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Impact of handedness on interlimb transfer depending on the task complexity combined with motor and cognitive skills

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ABSTRACT

Purpose: Task complexity could affect acquisition efficiency of motor skills and interlimb transfer; however, how task complexity affects interlimb transfer remains unclear. We hypothesized that left- and right-handed participants may have different interlimb transfer efficiency depending on the task complexity.

Methods: Left-hand (n = 28) and right-hand (n = 28) dominant participants (age = 24.70 ± 4.02 years, male: female = 28:28) performed a finger sequence test with two levels of complexity (simple: one-digit with four fingers vs. complex: two-digit with five fingers) before and after ten trials of 2-min practice each on the same apparatus. The speed and task errors were measured and analyzed.

Results: Right-handed participants failed to improve performance on their right hand (non-trained hand) after contralateral left-hand practice in the simple finger sequence task. In contrast, the left-handed participants improved performance on non-trained hands both right and left after contralateral practices. In the complex task, however, both the left- and right-handed participants improved performance on non-trained hands by contralateral practices.

Conclusion: Our results showed that task complexity of skilled practice gave different effects on interlimb transfer between right- and left-handed subjects. It appears that a certain level of appropriate complexity is necessary to detect inter-limb transfers in motor learning in right-handed subjects.

1. Introduction

Motor learning is an asymptotic process in which appropriate movements are gradually acquired through repeated practice. For instance, playing the piano and dancing can be done with extensive training, even though they appear complicated at first. Motor learning can be affected by many factors, such as the use of different hands [1], increasing difficulty [2,3], the number of repetitions [4,5], and even sleep after learning [6]. Therefore, it is important to further understand the neurological relationship between acquisition efficiency and the contribution of these factors to establish a general principle of efficient motor learning.

Motor learning is a complex process. An early study described an interesting phenomenon showing improved performance of the trained limb and untrained contralateral limb [7]. This phenomenon, called cross-education or interlimb transfer, has been demonstrated in various tasks such as finger tapping [8–12], pegboard tasks [13,14], and visuomotor tasks [15–18] several decades ago. Several studies have

Abbreviations: ANOVA, Analysis of variance; SLHLP, left-hand dominant participants performed left-hand motor practice with a simple task; SLHRP, left-hand dominant participants performed right-hand motor practice with a simple task; SRHLP, right-hand dominant participants performed left-hand motor practice with a simple task; SRHRP, right-hand dominant participants performed right-hand motor practice with a simple task; CLHLP, left-hand dominant participants performed left-hand motor practice with a complex task; CLHRP, left-hand dominant participants performed right-hand motor practice with a complex task; CRHLP, right-hand dominant participants performed left-hand motor practice with a complex task; CRHRP, right-hand dominant participants performed right-hand motor practice with a complex task; SD, standard deviation.

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reported asymmetrical transfer during a trajectory task with right-handed participants, resulting in transfer occurring only from the dominant to the non-dominant hand [19]. Another study reported symmetrical transfer during visuomotor adaptation tasks under different viewing conditions in right-handed participants [17]. Our previous study also showed symmetrical transfer in left-handed participants but an asymmetrical transfer in right-handed participants during a grooved pegboard task [13].

A possible reason for the discrepancy in previous studies may be the hemispheric dominance. Hemispheric dominance is an important topic in motor control and has been widely investigated in relation to handedness. Approximately 90% of humans are right-handed [20], and left-handed individuals are rarely considered in most motor skill learning experiments. However, handedness should be considered because neurological studies have shown that left-handed and right-handed individuals have different hemispherical activation patterns during task execution. A fMRI study clearly showed that ipsilateral motor cortex activity in single hand tasks is different between left-handed and right-handed individuals, and relates to task complexity in the single-, chords- or sequence- finger movements [21]. Furthermore, left-handed individuals exhibit fewer hemispherical asymmetries than right-handed individuals, which may further influence the behavioral performance of motor learning [22–25]. Therefore, handedness reflecting hemispheric dominance should be considered when studying interlimb transfer in motor learning.

The complexity of training tasks is another critical factor in motor learning [26–28] because more complex tasks require higher cognitive ability, which leads to changes in the brain regions responsible for processing information. Sequential finger movements, for example, affected the regional cerebral blood flow reflecting local brain activity, depending on the complexity or handedness in the brain imaging studies [26,27]. A previous fMRI study also reported that single finger movements showed slight brain activation with strong laterality while sequential finger movements induced intense brain activation in different bilateral regions with right-handed participants [21]. A fNIRS study also reported that more complex movements involve more ipsilateral hemisphere activation during uni- vs. bimanual tasks [29]. Although more complex movements would require coordination between motor and cognitive skills to increase motor learning performance, these studies mainly consider complexity in motor skills or coordination of both hands. Therefore, it remains whether complicated phenomena such as interlimb transfer could be affected by task complexity in motor, cognitive, or both skills.

Considering studies mentioned above [21,26,27,29]] and our previous study [13], we first attempted to elucidate the relationship between handedness and complexity on motor or cognitive tasks in the interlimb transfer. A preliminary experiment, however, suggested that only single task complexity was insufficient to observe robust interlimb transfer alteration dependent on task complexity in right-handed individuals (data not shown). In the current study, therefore, we further hypothesized whether left- and right-handed individuals could show different performance of interlimb transfer depending on task complexity in which motor and cognitive skills are combined.

2. Materials and Methods

2.1. Participants

Statistical power analysis in G*Power version 3.1 [30] was performed for sample size estimation. Power analysis for repeated measures analysis of variance (ANOVA) indicated a total sample size of 56, assuming type I error of 0.05, with an effect size of 0.4 and power of 0.80, the number of groups was set to 8, and the number of measurements was set to 2.

Based on the power analysis, fifty-six healthy adults were enrolled in this study (age: mean ± SD = 24.70 ± 4.02 years, 18–36 years; 28 male and 28 female). Handedness was determined using the Edinburgh Handedness Inventory [31]. The laterality index was calculated by summing the number of tasks performed by the right limb *(R)* and the number of tasks performed by the left limb *(L)* as follows: $(R - L)/(R + L)$. The laterality index for dominant left- and right-hand participants was −74.78 ± 17.76 and 88.04 ± 16.57, respectively. Participants were randomly assigned equal numbers to one of the following groups:

SLHLP: left-handed participants practiced left-hand motor skills using a simple task.
SLHRP: left-handed participants practiced right-hand motor skills using a simple task.
CLHLP: left-handed participants practiced left-hand motor skills with a complex task.
CLHRP: left-handed participants practiced right-hand motor skills with a complex task.
SRHLP: right-handed participants practiced left-handed motor skills using a simple task.
SRHRP: right-handed participants practiced right-hand motor skills with a simple task.
CRHLP: right-handed participants practiced left-handed motor skills with a complex task.
CRHRP: right-handed participants practiced right-hand motor skills with a complex task.

All participants had no history of neurological or orthopedic disorders. After providing verbal and written explanations of the experimental protocol by researchers, all participants provided written informed consent in accordance with the Declaration of Helsinki. The study was conducted in accordance with the recommendations of the Tohoku University Medical Ethical Committee (Approval No. 2020–1-1139).

2.2. Apparatus

Computer software was used to present either a simple one-digit movement task (Fig. 1A) or a complex two-digit movement task (Fig. 1B) in this study. Four fingers were used in the one-digit movement task, except the thumb; however, only one finger was used to press the keyboard (Fig. 1A). In the two-digit movement task, five fingers were used, and two different fingers were used to press the keyboard simultaneously (Fig. 1B). The completion time, error, and quantity were measured and recorded.

2.3. Experimental procedure

Computer programming was used in this study. The participants were assigned tasks and instructed to use a computer keyboard to input numbers following the computer screen (Fig. 1).

a) Simple tasks: continuous tapping tasks using the second to fifth fingers. The corresponding numbers of the four fingers were: “1″ corresponding index finger, ”2″ corresponding middle finger, “3″ corresponding ring finger, ”4″ corresponding little finger. The sequence was displayed as “1324312341,” and the participants pressed the keys quickly and accurately as instructed. A sequence of ten of one-digit numbers was presented per session. b) Complex tasks: Tapping tasks in which two consecutive fingers use the first to fifth fingers simultaneously. The corresponding numbers of the five fingers were: ”1″ corresponding thumb, “2″ corresponding index fingers, ”3″ corresponding middle fingers, “4″ corresponding ring fingers, ”5″ corresponding little fingers. The sequence was displayed as “51 24 31 52 45 42 13 35 14 21″. A sequence of ten of two-digit numbers was presented as a sequence per session. All the numbers were displayed randomly, with half in reverse order and the other half in positive order: ”51″ and “15″. Moreover, the participants were asked to complete the task quickly with the lowest error rate. If the pressing time difference between two fingers was <0.3 s,

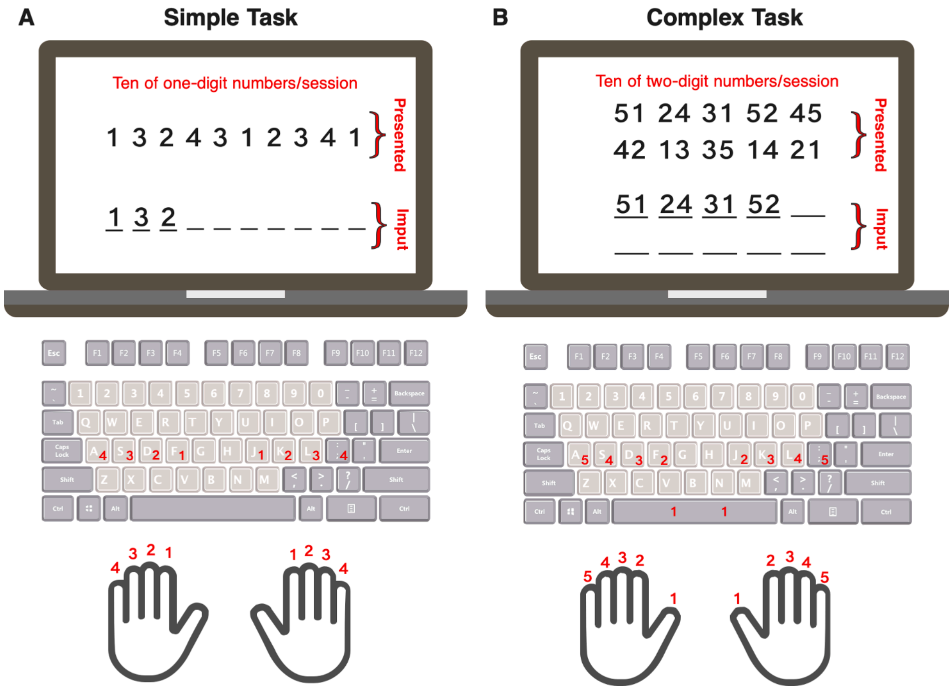

Fig. 1. Experimental setup Illustration of a simple and complex task during motor skill practice. A. The simple task is a series of continuous tapping tasks using the second to fifth fingers of left or right hand. B. The complex task is a series of tapping tasks in which two consecutive fingers use the first to fifth fingers of left or right hand. In both tasks, the participants were asked to press the keys quickly and accurately.

it was considered the same. The participants were required to press the corresponding button without delay on the premise that it was good. There was a 3-second rest between each session. The pre-test and post-test consisted of 10 sessions. In the training block, the participants were required to complete sessions as much as possible in a trial for 2-min. In the training block, trials were repeated 10 times (Fig. 2).

2.4. Statistical analyses

All data were analyzed using SPSS Statistics version 28.0. First, the normality of the behavioral variables was checked using the Shapiro–Wilk test. Second. The effects of group (right-handed left practice, right-handed right practice, left-handed right practice, or left-handed left practice) and task (simple or complex) on baseline were assessed using two-way ANOVA. Subsequently, one-way repeated measures ANOVA was used to evaluate the effects of time points (from 1st to 10th)

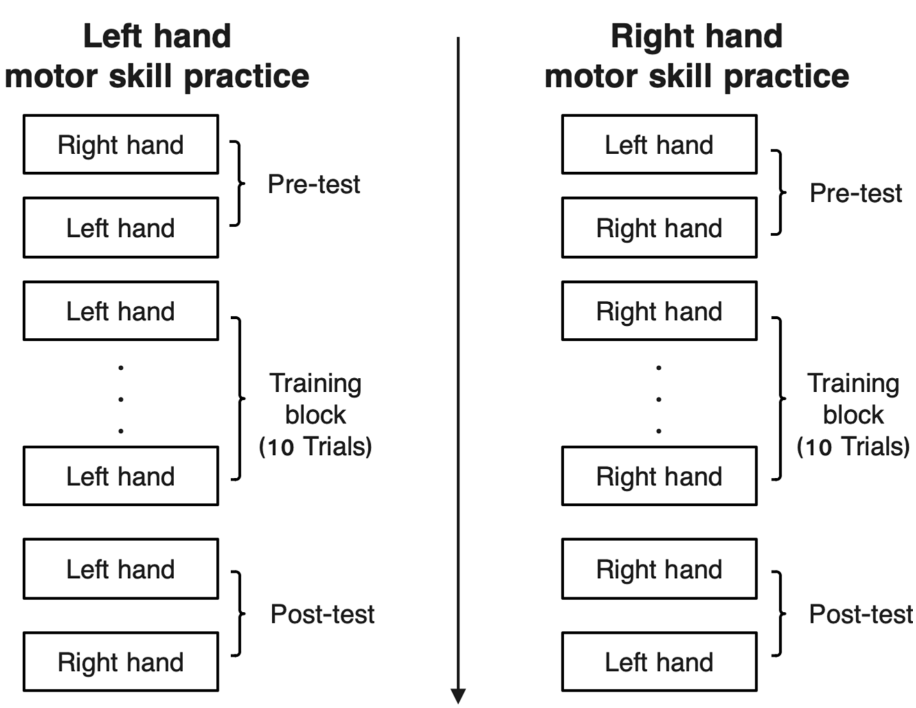

Fig. 2. Experimental design. Left-and right-hand dominant participants were randomly assigned to the same numbers of simple and complex motor skill practice groups, with half practicing on the left and the other half on the right. Participants completed one test (pre-test) with each hand separately. The participants were timed on their speed and task errors. The same procedure was repeated for the second trial (post-test) after undergoing four blocks of unilateral hand motor skill practice with the assigned hand using the same apparatus.

on learning. Separate ANOVAs were performed for each condition. Finally, mixed-ANOVA was used to compare the between-subject factor (condition) and within-subject factor (time) among the eight groups with interlimb transfer. The separation was conducted for the completion time and error. Complementary post hoc analyses (paired sample t-tests) were used when indicated. Cohen's effect size (d) was computed as appropriate. The Greenhouse-Geisser correction was used when the assumption of sphericity was violated. For all analyses, regarding a significant F-value, Tukey's post hoc test was used to test for multiple comparisons and identify the means that were significantly different at $p < 0.05$.

3. Results

Table 1 presents the baseline level of the trained hand under each condition. The complexity of the task had a significant impact on the baseline levels. The ANOVA confirmed a significant main effect related to the task (F (1, 48) = 81.37, $p < 0.001$). ANOVA also confirmed that there was no difference in baseline levels between groups with different handedness using different practice hands (F (3, 48) = 1.744, $p = 0.171$) or the interaction between task difficulty and group (F (3, 48) = 1.755, $p = 0.169$).

Learning development was investigated during each training phase (Fig. 3). These learning curves indicate that learning was acquired during practice, as the quantity completed consistently increased for all conditions ($p < 0.01$). This implies that our training procedure achieved the desired effect. Furthermore, Dunnett's post-hoc test revealed significant differences between the first practice results and the results of subsequent practice. However, each group's acquisition time course varied. Three out of four left-handed groups received training effects by the fourth trial, whereas skill acquisition was highly dependent on handedness and task difficulty in the right-handed groups.

Mixed-ANOVA with repeated measures on time was performed to evaluate the interlimb transfer for the completion time of all eight conditions of pre-training and post-training. The analysis revealed a main effect of time (F (1, 48) = 106.969, $p < 0.001$) and a significant interaction effect of time × group (F (7, 48) = 9.603, $p < 0.001$) (Fig. 4). Left-handed participants showed an increase in performance in both groups following training, irrespective of task complexity. Contrarily, right-handed participants failed to improve manual performance in their right hand after the left-hand simple motor skill practice ($p = 0.2656$, d = 1.002); however, they showed improvement on the right hand in the complex motor skill practice ($p = 0.011$, d = 2.982) and left-hand performance after the motor skill practice ($p = 0.003$, d = 3.856, $p = 0.003$, d = 3.966, respectively). An ANOVA performed to evaluate the error of all eight conditions did not show a significant interaction between the time point and group (F (7, 48) = 2.102, $p = 0.061$), suggesting that the completion time is a more reliable measure of performance. Furthermore, there was no increase in the error rate between pre- and post-training, suggesting that the observed decrease in completion time was not obtained to the detriment of lower accuracy.

Table 1
Time (second) required for completion of each task.

	Right-Handed Left Practice	Right-Handed Right Practice	Left-Handed Right Practice	Left-Handed Left Practice
Simple task	83.16 ± 14.45	84.49 ± 17.18	80.80 ± 8.54	82.57 ± 9.34
Complex task	189.74 ± 58.32	173.39 ± 68.51	182.20 ± 30.21	132.77 ± 26.26

Values are expressed as mean ± SD.

4. Discussion

This study aimed to determine whether handedness and task complexity would affect manual performance and interlimb transfer in sequence tasks. To the best of our knowledge, this is the first study comparing right- and left-handed motor skill acquisition after right- or left-hand practice. This study also demonstrated the differences between simple and complex sequence tasks for left-handed and right-handed participants. This study results showed that the interlimb transfer of skill acquisition was different between completing simple and complex tasks or between the left -and right-handed. In the simple task, the left-handed participants showed an increased performance of the opposite non-trained hand in both the right-hand and the left-hand training. In contrast, the right-handed participants failed to improve the performance of their right hand after the opposite left-hand training. There was a slight difference in motor skill performance between the left- and right-hand training after the right- and left-hand training for the left-handed, as they showed better performance stability. In the complex task, the right- and left-handed participants showed performance improvement, regardless of the trained hand but included the opposite non-trained hand. The effect of handedness on interlimb transfer was no longer visible for complex tasks. Our results supported our hypothesis and fit into our daily experience that the left-handed and right-handed do not show much difference in life complexity.

The result in the present study may partly explain the previous contradictory observations in a trajectory task with right-handed participants by showing that interlimb transfer occurs only from the dominant to the non-dominant hand [19]. Our previous result showed that motor skill learning transfers only occurred from the dominant to the non-dominant right-hand and no improvement in performance after right-hand training using the grooved pegboard test [13]. In contrast, symmetrical transfer has been observed during a nine-keyboard with 1–3 keys to respond to tasks for right-handed individuals [32] or during an eight-digit random and fixed sequence number tapping task for both right-handed and left-handed individuals [33]. In this study, we observed that task difficulty combined with motor and cognitive skills could have a different effect between left- and right-handed individuals, which may provide insight into a better experimental design to analyze interlimb transfer.

Hemispheric structural asymmetries in the previous studies may explain our simple task results. Neurological studies have shown that the dominant hand of the right-handed has a larger hand motor area than the non-dominant hand [25], while the left-handed had no significant difference in the somatosensory cortex between the dominant and non-dominant hands [23]. These reports suggest that the left-handed may have less obvious hemispherical features [22]. Furthermore, left-handed performance between the dominant and non-dominant hemispheres shows greater symmetry compared with right-handed [25]. The difference in hemispheric structural asymmetries between left- and right-handed individuals should be more considered in the interlimb transfer studies.

The excitability of contralateral M1 of the trained hand significantly increased with increased task complexity [29,34]. In addition, there is evidence that the premotor motor area, auxiliary motor area, and attentional cognition area are also involved in the learning of complex sequential motor tasks [26–28,35–38]. Because of multi-region cooperation, the effect of interhemispheric asymmetry of handedness will disappear. These theories can be an explanation for our complex task results. Previous studies reported that M1 plays a more significant role in complex than simple finger sequential movement [39], Dirren and colleagues found changes in connectivity between untrained and trained M1 before and after sequential movement training correlated with transfer [12]. In addition, TMS and fMRI studies showed that the intracortical facilitation (ICF) and activation changes in the cerebellar were associated with interlimb transfer [40,41]. These findings may give a plausible explanation for our results.

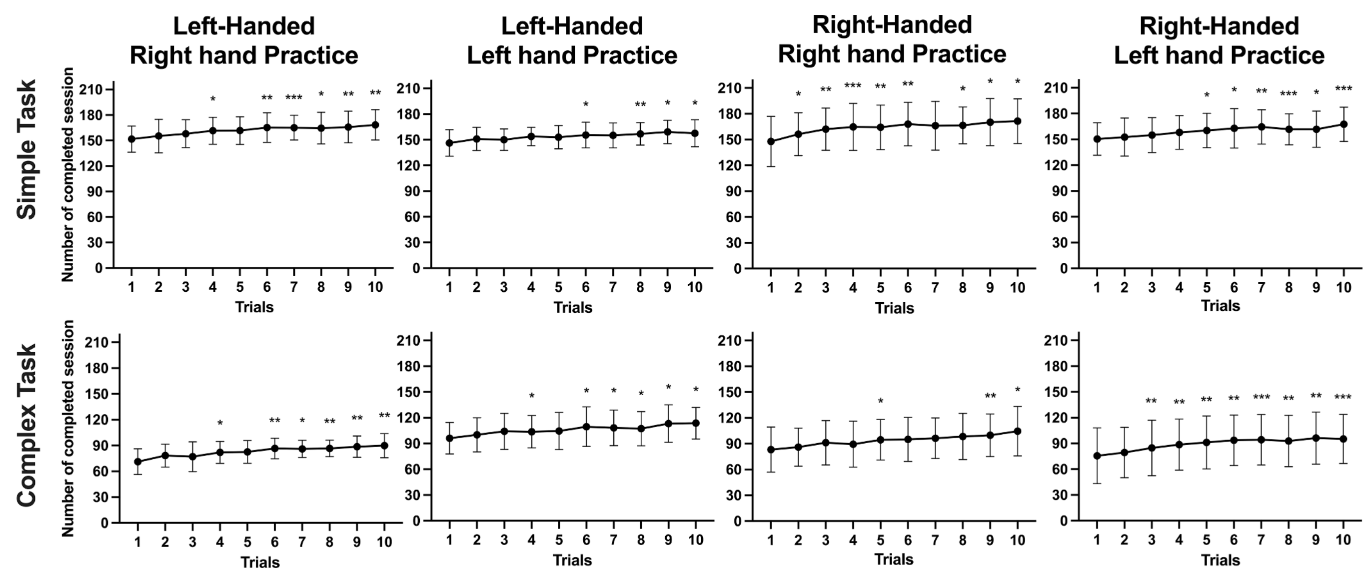

Fig. 3. Acquisition curve of a simple and complex task during ten-times practice. Learning curves were constructed for each condition during the training phase. These learning curves showed that some learning occurred during practice, as the quantity completed consistently increased for all conditions (all $p < 0.05$). Dunnett's post-hoc test revealed significant differences between the first practice results and the results of subsequent practice.

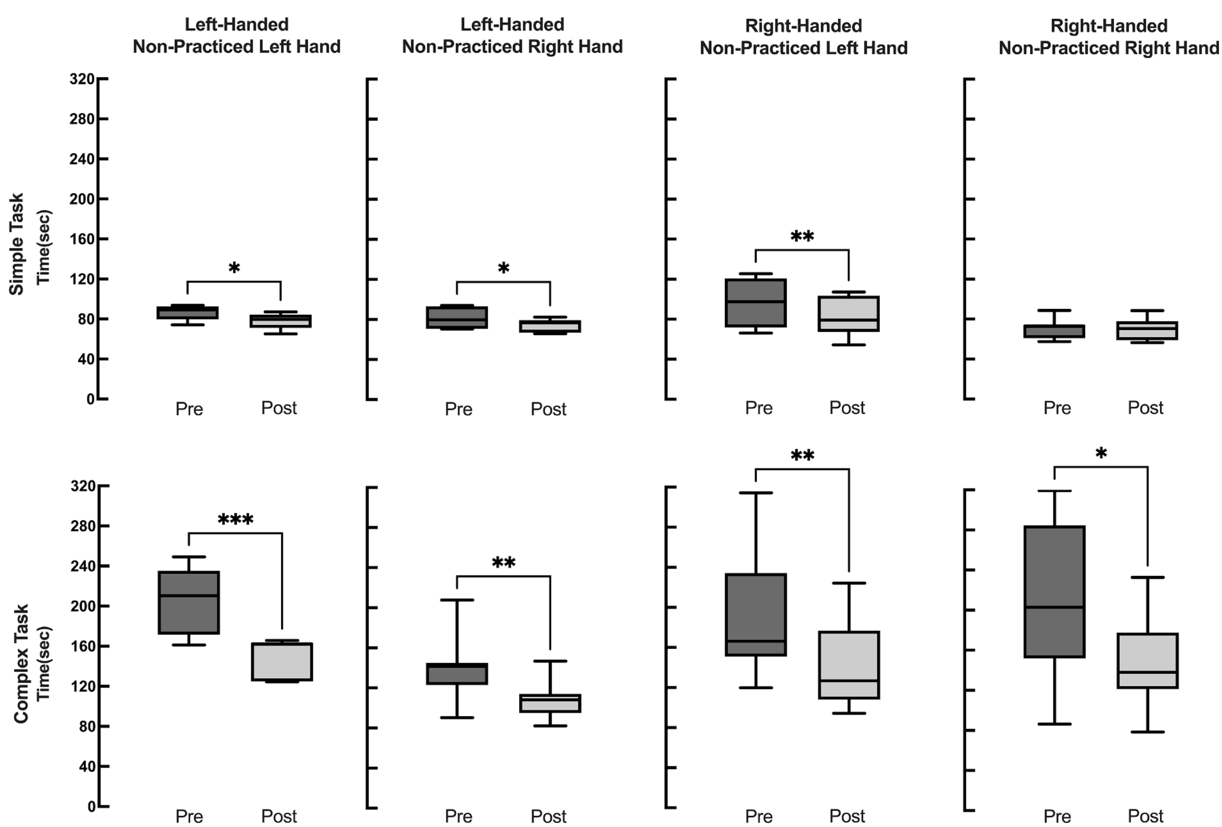

Fig. 4. Interlimb transfer in a simple or complex task. The untrained hands of the left-handed participants performed faster at post-test (white boxes) compared to pre-test (gray boxes) after the simple motor skill practice and after the complex motor skill practice. However, after the left-hand simple motor skill practice, the right-handed participants failed to improve manual performance in their right hand. Although they showed improvement on the right hand in the complex motor skill practice, regardless of which conditions, their left-hand performance improved after the motor skill practice. The boxplots show the median, upper, and lower quartiles and the minimum and maximum values of the groups. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

This study had mainly two limitations. First, a small sample size of eight groups (each group, $n = 7$) was used. We adopted parallel research instead of a crossover study because previous studies have shown that interlimb transfer has a more prolonged retention effect. For instance, a study indicated that interlimb transfer had a 100% retention effect on the second day [42]. Another study suggested that the retention of interlimb transfer was > 50% after 1 month [43]. Second, we did not conduct a functional study to investigate the possible dynamic changes in the two hemispheres using EEG or fMRI. Future studies using carefully designed experiments with functional approaches are required to understand the differences in the neural mechanisms of motor skill acquisition and learning and interlimb transfer between the left- and right-hand dominant individuals.

5. Conclusion

In conclusion, we detected differences in manual performance and interlimb transfer after simple and complex short-term unilateral hand practice between left- and right-hand dominant individuals. Although our findings are hard to be directly applied to patients with movement disorder such as ataxia, they provide some meaningful information that may be clinically useful and serve as a basis for future studies on patients with neurological disorders. Furthermore, our findings may support rehabilitation success for unilateral hand injuries. In addition, they may provide valuable information for neurological research focusing on the difference between the two hemispheres and neuroplasticity.

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CRediT authorship contribution statement

Yi Fan Wang: Conceptualization, Methodology, Data curation, Writing – original draft. **Jun Zhao:** Conceptualization, Methodology, Data curation, Writing – original draft. **Hitoshi Inada:** Data curation, Writing – review & editing. **János Négyesi:** Conceptualization, Methodology, Writing – review & editing. **Ryoichi Nagatomi:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neulet.2022.136775.

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