). There was a statistically significant interaction effect of group $\times$ trial on the number
17 of errors in the MD task ($F(1, 52) = 6.486, p = .014, \eta^2 = .111$). Statistically significant main
18 effects of group ($F(1, 52) = 23.947, p < .001, \eta^2 = .315$) and trial ($F(1, 52) = 10.654, p$
19 $= .002, \eta^2 = .170$) were observed on the number of errors in the MD task. In the post hoc test,

although there was no statistically significant difference ($p = .600$) between the final trial and retest for the number of errors in the MD task in the control group, the number of errors showed a statistically significant increase in the retest compared with the final trial in the older adult group ($p < .001$) (Figure 5D). These findings suggested that, after one week, MD task performance had decreased in the older adult group.

Associations Among Skill Learning Abilities and IPAQ Score, Daily Steps, Muscle Strength, and Gait Velocity

The multivariate regression analysis showed that there were statistically significant differences for “age” and “IPAQ” for the rate of improvement in MD time (Table 4). This finding suggested that high levels of habitual exercise (i.e., IPAQ) in the higher age categories were associated with high rates of improvement in skill learning (i.e., the mirror drawing task). There was a statistically significant difference for “age” in the retention in TOH time ($F(1,53) = 5.923, p = .018$), which had an explanatory variance of 98.4%. No statistically significant differences were observed for age, muscle strength, gait velocity, daily number of steps, and IPAQ score in the rate of improvement and retention in the TOH and MD tasks, respectively.

Discussion

This study investigated the relationship between skill learning and habitual exercise in older adults. As we expected, the performance on both the TOH and MD, which have been used as skill tasks in previous studies, was lower in older adults than in younger participants at the baseline. The correlation analysis showed that performance of the TOH task at the baseline was related to the average steps per day (Figure 3). Moreover, the multiple regression analysis revealed a statistically significant association between skill acquisition in the MD task and IPAQ score (Table 4). These results partially supported our primary hypothesis about the positive effect of habitual exercise. Performance on the MD task at retest decreased compared with that in the final trial in only the older adult group, although skill acquisition in the MD task was observed in both groups. This supported previous findings of characteristics of skill learning in older adults (Bhakuni & Mutha, 2015; Brosseau et al., 2007; Gal et al., 2019; Kennedy et al., 2008; Lemieux et al., 2014; Müller et al., 2016; Rodrigue et al. 2005). The present results are in line with previous studies that revealed a deficit in cognitive function in older adults based on a comparison of scores in the TOH and MD tasks at the baseline between the older adult and control groups (Colcombe & Kramer, 2003; Voelcker-Rehage, 2008). There are numerous neurophysiological studies on cognitive function in older adults and changes in cellular and molecular mechanisms with aging. Brain volume (Watanabe et al., 2021) and brain-derived neurotrophic factor (BDNF) gene expression (Buchman et al., 2016) decrease with age. Moreover, BDNF is considered to increase in

many areas (e.g., the cerebral cortex, cerebellum, hippocampus, and striatum) after exercise, and physical exercise is recommended to prevent deficits in cognitive function (Bloomberg et al., 2023; Colcombe & Kramer, 2003; Hübner & Voelcker-Rehage, 2017; Martin et al., 2023; Roig et al., 2012; Smiley-Oyen et al., 2008; Wanner et al., 2020). Although this study did not investigate neurophysiological biomarkers such as BDNF, our findings directly supported the idea that the motor task with the cognitive function was associated with age and physical activity. Consistent with our results, previous studies have shown that muscle strength and gait speed are associated with cognitive function (Cabett Cipolli et al., 2019; Sui et al., 2020) but have not specifically shown which domains of cognitive function are most positively related to muscle strength (Sui et al., 2020). Increased completion time in older adults could not fully eliminate the effects of reduced reaction times and motor velocities owing to a decline in muscle strength because the TOH and MD tasks, which mainly evaluate executive function or skill acquisition, were performed with the upper limb. However, muscle strength was related to completion time and the number of disk movements or errors.

Although this study did not examine the neurophysiological mechanisms underlying the relationship between muscle strength and cognitive function, several potential mechanisms, such as the accumulation of Alzheimer's disease pathology in motor-related brain sections, an increasing number of senescent cells during aging (e.g., secretion of pro-inflammatory cytokines, growth factors, and proteases), and low sex steroid levels leading to muscle loss,

were speculated to explain the relationship between lower muscle strength and cognitive dysfunction in older adults (Orchard et al., 2022). Thus, these findings suggest that muscle strength reflects peripheral changes (i.e., intramuscular coordination or hypertrophy) and central adaptations in skill learning and that motor control related to cognitive function may decrease in older adults.

Skill acquisition in older adults was similar to that in the control group in the TOH and MD tasks, which was also consistent with the findings of previous studies on skill learning (Brosseau et al., 2007; Voelcker-Rehage, 2008). Whereas this study revealed an improvement in the completion time and number of errors during the MD task in both groups, the number of disk movements in the TOH task did not improve. Although instructions to participants in both skill learning tasks were the same, “as fast and as accurate as possible,” several participants stopped moving the disk temporarily (i.e., thinking time) to search for the optimal position during the TOH. Thus, for the TOH to be used as the cognitive skill learning task, instructions to participants were crucial, and the results should have been cautiously compared with those of previous studies and their interpretations.

Similar to the results of skill acquisition, age-related retention of acquired skills after one week varied between tasks. These findings supported a difference in the dependence on working memory during skill-learning tasks (Gabrieli et al., 1997). In neuropsychological assessments, TOH is considered a measure of response inhibition, planning abilities,

1 visuospatial memory, working memory, and problem-solving (Viejo-Sobera et al., 2017).

2 Executive functions in TOH are presumably mediated by the frontal and temporal lobe neural
3 systems (Welsh et al., 1999). The MD is a perceptual-motor skill or sensorimotor adaptation
4 task in a mirror environment (i.e., left-right and up-down reversal), in which participants are
5 expected to transfer and adapt the normal coordination system from the sensorimotor system
6 to the mirror environment. Therefore, adaptation is considered more important to MD than
7 working memory (Gabrieli et al., 1997), and age-related deficiencies in visuomotor
8 adaptation can result in decreased ability to engage spatial working memory effectively (Wu
9 et al., 2016).

10 Deficits in the MD task are often observed in patients with neurodegenerative diseases of the
11 striatum (such as Parkinson's disease) (Martin et al., 2023). Thus, the necessary capabilities
12 differ among motor skill tasks (Brosseau et al., 2007), and the degree of retention is
13 speculated to possibly differ among the motor skill tasks in older adults based on the current
14 and previous studies' findings (Rodrigue et al., 2005; Schiff & Vakil, 2015). For the retention
15 of perceptual motor skills in older adults, repetitive retrieval and recall of acquired skills are
16 crucial (Bhatt et al., 2012; Kantak & Winstein, 2012).

17 Physical exercise seems beneficial to physical and cognitive functioning (Hübner &
18 Voelcker-Rehage, 2017; Loprinzi et al., 2021); therefore, we expected that skill learning
19 would be improved as a result of enhancement of cognitive function through physical activity

1 in older adults. Physical exercises examined in previous studies were time-limited (i.e., short-
2 or long-term) and comprised interventional exercise and not habitual exercise (Fröhlich et al.,
3 2024; Kumar et al., 2022; O'Brien et al., 2024; Yang et al., 2020). Roig et al. (2012) and
4 Hung et al. (2021) reported that a single bout of aerobic exercise improved skill acquisition
5 and retention in a visuomotor force tracking task.

6 Conversely, in other studies, no advantage was found for motor learning in exercise groups
7 that performed a bout of high-intensity interval exercise (Brown et al., 2021; Greeley et al.,
8 2021; Hung et al., 2021), and high-intensity acute exercise before skill learning negatively
9 impacted motor performance during learning in older adults (Taylor et al., 2024). Thus, the
10 effects of specific aspects of training programs (e.g., task, exercise duration, intensity) on
11 skill learning remain controversial in older adults (Hübner & Voelcker-Rehage, 2017;
12 Loprinzi et al., 2021). Gökçe et al. (2022) assessed habitual physical activity levels with the
13 Baecke Physical Activity Questionnaire and reported no effect of habitual physical activity
14 on multitasking motor tasks such as driving. Zwingmann et al. (2021) reported that regular
15 participation in leisure time activities seemed to prevent age-related decline and facilitate
16 motor sequence performance and learning in older adults.

17 Zheng et al. (2023) investigated the relationship between cognitive function and long-term
18 habitual physical activity with daily steps for one year in the United States and reported that
19 higher levels of physical activity were associated with better cognitive function in the older

adult population. Our results showing the association between habitual activities (i.e., daily number of steps and IPAQ score) and skill learning task (i.e., TOH and MD) partially supported findings in recent studies (Zheng et al., 2023; Zwingmann et al., 2021).

This study has several limitations. First, it used a cross-sectional design that does not allow for the inference of causality, and future longitudinal studies are necessary to test the current conclusions. The second limitation is the age range of each group. The sample size in this study was the minimum size determined by G*Power. The age range of the control group was extremely wide (20–62 years), whereas that of the older group was narrow (i.e., 65–78 years). To overcome this limitation, it may be necessary to adjust the demographic structure of the groups differently, for example, by dividing the control group into the young and middle-age group and adding participants aged over 80 years to the older group. However, in the case of adding participants over 80 years, it will be important to ensure that their cognitive function is typical for their age since otherwise the number of older adults with mild cognitive impairment could increase in the group. The third limitation concerns the control of daily behaviors for approximately one week prior to the retest. During the study period, some older participants fortuitously engaged in irregular events (hillwalking, marathon, short trip, etc.). Thus, physical activity in older adults may be overestimated in this study. The final limitation was the assessment of physical activities using the number of daily steps measured with a triaxial accelerometer, which could not measure the intensity of the exercise. Nevertheless,

previous studies have reported that exercise intensity does not modify motor learning (Hung et al., 2021; Ishihara et al., 2021; Wanner et al., 2020). Simple physical activity partially contributed to the cognitive and perceptual-motor skill learning used in this study, and other interventions, such as repetition, acquired skills, and rehearsal, may be needed. Furthermore, longitudinal studies are needed to confirm the possibility of a synergistic effect of exercise and rehearsal.

Conclusion

The findings of this study are key to improving skill learning in older adults. They suggested that physical performance (i.e., muscle strength and gait speed) and cognitive function (i.e., scores in TOH and MD task) in older adults were related to physical activities at baseline.

Basic physical performance and cognitive functioning were lower in older adult than in younger participants; however, skill acquisition was maintained regardless of age. Moreover, the ability to retain the acquired skills decreased significantly among older adults. Therefore, higher habitual exercise levels and more social or recreational participation may maintain and improve cognitive function and motor skill learning in older adults. Our findings are useful to therapists working with older adults and their families in the rehabilitation and healthcare fields.

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Table 1*Characteristics of the Control and Older Adult Groups*

	Control group (<i>n</i> = 29)	Older adult group (<i>n</i> = 26)	<i>p</i> value
Age (years)	39.0 ± 2.8	70.9 ± 0.8	< .0001
Men/Women	18/11	15/11	
Height (cm)	165.6 ± 1.5	160.0 ± 1.5	.012
Weight (kg)	61.4 ± 2.1	57.5 ± 2.0	.191
BMI (kg/m ²)	22.3 ± 0.6	22.7 ± 0.5	.602
ROM test (degree)	18.8 ± 0.5	17.7 ± 0.8	.512
Muscle strength (kgf)	69.2 ± 3.7	58.6 ± 3.6	.0368
Maximum gait velocity (m/s)	2.0 ± 0.1	1.8 ± 0.1	.006
Average step (steps/day)	7366.7 ± 634.7	5366.4 ± 518.1	.016
IPAQ	2597.2 ± 381.3	2349.5 ± 371.2	.590

Note. Values are presented as mean ± standard error. Abbreviations: BMI, body mass index;

ROM, range of motion; IPAQ, International Physical Activity Questionnaire.

Table 2

Comparisons Between Trials on the Tower of Hanoi Task During Skill Learning

	Baseline	1st Trial	2nd Trial	3rd Trial	Retest
The completion time					
(s)					
Control group	295.6 ±	245.9 ±	171.3 ±	110.7 ± 15.7	107.0 ± 11.5
	41.3 *	36.4	26.8 *	*, †, ‡	*, †, ‡
Older adult	520.7 ±	328.9 ±	319.2 ±	252.0 ± 53.9	177.2 ± 30.9
group	60.1	51.3 †	54.3 †	†	†, ‡, §
Number of disk					
movements (n)					
Control group	84.3 ± 9.9	83.5 ±	77.2 ±	57.8 ± 8.2	51.2 ± 4.1 †, ‡
	*	7.6	14.6		‡
Older adult	113.1 ± 8.1	93.5 ±	110.7 ±	92.8 ± 21.8	64.0 ± 8.0†, ‡
group		11.0	18.5		

Note. * indicates a statistically significant difference between groups ($p < .05$). †, ‡, and § indicate the comparison with the baseline, 1st trial, and 2nd trial, respectively ($p < .05$).

PHYSICAL ACTIVITY AND SKILL LEARNING

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Table 3*Comparisons Between Trials on Mirror Drawing Task During Skill Learning*

	Baseline	1 st	2 nd Trial	3 rd Trial	Retest
	Trial				
The completion					
time (s)					
Control	112.3 ±	79.0 ±	69.1 ± 9.7 *	60.3 ± 8.1	68.4 ± 9.9
group	23.4 *	12.2 *		*	*
Older adult	300.8 ±	209.3 ±	163.5 ± 17.8	124.5 ± 10.2	163.5 ± 21.0
group	32.4	27.2 †	†, ‡	†, ‡, §	†, ‡,
Number of errors					
(n)					
Control	25.1 ± 5.2	12.2 ±	11.7 ± 2.0 *	8.6 ± 1.5	10.6 ± 1.7
group	*	2.0 *		*	*
Older adult	75.2 ± 9.7	44.3 ±	33.7 ± 5.1 †	25.3 ± 3.3	41.5 ± 7.4
group		8.4 †		†, ‡	†,

Note. * indicates a statistically significant difference between groups ($p < .05$). †, ‡, §, and || indicate the comparison with the baseline, 1st trial, 2nd trial, and 3rd trial, respectively ($p < .05$).

Table 4

Stepwise Multivariate Linear Regression Models for the Rate of Improvement of the Mirror Drawing Task

	<i>B</i> (95% CI)	Standardized β	<i>p</i> value	VIF
Time				
Model 1 ($R^2 = .209$, adjusted $R^2 = .194$, $p < .001$)				
Age	0.589 (0.273 to 0.904)	0.457	< .001	1.000
Model 2 ($R^2 = 0.274$, adjusted $R^2 = 0.246$, $p < .001$)				
Age	0.656 (0.968 to 0.345)	0.510	< .001	1.042
IPAQ	0.003 (0.000 to 0.006)	0.261	.035	1.042

Note. *B*: unstandardized regression coefficient; CI: confidence interval; VIF: variance inflation factor; IPAQ: International Physical Activity Questionnaire.

Figure Legends

Figure 1. Mirror drawing at baseline (A) and Trial 3 (B) in one older participant.

Figure 2. Correlations between procedural memory tests and strength (A-D) and gait velocity (E, F) at baseline

Figure 3. Correlation between the number of moving disks in the TOH and average steps at baseline

Figure 4. Progression of skill learning during the TOH (A and B) and MD tasks (C and D).

Black and white circles indicate the older and control groups, respectively. * indicates significant differences between groups and trials

Figure 5. Interquartile range boxes and whiskers of retention in TOH (A and B) and MD (C and D) tasks in the older and control groups. Box plots show the median values and interquartile ranges of the entire sample for each measurement. The upper and lower whiskers indicate the maximum and minimum values, respectively. Dots are plotted as data for each subject. * indicates statistically significant differences between groups or between the final trial and retest ($p < 0.05$)

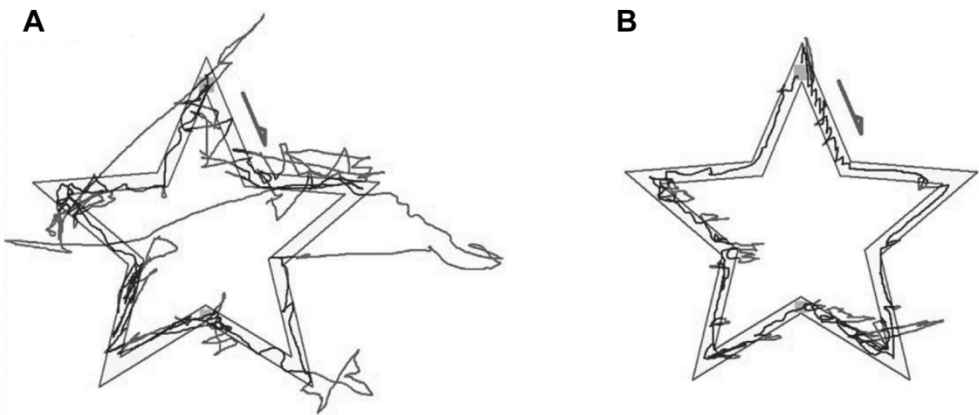


Figure 1. The mirror drawing at baseline (A) and trial 3 (B) in one older participant.

140x61mm (300 x 300 DPI)

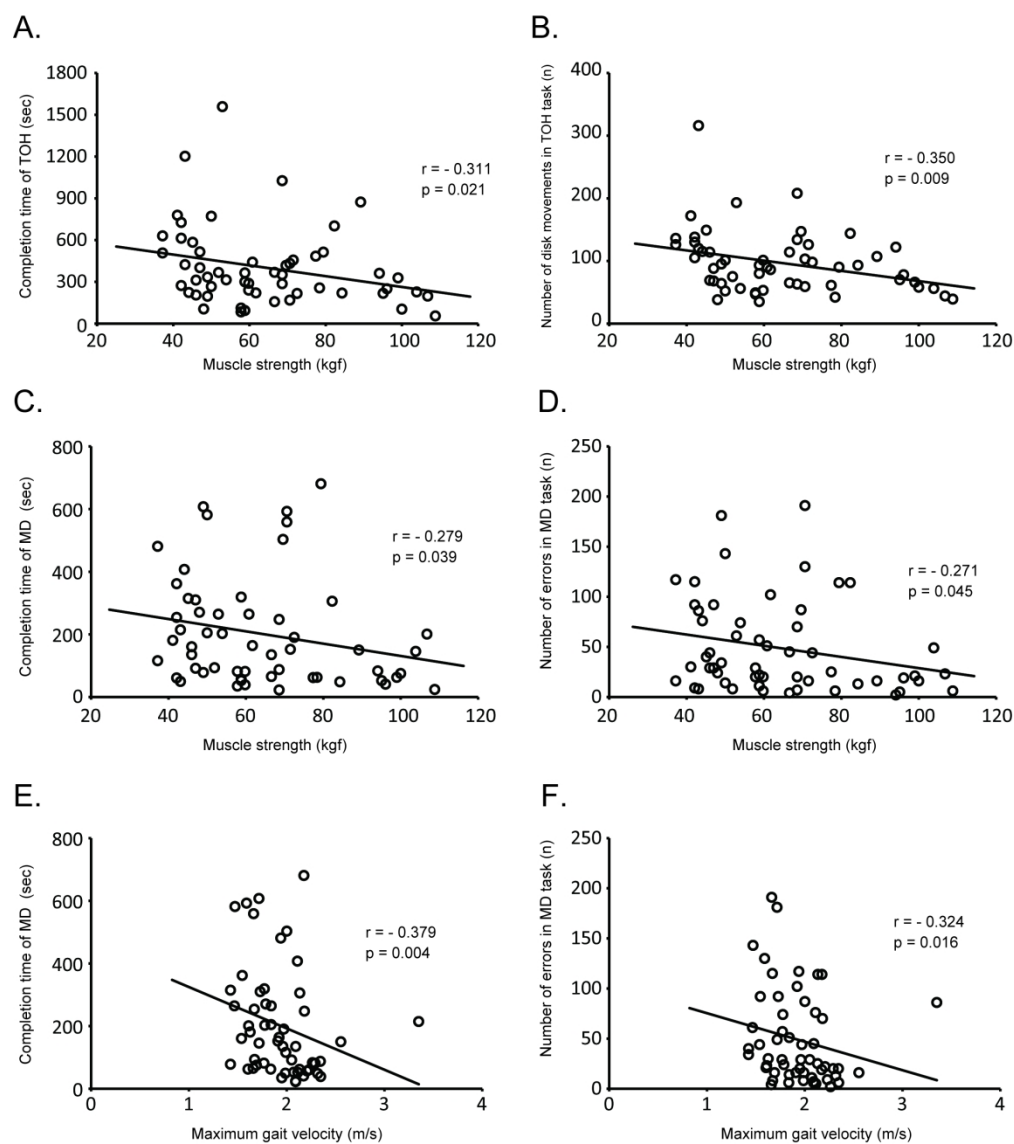


Figure 2. Correlations between procedural memory tests and strength (A-D) and gait velocity (E, F) at baseline.

206x233mm (300 x 300 DPI)

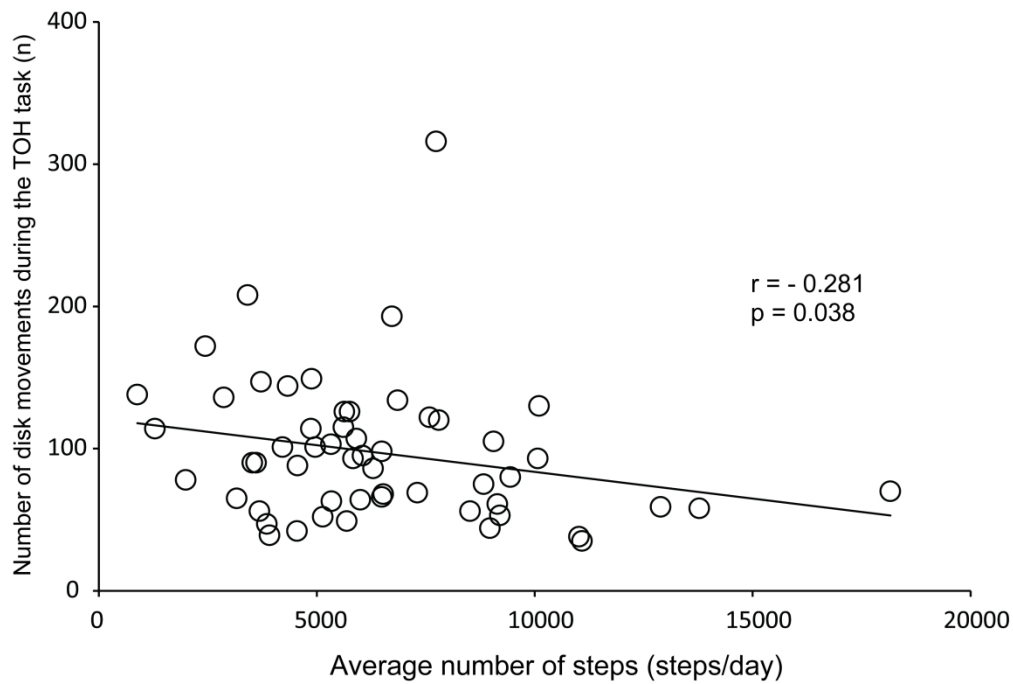


Figure 3. Correlations between number of disk movements during the TOH task and average number of steps at baseline.

268x181mm (300 x 300 DPI)

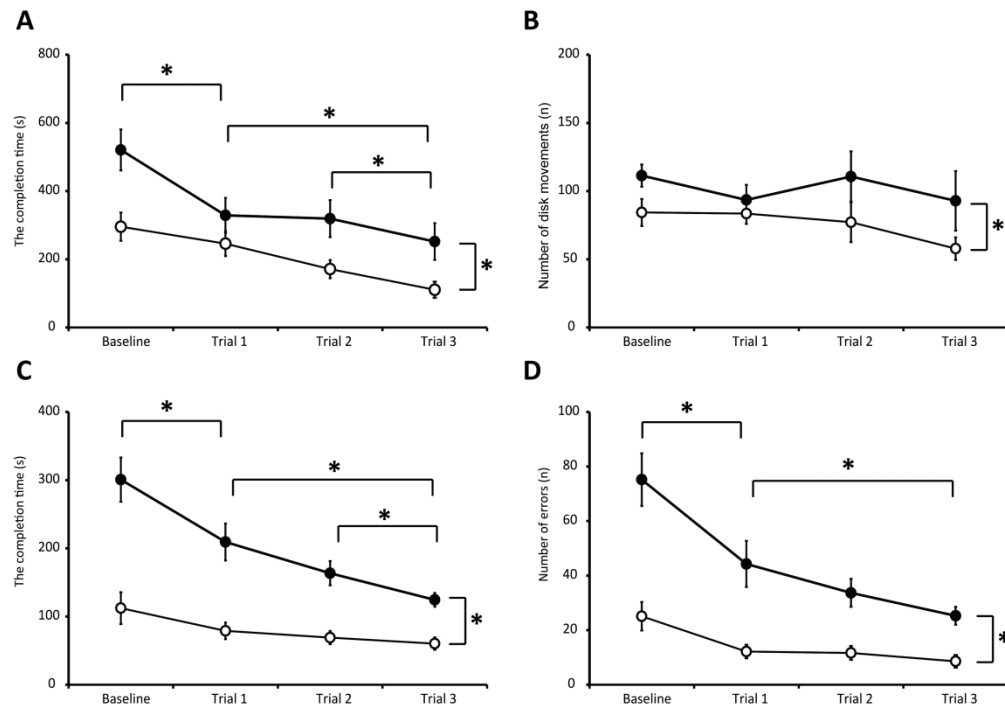


Figure 4. Progression of skill learning during the TOH (A and B) and MD task (C and D). The black and white circles indicate the older and the control group, respectively. * indicates significant main differences between groups and trials.

272x191mm (300 x 300 DPI)

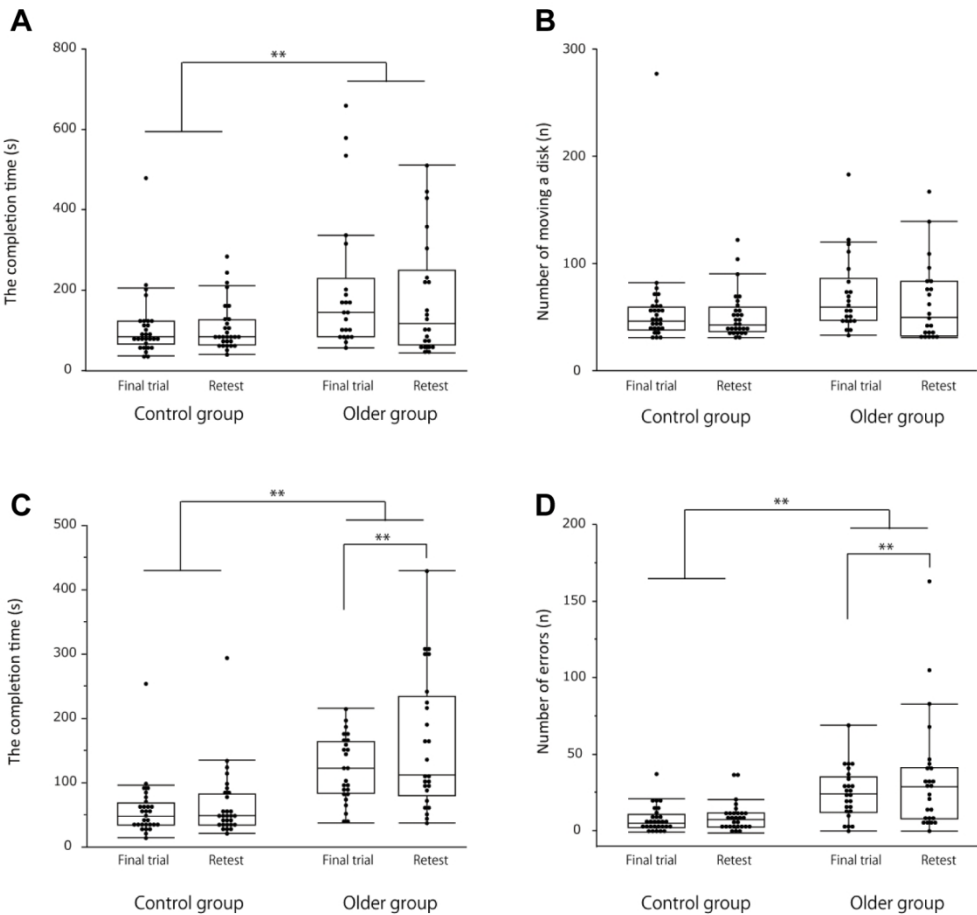


Figure 5. Interquartile range boxes and whiskers of retention in TOH (A and B) and MD (C and D) tasks in the older and control groups. Box plots show the median values and interquartile ranges of the entire sample for each measurement. The upper and lower whiskers indicate the maximum and minimum values, respectively. Dots are plotted as data for each subject. * indicates statistically significant differences between groups or between the final trial and retest ($p < 0.05$)

140x130mm (300 x 300 DPI)