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Short-term mirror visual feedback training enhances performance gains in the untrained hand for a complex motor sequence learning task

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Abstract

Mirror Visual Feedback (MVF) is an experimental paradigm that simultaneously combines action observation and cross-education, and has been proposed to produce greater performance gains in the untrained limb than either action observation or cross-education alone. Existing studies investigating the effects of unilateral training under MVF on the performance of the untrained limb are limited, and their findings are mixed. In this between-groups study, we investigated the effects of MVF training on untrained left-hand performance in a complex motor sequence learning task involving fine finger movements. Statistically significant performance gains were observed in the untrained left-hand following dominant right-hand training under both normal visual feedback (NVF) and MVF conditions. Critically, the magnitude of performance gains was significantly greater following MVF training than following NVF training, indicating that MVF enhanced untrained-hand performance beyond that associated with cross-education alone. We also investigated the effects of MVF training on the untrained left-hand's performance for novel movement sequences (i.e., movement sequences not practiced by the right-hand during training). Statistically significant performance gains for these novel movement sequences were observed in the untrained left-hand following right-hand training under both NVF and MVF conditions; however, the magnitude of these gains was comparable. Thus, the additional performance benefit associated with MVF in the untrained left-hand for sequences practiced by the right-hand during training did not extend to novel movement sequences. Finally, we highlight several task-design considerations that may inform future studies seeking to enhance MVF-related performance gains in the untrained limb.

Keywords: motor learning, mirror visual feedback, cross-education, intermanual transfer, action observation, motor sequence learning, virtual reality

1. Introduction

Motor learning can be broadly defined as the experience-dependent improvement in performance (Krakauer et al., 2019). Within this broad definition, motor learning can include both the acquisition of new skills and the maintenance of previously acquired skills under changing conditions (Krakauer et al., 2019). The most effective way to achieve motor learning is through physical practice. However, motor learning can also occur through alternative modes, such as action observation (Vogt & Thomaschke, 2007; Ste-Marie et al., 2012), motor

imagery (Toth et al., 2020; Lindsay et al., 2023), and cross-education (Zhou, 2000; Carroll et al., 2006). Action observation involves observing another individual, model, or visually represented limb performing movements and can facilitate the acquisition or refinement of motor skills. Motor imagery involves mentally simulating or rehearsing movements without overt physical execution. Cross-education refers to the phenomenon whereby training a task with one limb results in performance improvements not only in the trained limb but also in the contralateral untrained limb (Scripture et al., 1894; Manca et al., 2021).

Mirror visual feedback (MVF) is an experimental paradigm that simultaneously combines the motor learning modes of action observation and cross-education. This paradigm has its origins in mirror therapy, which is a simple but unique method that has garnered considerable interest over the last three decades for its potential application in stroke rehabilitation. Its use was first demonstrated in 1996 for alleviating phantom limb pain in amputees by Ramachandran and Rogers-Ramachandran (Ramachandran & Rogers-Ramachandran, 1996). Subsequently, a 1999 study from the same group demonstrated its potential to augment stroke rehabilitation outcomes (Altschuler et al., 1999).

In their seminal 1999 study, a mirror was positioned along the patients' midsagittal plane, with the hands placed on either side of the mirror. The patients were instructed to attempt making symmetrical movements with both hands simultaneously while viewing the mirror reflection of the unaffected hand. The setup was arranged such that the reflection appeared superimposed on the paretic (weakened or partially paralyzed) limb hidden behind the mirror, thereby creating the illusion that the paretic limb was moving normally. In this way, the intervention used by Altschuler et al. (1999) simultaneously incorporated three motor learning modes in relation to the paretic limb: 1. physical practice – through movement of the paretic limb to the extent possible, 2. action observation – through viewing the illusion of the paretic limb as moving normally, and 3. cross-education – arising from practice with the unaffected limb. The promising findings of this study subsequently motivated numerous studies to investigate the effectiveness of mirror therapy in stroke rehabilitation (Pérez-Cruzado et al., 2017; Broderick et al., 2018; Thieme et al., 2018; Hsieh et al., 2025).

Beyond its clinical application, mirror therapy also motivated a separate line of fundamental research in neurologically intact individuals, aimed at understanding the effects of mirror feedback on motor learning in the untrained limb (for a review, see Chen et al., 2019). In contrast to the mirror-therapy procedure used by Altschuler et al. (1999), the hand placed behind the mirror in these studies remained stationary, thereby eliminating actual or attempted movement of the hidden limb. Consequently, any motor learning effects observed in the stationary limb were likely mediated by action observation of the mirror reflection of the contralateral limb, cross-education arising from contralateral limb practice, or a combination of both. This experimental paradigm is commonly referred to as *mirror visual feedback* (MVF).

A few studies have demonstrated that MVF can facilitate motor learning in the untrained limb beyond that achieved through cross-education or action observation alone. In a set of functional hand motor tasks, MVF produced greater performance gains than both cross-education (Hamzei et al., 2012; Bähr et al., 2018) and action observation (Bähr et al., 2018). Similarly, in a sequential finger movement task, Ossmy and Mukamel (2016) found that MVF produced significant performance gains even though neither action observation nor cross-education alone yielded significant improvement. In a three-week resistance training intervention involving dynamic wrist flexion, MVF produced greater strength gains in the untrained hand than cross-education alone (Zult et al., 2016). Interestingly, in a basketball dribbling task, MVF produced greater performance gains than cross-education in participants with pre-existing task expertise but not in novices (Steinberg et al., 2016). Finally, in a fine-motor chopstick manipulation task, MVF-based training of the dominant hand produced significant performance gains in the untrained non-dominant hand (Park & Son, 2022). Strikingly, the magnitude of this improvement was comparable to that achieved through direct training of the non-dominant hand. An important consideration in interpreting this finding is that the study was conducted in a population with lifelong experience using chopsticks. Given the expertise-related differences in MVF outcomes reported in the basketball dribbling study (Steinberg et al., 2016), prior familiarity with chopstick use may also have influenced the magnitude of MVF-mediated learning.

However, findings from some MVF-based studies are mixed. In a two-ball rotation task, Nojima and colleagues (2012) reported significant performance improvement due to both MVF and action observation, but not due to cross-education (Nojima et al., 2012). This suggests that the improvement associated with MVF in this task may have been driven primarily by the action observation component of MVF rather than by its cross-education component. This view was further supported by a follow-up study by Nojima and colleagues (2013), which reported MVF-mediated performance improvement in the untrained hand in two patients with callosal disconnection (Nojima et al., 2013). Given that callosal interactions have been proposed as one mechanism underlying cross-education (Calvert & Carson, 2022), this finding suggests that the contribution of cross-education to MVF-mediated performance gains in the two-ball rotation task may have been limited.

In contrast, two separate studies using the same two-ball rotation task reported significant performance improvements in the untrained hand due to both MVF and cross-education (Reissig et al., 2015a; Rjosk et al., 2017). Interestingly, while one study reported comparable magnitudes of improvement between MVF and cross-education (Reissig et al., 2015a), the other reported greater improvements due to MVF (Rjosk et al., 2017). Overall, the studies that employed the same general two-ball rotation task differed in aspects of task implementation and experimental design, including ball size and weight, as well as practice duration. Such methodological differences may have contributed to the divergent behavioral outcomes; however, the specific factors responsible remain unclear.

Finally, in a separate study involving a ballistic finger-abduction task, MVF and cross-education produced comparable performance gains (Reissig et al., 2015b). Reissig et al. suggested that the lack of an additional MVF benefit may have arisen because successful performance of the task did not rely strongly on continuous online visual feedback. Building on this, we speculate that the reduced reliance on visual feedback may have limited the contribution of MVF's action-observation component to overall performance improvement, potentially contributing to the absence of an additional MVF benefit beyond cross-education.

Collectively, across different motor tasks, existing studies show variability in whether MVF produces greater performance gains in the untrained limb than those achieved through alternative motor learning modes of action observation or cross-education. Furthermore, several factors may influence MVF-mediated performance outcomes. Participants' pre-existing task expertise appears to be one such factor, as demonstrated for a basketball dribbling task by Steinberg et al. (2016). Other factors, such as the degree to which a task depends on visual feedback for successful execution and the relative contributions of action observation and cross-education within MVF to overall performance improvement, are plausible influences on MVF outcomes, although their influence has not been directly established. Overall, there is currently no clear consensus that MVF-mediated motor learning in the untrained limb is superior to other non-physical motor learning modes such as cross-education and action observation (Chen et al., 2019). This highlights the need for further studies investigating the effectiveness of MVF across different types of motor tasks.

To address this need, we investigated the effects of short-term MVF training on a complex motor sequence learning task involving fine finger movements. Our study builds on the 2016 study by Ossmy and Mukamel (2016), which investigated the short-term effects of MVF training on a different motor sequence learning task. In both studies, MVF was delivered through a virtual reality (VR) headset. However, the task used in the present study was more complex, requiring participants to execute spatially targeted sequences of fine finger movements with increased multi-joint and multi-finger coordination demands. In contrast, the task used by Ossmy and Mukamel involved repeated execution of a fixed sequence of finger flexion–extension movements. An additional layer of complexity in the present study was that participants were required to repeatedly perform seven different movement sequences in a randomized order within each trial, whereas Ossmy and Mukamel used only one movement sequence. More broadly, most existing MVF studies had tasks that required performing the same or highly similar movements repeatedly throughout the training period. In some cases, such a repetitive task structure may facilitate faster learning and consequently earlier automatization of task execution.

The task in the current study had a few important aspects worth noting. First, its successful execution inherently required a high degree of dependence on continuous visual feedback. During MVF, this meant that the participants had to use visual information from the mirrored hand while performing the task. We speculate that this sustained visual engagement with the

mirrored hand could more effectively leverage the action observation component of MVF, potentially contributing to greater performance improvement in the untrained hand. Second, unlike tasks used in previous MVF studies, the present task incorporated a points-based performance feedback scheme in which the participant's score was updated in real time throughout each trial. This was intended to motivate performance improvement both within and across trials. Finally, the task was novel, involving movement patterns not typically acquired through everyday functional activities. The novelty of the task was expected to reduce the potential influence of pre-existing task expertise on MVF-mediated performance outcomes.

With respect to this motor sequence learning task, the current study had two primary objectives. The first was to examine the effects of cross-education alone and MVF on performance gains in the untrained, non-dominant left hand. The second was to determine whether MVF enhances performance in the untrained left hand beyond that achieved through cross-education alone. We hypothesized that dominant right-hand training would lead to performance improvements in the untrained left hand under both normal visual feedback (reflecting cross-education effects) and mirror visual feedback, and that mirror visual feedback would produce greater gains than normal visual feedback. In addition, the study included an exploratory objective to examine whether the untrained left hand showed performance gains for novel movement sequences (i.e., movement sequences not practiced by the trained right hand) and whether the magnitude of these performance gains differed between the mirror and normal visual feedback conditions.

2. Materials and Methods

2.1 Overview

The primary aim of this study was to investigate whether mirror visual feedback (MVF) produces greater performance gains in the untrained, non-dominant left hand than cross-education alone in a complex motor sequence learning task involving fine finger movements. The experiment employed a between-participants design in which right-handed individuals were recruited and assigned to either a control group or a mirror group.

Participants wore a VR headset that displayed a pair of virtual hands that accurately replicated the movements of the two real hands in real time. The experimental task required participants to perform various sequences of fine finger movements with the instructed hand (see Section 2.5: *Experimental Task* for more details). Task performance was assessed in both hands before and after a practice session performed with the dominant right hand. The primary outcome of interest was the change in performance of the untrained left hand from pre- to post-practice.

The two groups differed only in the visual feedback provided during the practice session. In the control group, each virtual hand faithfully replicated the movements of its corresponding real hand. In the mirror group, movements of the real right hand were mirrored by the virtual

left hand, while the virtual right hand remained fixed in a pre-defined posture (see Section 2.6: *Mirror Visual Feedback (MVF)* for more details). Participants in this group therefore practiced with the real right hand while viewing the virtual left hand for visual feedback.

2.2 Participants

Twenty right-handed adults (6 female) participated in the experiment and were assigned to either a control group (n = 10; 3 female) or a mirror group (n = 10; 3 female). For the control group, the mean ± SD age, height, and weight were 25.8 ± 4.4 years, 165.4 ± 8.2 cm, and 67.7 ± 11.1 kg, respectively. For the mirror group, these values were 23.3 ± 3.2 years, 169.3 ± 8.9 cm, and 63.6 ± 10 kg, respectively. Each participant received an honorarium of INR 1,000 for their participation.

Ethical approval for the study was obtained from the Institute Ethics Committee of the Indian Institute of Technology Madras (approved project no: IEC/2022-2/SKM/03/09). All experimental sessions were conducted in accordance with the procedures approved by the Institute Ethics Committee. Written informed consent was obtained from all participants prior to their involvement.

2.3 Participant Inclusion and Exclusion Criteria

More than 75 individuals were screened for the experiment, of whom 26 met the eligibility criteria. Of these, 20 participants ultimately enrolled and completed the study. Eligibility criteria included a self-reported preference for using the right hand, no history of serious hand injury (e.g., fractured finger bones), no history of training in musical instruments, no history of training in classical Indian dance forms involving intricate hand postures (e.g., Bharatanatyam), and no regular engagement in video gaming (mobile, PC, or console), particularly games requiring rapid and repetitive finger movements (e.g., shooting or racing games).

Hand preference in the enrolled sample was subsequently characterized using the Edinburgh Handedness Inventory – Short Form (EHI-SF; Veale, 2014). Nineteen participants were classified as right-handed, while one participant was classified as mixed-handed. Despite this classification, the participant reported a clear preference for using the right hand in daily activities and was therefore retained. The laterality quotient derived from the EHI-SF had a mean ± SD of 88.8 ± 16.2, with values ranging from 50 to 100.

2.4 Experimental Setup

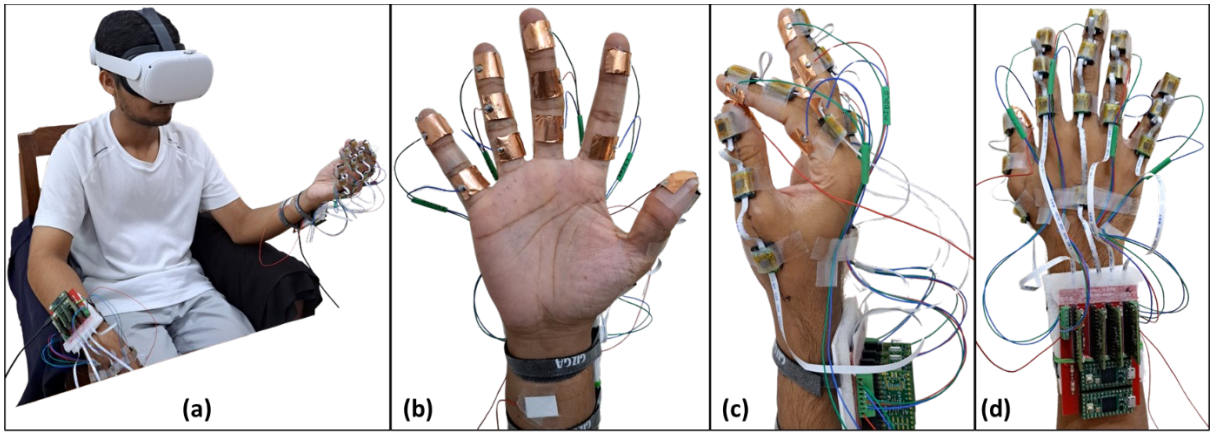


Figure 1. Experimental setup mounted on the participant. (a) Participant with the VR headset mounted on the head and the HKMS and TIS mounted on both hands. **(b)** Palmar surface of the participant's hand with the TIS copper patches affixed to the appropriate finger phalanges. **(c)** Participant touching the copper patch on the distal phalanx of the index finger with the copper patch on the distal phalanx of the thumb. The onset of this contact is detected by the TIS as a key press event. **(d)** Dorsal surface of the participant's hand with 16 IMU's of the HKMS affixed on all the finger phalanges, and one affixed on the metacarpal region. The HKMS–TIS board, which contains five HKMS microcontrollers and one TIS microcontroller, is strapped below the wrist.

The experimental setup consisted of three tightly synchronized systems: **(i)** a Hand Kinematics Measurement System (HKMS), **(ii)** a Text Input System (TIS), and **(iii)** a Virtual Reality (VR) system. The design and validation of the HKMS have been described in detail in our previous publication (Shenoy, Gupta, and SKM, 2022). Comprehensive technical details of the complete experimental setup are provided in our prior work (Gupta & SKM, 2026). The present subsection, therefore, provides only a brief overview of the main components of the experimental setup.

(A) Hand Kinematics Measurement System (HKMS): The HKMS tracks hand and finger kinematics using 16 inertial measurement units (IMUs; BNO055, Bosch Sensortec) affixed to the dorsal surfaces of all finger phalanges, including one on the metacarpal region a few centimeters below the middle finger (see Fig. 1(d)). The system outputs the orientation (as quaternions) of all 16 IMUs at 100 Hz (Shenoy, Gupta, and SKM, 2022).

(B) Text Input System (TIS): This is a custom-built typing device used to implement the experimental task. It consists of ten copper patches affixed to the palmar surfaces of the finger phalanges and one copper patch on the tip of the thumb (see Fig. 1(b)). Each phalanx-mounted copper patch functions as a key and is mapped to a specific character (see virtual hands in Fig. 2 for mapping). To type a character, the corresponding phalanx copper patch is touched with the thumb copper patch by performing a finger–thumb opposition movement (see Fig. 1(c)). The TIS detects, with millisecond resolution, the time instant when contact between the thumb copper patch and a phalanx copper patch is established (analogous to a key press) and the time instant when this contact is completely removed (analogous to a key release). For each detected event, the TIS outputs the timing information together with the character associated with the contacted phalanx copper patch.

(C) A Virtual Reality (VR) system: This system implements the VR environment for the experiment. It consists of a VR headset (Meta Quest 2; See Fig. 1(a)), which is connected to a computer via a high-speed USB-C cable. The computer runs a PC-VR application (built using the Unity game engine software) that generates and manages the virtual environment that is displayed through the headset. The PC-VR application accepts real-time data from the HKMS and TIS of both hands. The orientation data from the HKMS is used to animate a pair of virtual hands in real time to either replicate movements of the two real hands or to provide mirror visual feedback. Simultaneously, the typing data from the TIS is used to update a word interface related to the typing task.

(D) System Integration: Appropriate communication protocols were designed and implemented between the three systems, and all three systems work in sync with each other. The microcontrollers of the HKMS and TIS were mounted on a single Printed Circuit Board (PCB), referred to as the HKMS-TIS board (See Fig. 1(d)). This board was designed with appropriate interconnections to enable communication between the two systems. Data from both systems is synchronized and transmitted as a single data frame every 10 ms to a computer via USB. Each data frame contains the orientation data from all 16 IMUs and typing data (if available) from the TIS. The computer runs a PC-VR application that accepts real-time data from the HKMS-TIS boards of both hands simultaneously. The PC-VR application also controls the operating modes of the HKMS-TIS boards, and it ensures that its own operating mode is in sync with that of the HKMS-TIS boards.

2.5 Experimental Task



Figure 2. Virtual task environment during a practice trial under normal visual feedback (NVF). The 3D word displayed above the virtual right hand is the word to be typed, and the green letters indicate characters that have been successfully typed. The screen above the 3D word displays the trial score, remaining trial time, and the participant's highest trial score across the completed practice trials. The virtual right hand's thumb tip is shown contacting the phalanx labelled "T," which corresponds to "T" being typed. The image of the participant's real right hand at the same time point is shown alongside.

A popular paradigm for investigating motor sequence learning involves performing sequential finger–thumb opposition movements, in which participants repeatedly touch the thumb to different fingers in a prescribed order (Karni et al., 1995; Karni et al., 1998). In this classic task, the thumb tip contacts four fingertip locations to generate a fixed five-element movement sequence that is practiced repeatedly across trials.

The current study builds on this paradigm by increasing both the number and spatial distribution of target locations involved in the finger–thumb opposition task. Instead of four fingertip targets, the thumb was required to contact ten distinct target locations, comprising all finger phalanges except the middle phalanges of the index and little fingers. In addition, rather than repeatedly executing a single fixed sequence, participants were required to perform multiple distinct six-element sequences, presented in a random order within the same trial.

Taken together, this modified finger–thumb opposition task exhibits increased spatial and sequential complexity, thereby imposing greater demands on fine motor control and finger coordination than the task described by Karni and colleagues. The current study's task is a close variant of the task previously used by our group to study long-term motor sequence learning (Rachaveti, 2019; Rachaveti & SKM, 2020; Rachaveti et al., 2020). The experimental task in the present study was implemented as follows:

The participants wore a VR headset and could see a pair of virtual hands in VR space that accurately replicated the movements of the two real hands in real-time. The phalanges of these virtual hands had characters superimposed (similar to a tattoo) on their palmar surface (see Fig. 2). These characters represented the key-character map of the TIS keys placed on the real hands, which was identical for all participants. In the VR environment, five lettered 3D words were presented to the participants, one at a time. The participants had to type these words with the instructed hand using the TIS by touching the appropriate phalanx copper patch with the thumb copper patch. In the VR environment, this was equivalent to touching the phalanx of the virtual hand containing the character to be typed with the tip of the virtual thumb (see Supplementary Video 2). When a letter was typed correctly, the 3D letter turned green (see Fig. 2); when typed incorrectly, it turned red, indicating to the participant to re-type the letter. Once all letters were typed correctly, the participant had to type the space character (indicated as “SP” on the virtual hand) for the next word to appear.

For an experimental trial, the participants were instructed to type the 3D words *as quickly as possible*. For each correctly typed character (including spaces, i.e., “SP”), the participant received two points. Participants were instructed to obtain the maximum possible score before the trial ended. The score was updated in real-time on a screen above the 3D word. This screen also displayed a countdown timer, indicating the trial time remaining in seconds (see Fig. 2). The 3D word to be typed was presented above the virtual hand that was performing the typing. There were no negative points for typing the wrong character; hence, the focus of the task was on typing speed and not accuracy. A break of 30s was given between each trial, which could be extended or reduced based on the participant's request.

2.6 Mirror Visual Feedback (MVF)

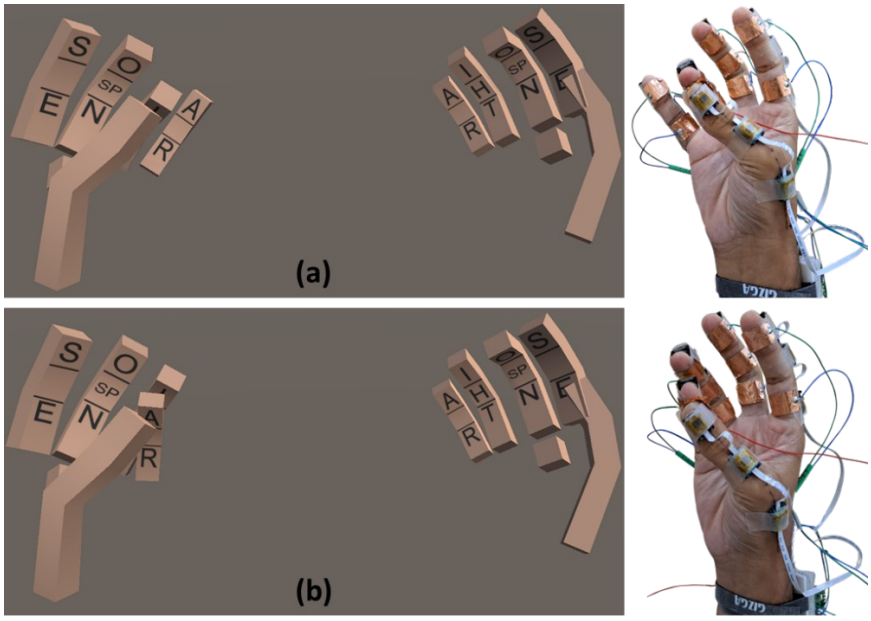


Figure 3. Virtual hands under mirror visual feedback (MVF). (a) Top row: the real right hand is shown touching the distal phalanx of the ring finger with the thumb tip. The corresponding virtual hand configuration under MVF is displayed, in which the virtual left hand mirrors the movements of the real right hand while the fingers of the virtual right hand remain fixed in a predefined posture. **(b)** Bottom row: the real right hand is shown touching the distal phalanx of the little finger with the thumb tip. The corresponding virtual hand configuration under MVF is displayed.

During all practice session trials in the mirror group, participants received mirror visual feedback (MVF), in which the movements of the real right hand performing the typing task were mirrored in real time by the virtual left hand (see Fig. 3; see Supplementary Video 3). Mirror feedback in this context refers to the hand movements one would observe when viewing the image of the right hand in a mirror placed along the body's mid-sagittal plane. For example, rotations of the real right hand about the wrist toward or away from the body's midline were replicated by corresponding rotations of the virtual left hand, while clockwise rotations of the real right hand resulted in anti-clockwise rotations of the virtual left hand, and vice versa. Details of the orientation transformations used to implement MVF are provided in our previously published work on the experimental setup (Gupta & SKM, 2026).

Throughout the MVF trials, participants were instructed to look at the virtual left hand for visual feedback while performing the task. The fingers of the virtual right hand remained fixed in a predefined posture to prevent participants from looking at it for feedback while performing the task (see Fig. 3). During these trials, the 3D words to be typed and the on-screen display of trial score and trial time remaining were positioned above the virtual left hand to facilitate visual access.

During pilot testing, it was observed that participants occasionally produced partial typing-like movements with the real left hand during the MVF trials, despite being instructed to keep it still. To prevent such unintended movements, participants were instructed to rest their left hand on the armrest with the palm facing downward throughout the MVF trials. This posture

eliminated overt finger movements, as confirmed by the experimenter's periodic monitoring of the participant's left hand.

2.7 Additional Methodological and Experimental Details

To obtain accurate hand segment orientations, a methodology was used to correct sensor-to-segment misalignment. Additionally, to achieve accurate thumb-to-phalanx touch replication by the virtual hand model – a necessary requirement for successful task execution – customized virtual hand models were built for each participant, matching the participants' real hand dimensions. These custom hand models were subsequently refined using a methodology to achieve the required thumb-to-phalanx touch accuracy. Detailed descriptions of these methodologies are provided in our previously published work on the experimental setup (Gupta & SKM, 2026; also see Supplementary Section S1.2).

The main experimental procedure was completed during a single laboratory visit and typically lasted **3 h to 3 h 45 min**, from the participant's entry into the laboratory to completion of the experiment. The approximate time required for the different stages was as follows:

1. **Approximately 20 min:** Participants read the experimental details and instructions. The experimenter then answered any questions and provided an additional verbal explanation of the experimental procedure. The lens spacing of the Meta Quest 2 VR headset was also adjusted based on participant feedback to obtain a clear view of the virtual environment.
2. **Approximately 30–60 min:** The HKMS and TIS were mounted on both hands of the participant. The time required depended primarily on whether an assistant was available to help with the mounting procedure.
3. **Approximately 45 min:** The sensor-to-segment alignment procedure was performed, and the virtual hand models were refined to achieve the required thumb-to-phalanx touch accuracy. Participants then completed the familiarization session.
4. **Approximately 1 h 10 min to 1 h 20 min:** Participants completed the four experimental sessions described in Section 2.10: *Experiment Sessions*. All four sessions were completed consecutively during the same laboratory visit. A 2 min break was provided between sessions, which could be increased or decreased upon the participant's request.
5. **Approximately 20 min:** The HKMS and TIS were removed from the participant's hands, followed by completion of the remaining experimental formalities, including payment of the honorarium and answering any questions from the participant.

On a separate day prior to the main experimental visit, the participant's hand measurements were obtained. This procedure typically took 30 min. These measurements were used to create participant-specific virtual hand models matching the dimensions of the participant's real hands using Blender software. Details of the hand-measurement procedure are provided in the Supplementary Material of our previously published work (Gupta & SKM, 2026).

2.8 Words Presented to the Participant

The words presented during each trial consisted of five-letter words selected from one of the following two word sets:

1. **Primary word set:** honor, oaths, ethos, risen, ratio, earth, saint**.**
2. **New word set:** heros, oasis, ether, rises, rhino, north, taint.

Each word set contained seven words. During a given trial, words were presented exclusively from a single word set. The New word set was used in only two trials (see Section 2.10: *Experiment Sessions*). In all other experiment trials, the Primary word set was used. The same word sets served as the Primary and New word sets for all participants; this was not counterbalanced across participants.

Within each trial, the seven words from the selected word set were presented once each in a randomized order until all seven had been typed. Once all seven words had been typed, their presentation order was randomized again, and a new seven-word cycle began. This process was repeated until the end of the trial.

2.9 Trial Format

During a trial, participants were instructed to perform the typing task for 15s, followed by a break of 5s during which they were instructed to keep their hands and fingers still. This alternating cycle of typing and break continued until the end of the trial. Figure 4 illustrates the trial format used in the Pre-Practice and Post-Practice sessions, in which each trial lasted 1 min 15 s and consisted of four 15 s typing periods separated by three 5 s breaks. For the Practice session, each trial lasted 2 min 35 s, with the same alternating structure consisting of eight 15 s typing periods separated by seven 5 s breaks.

During each 5s break period, the virtual hands disappeared from the VR environment, indicating to the participant to stop typing and keep their hands still. Simultaneously, the TIS was temporarily disabled, and a screen displaying a 5s countdown timer appeared in front of the participant (see Supplementary Videos 2 and 3). At the end of the break period, the TIS was re-enabled, and the virtual hands reappeared, indicating to the participant to resume typing.

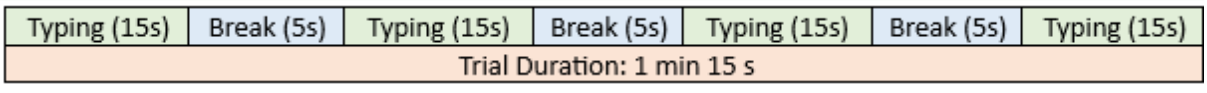


Figure 4. Trial format for trials in the Pre-Practice and Post-Practice sessions. These trials consisted of alternating typing periods (15 s) and break periods (5 s), repeated until completion of the 1 min 15 s trial duration. The same alternating structure was used in the other experimental sessions, with the number of typing and break periods adjusted according to the total trial duration.

This trial format was implemented for the following reasons:

1. During pilot testing, some participants typed at extremely high speeds during the later trials of the experiment. When this happened, it was observed that the IMU orientation data became progressively inaccurate as the trial progressed. This inaccuracy resulted from drift in the sensor values caused by continuous, rapid finger movements. Consequently, errors in the orientation data were reflected in the virtual hand animation, resulting in crooked fingers and reduced animation accuracy. This drift could be substantially reduced by keeping the IMUs stationary following a period of continuous movement. Accordingly, a 5 s break period was introduced after every 15 s of typing, during which participants kept their hands and fingers still.
2. The break period also gave the participants some time to look at the current score and evaluate their performance thus far.

2.10 Experiment Sessions

Prior to the main experiment, participants underwent a brief familiarization session to become acquainted with the task (see Supplementary Section S1.1: *Familiarization Session* for details). The experiment itself consisted of four sessions that are described in this sub-section:

I. Pre-Practice Session

a) ***Aim*:** To determine the baseline task performance of both hands.
b) ***Details*:** This session comprised two trials of 1 min 15 s each. The first trial was performed with the left hand and the second with the right hand. Words from the Primary word set were used in both trials.
c) ***Instructions*:** Before both the trials in this session, the participants were informed that the trials in this session were very important and that they should put in their best effort and concentration to achieve the highest possible score by typing as quickly as possible.

II. Practice Session

a) ***Aim*:** To make the control group practice the task under normal visual feedback (NVF) and the mirror group practice the task under mirror visual feedback (MVF).
b) ***Details*:** This session comprised 12 trials of 2 min 35 s each. In all trials, participants performed the typing task with the right hand using words from the Primary word set. The two groups differed only in the visual feedback provided during the trials. In the control group, both virtual hands accurately replicated the movements of the corresponding real hands (see Supplementary Video 2 for an example of a practice-session trial under NVF). In the mirror group, movements of the real right hand were mirrored by the virtual left hand (see Section 2.6: *Mirror Visual Feedback (MVF)* for details; also see Supplementary Video 3 for an example of a practice-session trial under MVF). Participants in the mirror group were instructed to *view the virtual left hand for visual feedback while performing the typing task with their real right hand*.

c) ***Instructions*:** Before beginning this session, the participants were instructed to try to beat their own highest score in each trial. The highest score was computed using the participant's previous practice-session trial scores and was displayed throughout the session.

d) ***Additional Details*: (1)** For the mirror group, the fingers of the virtual right hand were frozen in a pre-defined posture to prevent participants from looking at it for visual feedback during the task (see Fig. 3). **(2)** The highest score was displayed both on the screen above the 3D word during the trial (see Fig. 2) and on a screen presented in front of the participant during the rest period in between trials (see Supplementary Fig. S2). **(3)** In the mirror group, since the participants were viewing the virtual left hand while typing, the 3D word to be typed and the screen displaying the trial score, trial time remaining, and highest score were positioned above the virtual left hand to facilitate visual access.

III. Post-Practice Session

a) ***Aim*:** To determine post-practice task performance of both hands for (1) the Primary word set (i.e., the words used in the previous sessions), and (2) the New word set (i.e., words not encountered previously, corresponding to novel movement sequences). The performance for the New word set was evaluated to examine performance gains for novel movement sequences (i.e., movement sequences not practiced by the trained right hand).

b) ***Details*:** This session comprised four trials of 1 min 15 s each. The first two trials were performed with the left hand, followed by two trials with the right hand. The Primary word set was used in the first and third trials, whereas the New word set was used in the second and fourth trials. This trial order was fixed across all participants.

c) ***Instructions*:** Similar to the Pre-Practice session, the participants were informed before each of the four trials in this session that these trials were very important and that the participant should put in their best effort and concentration to get the highest possible score by typing as quickly as possible.

IV. Exploratory Left-Hand Practice Session

a) ***Aim*:** To explore whether the rate of performance improvement due to physical practice with the left hand following practice with the right hand differed between the mirror and control groups.

b) ***Details*:** This session comprised five trials of 1 min 15 s each, all performed with the left hand. The Primary word set was used in all five trials.

c) ***Instructions*:** Before the beginning of this session, the participants were instructed to try to beat their own highest score in each trial. The highest score was computed using the participant's previous trial scores within this session and was displayed throughout the session, similar to the Practice session.

d) ***Motivation*:** Previous MVF-based studies have typically examined the performance of the untrained hand following mirror visual feedback training and compared it with performance following other training conditions, such as normal visual feedback or action observation (Nojima et al., 2012; Hamzei et al., 2012; Ossmy & Mukamel, 2016; Bähr et al., 2018). However, we felt that, in addition to examining performance in the untrained hand following these different training conditions, it would be interesting to explore whether subsequent physical practice with the untrained hand resulted in different rates of performance improvement. Because this was an exploratory question, we did not formulate a specific directional hypothesis.

e) ***Scope of the Present Paper*:** Data from this exploratory session are not analyzed as part of the present paper because we wanted to maintain the focus on the main objectives of the study. We plan to conduct and report the analysis of this exploratory session separately.

2.11 Data Analysis

2.11.1 Data Processing Overview: Raw typing data acquired from the Text Input System (TIS) were first pre-processed using MATLAB (R2023b; The MathWorks, Inc., 2023). Pre-processing included data parsing, data cleaning, and computation of trial-level performance variables. The processed data were then organized into a tabular format and imported into R (version 4.4.2; R Core Team, 2024) for statistical analysis.

2.11.2 Analysis Variables: The typing data acquired from the Text Input System (TIS) were used for data analysis. This dataset comprised the sequence of characters typed during each trial and the corresponding timestamps, in milliseconds, associated with key-press and key-release events. From the typing data, three task performance variables were computed for analysis:

i. Correct Characters Typed (CCT): The total number of correctly typed characters (including the space character) within a trial.
ii. Press Duration (PD): The duration in ms between key press and key release events for a given character.
iii. Movement Time (MT): The duration in ms between the key release of a correctly typed character and the key press of the subsequent correctly typed character.

CCT was treated as the primary performance measure because it directly quantifies the task objective: typing words as quickly as possible to achieve the maximum possible score within the trial duration. PD and MT were treated as secondary performance measures, and they represent the timing of two key aspects of task execution. Reductions in PD and MT reflect faster task execution and consequently contribute to improvements in CCT. However, minimizing PD and MT was not the explicit objective of the task; therefore, these variables were treated as secondary performance measures. Analyzing PD and MT nevertheless provides insight into the learning-related changes in different components of task execution that accompany improvements in CCT.

Only typing data associated with correctly typed characters was used for the computation of the three variables. Analyses were restricted to left-hand trials from the Pre-Practice and Post-Practice sessions. For each trial, CCT, mean PD, and mean MT values were computed.

2.11.3 Data Pre-Processing: As the first step, for each trial, the TIS data associated with any characters mistakenly typed during the intra-trial break periods (See Fig. 4) and the data associated with falsely typed characters were removed. For the PD and MT variables, outliers were removed in each trial by discarding MT/PD data outside the following range: $\mu \pm 3\sigma$, where μ represents the trial's mean and σ represents the standard deviation for the MT/PD variable. However, before removing the outliers, some additional pre-processing was performed on the MT and PD variables; the details of this are provided in the Supplementary Section S1.5: *Data Pre-Processing*. After outlier removal, the mean PD and mean MT were calculated for each trial.

2.11.4 Statistical Model – Primary Word Set Analysis: A 2×2 mixed-design ANOVA was used to evaluate right hand (RH) training–related changes in untrained left hand (LH) performance and to determine whether these changes differed between groups. The analysis was performed separately for each performance variable (CCT, mean PD, and mean MT) derived from the LH Primary word set trials of the Pre-Practice and Post-Practice sessions. Session (Pre-Practice, Post-Practice) served as the within-subject factor, and Group (mirror, control) served as the between-subjects factor. Generalized eta squared (η_G^2) was reported as the effect size for each ANOVA effect, and statistical significance was evaluated at $\alpha = .05$. Because Session had only two levels, sphericity corrections were not applicable.

To further examine significant ANOVA effects, simple-effects analyses were conducted. For variables showing a significant main effect of Session, paired t-tests were performed separately within each group to examine group-specific pre- to post-practice changes. Cohen's *dz* was reported as the effect size for these paired comparisons. For CCT, which additionally exhibited a significant Group × Session interaction, an independent-samples t-test was performed on the difference values (ΔCCT; Δ = Post-Practice − Pre-Practice) to determine which group showed greater improvement. The magnitude of the difference in improvement between groups was quantified using Hedges' g, and the 95% confidence interval for Hedges' g was estimated using the noncentral t distribution (as implemented in the *effsize* package, version 0.8.1, in R).

2.11.5 Assumption Checks – Primary Word Set Analysis: To verify that the data met the assumptions required for the 2x2 mixed-design ANOVA, assumption checks were conducted on the CCT, mean PD, and mean MT values computed per participant from the LH Primary word set trials of the Pre-Practice and Post-Practice sessions. Normality for each Group × Session combination (control–Pre, control–Post, mirror–Pre, mirror–Post) was examined using the Shapiro–Wilk test. Homogeneity of variances between groups for the Pre-Practice session and the Post-Practice session was examined using Levene's test.

Baseline differences between groups were examined using independent-samples t-tests on the Pre-Practice LH Primary word set trials to verify that the groups did not differ prior to training.

For the subsequent simple-effects analyses, additional assumption checks were conducted on the difference values (ΔCCT, Δ mean PD, and Δ mean MT; Δ = Post-Practice − Pre-Practice). Normality of these difference values was assessed using the Shapiro–Wilk test separately for each group. Homogeneity of variance between groups was examined for ΔCCT using Levene's test.

2.11.6 Statistical Model – New Word Set Analysis: To evaluate the effects of RH training using the Primary word set on untrained LH performance for the New word set (i.e., novel sequences), a series of statistical comparisons was conducted. The Pre-Practice LH Primary word set trial was designated as the common baseline for both the Post-Practice LH Primary word set and LH New word set trials. A separate Pre-Practice LH trial to determine the baseline performance for the New word set was intentionally omitted to minimize motor learning in the LH resulting from physical task execution. This design choice helped ensure that the contribution of direct LH physical practice to Post-Practice LH performance was minimal.

The decision to use the Pre-Practice LH Primary word set trial as the common baseline was based on the assumption that performance during the first LH trial would reflect the participants' baseline ability for the experimental task overall, rather than merely their ability with the specific word set presented. Since participants engaged with the task for the first time during this trial, typing words from either word set was assumed to pose a comparable level of difficulty. Thus, baseline performance was assumed to be comparable across word sets.

Based on this rationale, the following analyses were performed on the LH New word set trials:

***I. Within-Group Improvement for the New Word Set*:** To assess whether LH performance for the New word set improved from pre- to post-practice, paired t-tests were conducted. Specifically, for each performance variable (CCT, mean PD, and mean MT), comparisons were made between the Pre-Practice LH Primary word set trial (baseline) and the Post-Practice LH New word set trial. These tests were performed separately for the mirror and control groups.

***II. Within-Group Comparison of Improvement Magnitudes: New vs. Primary Word Sets*:** To assess whether the magnitude of LH performance improvement differed between word sets within each group, the magnitude of pre- to post-practice performance improvement for the New word set (Δ_{NEW}) was compared with that of the Primary word set ($\Delta_{PRIMARY}$). Specifically, for each performance variable – CCT, mean PD, and mean MT – comparisons were made between Δ_{NEW} and $\Delta_{PRIMARY}$ using paired t-tests or, when the normality assumption was violated, Wilcoxon signed-rank tests.

These tests were performed separately for the mirror and control groups. Rank-biserial correlation was reported as the effect size for Wilcoxon signed-rank tests, whereas Cohen's *dz* was reported for paired t-tests.

The improvement magnitudes for each performance variable were computed as follows:

$$\Delta_{NEW} = [Post \quad Practice]_{NEW} - [Pre \quad Practice]_{PRIMARY}$$

$$\Delta_{PRIMARY} = [Post \quad Practice]_{PRIMARY} - [Pre \quad Practice]_{PRIMARY}$$

where the bracketed term denotes the session, and the subscript indicates the specific word set used in the trial.

***III. Between-Group Comparison of Improvement on the New Word Set*:** To assess potential group-level differences in the magnitude of LH performance improvement from pre- to post practice for the New word set (Δ_{NEW}), independent samples t-tests were conducted. Specifically, for each performance variable – CCT, mean PD, and mean MT – the magnitude of improvement (Δ_{NEW}) was compared between the two groups.

Note: For each of the three sets of statistical tests described above, the Holm–Bonferroni correction was applied. Within each set, the correction was applied separately to two families of tests: one corresponding to the primary performance variable (CCT) and one corresponding to the secondary performance variables (PD and MT).

2.11.7 Assumption Checks – New Word Set Analysis: Prior to conducting the three sets of statistical tests described in the New word set analysis, the following assumption checks were performed:

***I. Within-Group Improvement for the New Word Set*:** For each performance variable (CCT, mean PD, and mean MT), the magnitude of pre- to post-practice change (Δ_{NEW}) was computed for both groups. Normality for Δ_{NEW} was assessed for each group × variable combination (2 × 3) using the Shapiro–Wilk test.

***II. Within-Group Comparison of Improvement Magnitudes: New vs. Primary Word Sets*:** For each performance variable, improvement magnitudes were computed for both the New word set (Δ_{NEW}) and Primary word set ($\Delta_{PRIMARY}$) for both groups. The normality was assessed for Δ_{NEW} - $\Delta_{PRIMARY}$ for each group × variable combination (2 × 3) using the Shapiro–Wilk test.

***III. Between-Group Comparison of Improvement on the New Word Set*:** For each performance variable, Δ_{NEW} was computed for both groups. The equality of variance between the two groups for Δ_{NEW} was assessed for each performance variable using Levene's test.

3. Results

3.1 Mixed ANOVA – Primary Word Set Analysis

Results of the 2×2 mixed-design ANOVA for each performance variable are presented below.

A. Correct Characters Typed (CCT): The main effect of Session was significant, F(1,18) = 147.193, $p < 0.001$, $\eta_G^2 = 0.564$, whereas the main effect of Group was not ($p = 0.294$). The Group × Session interaction was significant, F(1,18) = 6.935, $p = 0.017$, $\eta_G^2 = 0.057$.

B. Mean Press Duration (PD): The main effect of Session was significant, F(1,18) = 22.558, $p < 0.001$, $\eta_G^2 = 0.173$. The Group effect ($p = 0.949$) and the Group × Session interaction ($p = 0.422$) were not significant.

C. Mean Movement Time (MT): The main effect of Session was significant, F(1,18) = 102.337, $p < 0.001$, $\eta_G^2 = 0.470$. The Group effect ($p = 0.431$) and the Group × Session interaction ($p = 0.263$) were not significant. Group-level means for the Pre- and Post-practice Primary word set trials for all performance variables are provided in Table 1.

To further elucidate the nature of the significant main and interaction effects identified in the mixed-design ANOVA, simple-effects analyses were performed.

D. Assumption Checks for 2x2 Mixed ANOVA: Shapiro–Wilk tests revealed no evidence against normality for any Group × Session combination across all performance variables (all $p \geq 0.068$). Levene's tests revealed no evidence against homogeneity of variances at either session across all performance variables (all $p \geq 0.115$).

Independent-samples t-tests revealed no evidence of baseline differences between groups for any of the performance variables: CCT, t(18) = −0.068, $p = 0.947$; mean PD, t(18) = 0.232, $p = 0.819$; and mean MT, t(18) = −0.247, $p = 0.808$.

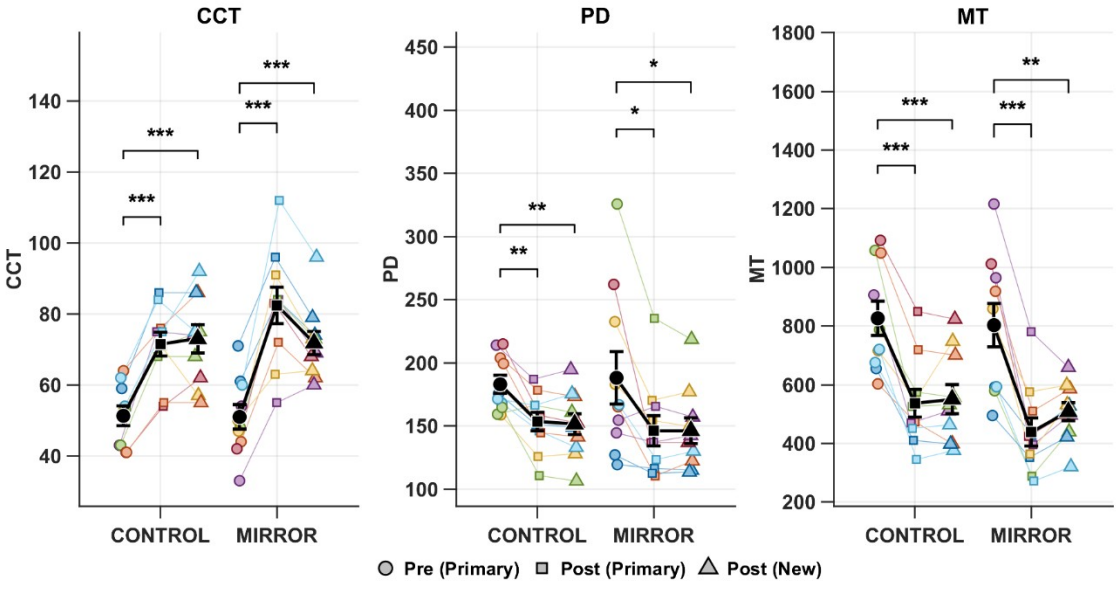


Figure 5. Left-hand performance across Pre-Practice and Post-Practice trials. Spaghetti plots show participant-level values (colored lines) for CCT, mean PD, and mean MT for the control and mirror groups. Line color uniquely identifies each participant within a group and is consistent across all three performance variables. Markers indicate the three trials: Pre-Practice (Primary word set), Post-Practice (Primary word set), and Post-Practice (New word set). Black squares and error bars denote group mean ± SEM. Significance brackets indicate statistically significant within-group comparisons only, shown for Pre-Practice (Primary) vs Post-Practice

(Primary) (uncorrected) and for Pre-Practice (Primary) vs Post-Practice (New) (Holm–Bonferroni corrected). Asterisks denote statistical significance ($p < 0.05$, $p < 0.01$, $p < 0.001$).

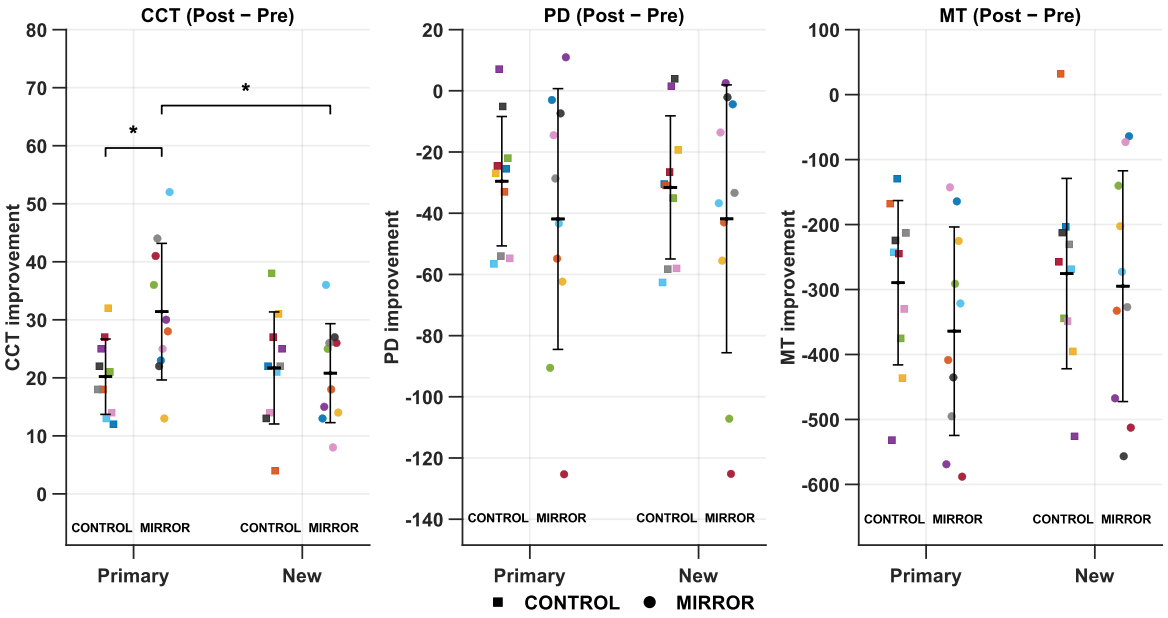


Figure 6. Left-hand improvement magnitudes for the Primary and New word sets. The magnitude of pre- to post-practice change in CCT, mean PD, and mean MT is shown for individual participants in the control (squares) and mirror (circles) groups for both the Primary and New word sets. Performance change for both word sets was computed relative to the Pre-Practice Primary word set trial as $\Delta_{PRIMARY}$ = Post-Practice (Primary) − Pre-Practice (Primary) and Δ_{NEW} = Post-Practice (New) − Pre-Practice (Primary). Colored points represent individual participant values; colors are unique within each group and consistent across all three performance variables for each participant. Black whiskers denote group mean ± SD (with a mean marker). Significance brackets indicate statistically significant comparisons only: for CCT, $\Delta_{PRIMARY}$ differed between groups (control vs mirror), and within the mirror group, $\Delta_{PRIMARY}$ differed from Δ_{NEW} (Holm–Bonferroni corrected). All other within-group and between-group comparisons were non-significant. Asterisks denote statistical significance ($p < 0.05$, $p < 0.01$, $p < 0.001$).

3.2 Simple-Effects Analyses

Results of the simple-effects analyses are reported below.

***A. Correct Characters Typed (CCT)*:** Paired t-tests revealed a significant pre- to post-practice increase in CCT in both groups (see Fig. 5). The control group showed a significant increase, $t(9) = 9.84$, $p < 0.001$, Cohen's $dz = 3.11$, 95% CI [15.55, 24.85]. The mirror group also showed a significant increase, $t(9) = 8.43$, $p < 0.001$, Cohen's $dz = 2.67$, 95% CI [22.97, 39.83].

An independent-samples t-test on ΔCCT revealed that the increase in CCT was significantly greater in the mirror group than in the control group (see Fig. 6), $t(18) = 2.63$, $p = 0.017$, 95% CI [2.26, 20.14]. The standardized effect size was Hedges' $g = 1.13$, with a corresponding 95% CI for Hedges' g of [0.21, 2.12].

***B. Mean Press Duration (PD)*:** Paired t-tests revealed a significant pre- to post-practice decrease in mean PD in both groups (see Fig. 5). The control group showed a significant decrease, $t(9) = -4.42$, $p = 0.002$, Cohen's $dz = -1.40$, 95% CI [−44.65, −14.42]. The mirror

group also showed a significant decrease, $t(9) = -3.11$, $p = 0.013$, Cohen's $dz = -0.98$, 95% CI [−72.37, −11.42].

C. Mean Movement Time (MT): Paired t-tests revealed a significant pre- to post-practice decrease in mean MT in both groups (see Fig. 5). The control group showed a significant decrease, $t(9) = -7.24$, $p < 0.001$, Cohen's $dz = -2.29$, 95% CI [−379.98, −199.00]. The mirror group similarly showed a significant decrease, $t(9) = -7.18$, $p < 0.001$, Cohen's $dz = -2.27$, 95% CI [−478.84, −249.31]. Group-level means of the pre- to post-practice improvement (Primary word set) for all performance variables are provided in Table 1.

***D. Assumption Checks for Simple-Effects Analyses*:** Shapiro–Wilk tests on the difference values (ΔCCT, Δ mean PD, and Δ mean MT; Δ = Post-Practice − Pre-Practice) revealed no evidence against normality for either group (all $p \geq 0.355$). Levene's test revealed no evidence against homogeneity of variances for ΔCCT between groups ($p = 0.131$).

Table 1. Group-level means for the three performance variables (CCT, mean MT, and mean PD) for the Mirror and Control groups across left-hand (LH) trials of Pre-Practice Primary word set, Post-Practice Primary word set, and Post-Practice New word set, along with mean pre- to post-practice improvement magnitudes ($\Delta_{PRIMARY}$ and Δ_{NEW}) for each word set.

Variable	Group	Pre-Practice (Primary word set)	Post-Practice (Primary word set)	Post-Practice (New word set)	$\Delta_{PRIMARY}$	Δ_{NEW}
CCT	Mirror	51.0	82.4	71.8	31.4	20.8
	Control	51.3	71.5	73	20.2	21.7
mean MT	Mirror	803.2	439.1	508.3	−364.1	−294.9
	Control	826.4	536.95	550.97	−289.5	−275.5
mean PD	Mirror	188.1	146.2	146.3	−41.9	−41.85
	Control	183.0	153.5	151.45	−29.5	−31.6

3.4 New Word Set Analysis

A. Within-Group Improvement for the New Word Set: Paired t-tests revealed significant differences between pre- and post-practice performance for all three performance variables – CCT, mean PD, mean MT – in both groups (all Holm-Bonferroni corrected p-values < 0.014) (see Fig. 5). Effect size (Cohen's dz) was large in all comparisons.

- **Mirror Group: CCT:** $p < 0.001$, Cohen's $dz = 2.44$, 95% CI [14.7, 26.9]; **mean PD:** $p = 0.014$, Cohen's $dz = -0.96$, 95% CI [−73.16, −10.54], **mean MT:** $p = 0.002$, Cohen's $dz = -1.66$, 95% CI [−421.84,−167.9].
- **Control Group: CCT:** $p < 0.001$, Cohen's $dz = 2.25$, 95% CI [14.79, 28.61], **mean PD:** $p = 0.004$, Cohen's $dz = -1.35$, 95% CI [−48.3, −14.84], **mean MT:** $p < 0.001$, Cohen's $dz = -1.88$, 95% CI [−380.28,−170.65].

Group-level means for the Post-Practice New word set trial for all performance variables are provided in Table 1.

B. Within-Group Comparison of Improvement Magnitudes: New vs. Primary Word Sets: Paired t-tests or Wilcoxon signed-rank tests (applied when normality was violated) revealed that the LH improvement magnitudes between the New and Primary word sets (i.e., Δ_{NEW} vs $\Delta_{PRIMARY}$) were significantly different only for CCT in the mirror group (see Fig. 6; $p = 0.029$ after Holm-Bonferroni correction, 95% CI [4.5, 16], median of ($\Delta_{PRIMARY} - \Delta_{NEW}$) = 12.5). The effect size was large (rank-biserial correlation = 0.79). All other comparisons were non-significant after Holm-Bonferroni correction (all $p > 0.09$). Group-level means of the pre- to post-practice improvement (New word set) for all performance variables are provided in Table 1.

C. Between-Group Comparison of Improvement on the New Word Set: Independent samples t-tests revealed no significant group differences in LH improvement magnitude of the New word set (Δ_{NEW}) for all three performance variables – CCT, mean PD, and mean MT (see Fig. 6; all $p > 0.5$, even before Holm-Bonferroni correction).

3.5 Assumption Checks -New Word Set Analysis

Prior to conducting the statistical tests for the New word set analysis, assumption checks were performed as described in Section 2.11.7: *Assumption Checks – New Word Set Analysis*.

A. Within-Group Improvement for the New Word Set: Shapiro–Wilk tests revealed no evidence against normality for the improvement magnitudes Δ_{NEW} for each Group x Variable combination (2 x 3; all $p \geq 0.1$).

B. Within-Group Comparison of Improvement Magnitudes: New vs. Primary Word Sets: Shapiro–Wilk tests were conducted on the paired difference scores ($\Delta_{PRIMARY} - \Delta_{NEW}$; denoted as ΔΔ) separately for each Group × Variable combination (2 × 3). Evidence against normality was found for ΔΔCCT in the mirror group ($p = .031$) and for ΔΔMT in the control group ($p = .011$). No evidence against normality was found for the remaining combinations (all $p \geq 0.096$). Accordingly, Wilcoxon signed-rank tests were used for these two comparisons, and paired t-tests were used in all other cases.

C. Between-Group Comparison of Improvement on the New Word Set: Levene's tests revealed no evidence against homogeneity of variances between groups for the improvement magnitudes Δ_{NEW} of CCT, mean PD, or mean MT (all $p \geq 0.18$).

4. Discussion

4.1 Summary of principal findings

The present study demonstrated that training the dominant right hand in a complex motor sequence learning task involving fine finger movements under both mirror visual feedback (MVF; mirror group) and normal visual feedback (NVF; control group) resulted in statistically significant performance gains in the untrained, non-dominant left hand. Importantly, for the

primary performance variable CCT, the magnitude of performance gain due to MVF training was significantly greater than that due to NVF training. These findings are consistent with our hypotheses. The superior performance improvement in the mirror group highlights the advantage of simultaneously combining the alternative motor learning modes of action observation and cross-education through mirror visual feedback, compared with cross-education alone.

In addition, both groups exhibited statistically significant performance gains in the untrained left hand for novel movement sequences (New word set; i.e., sequences not practiced by the trained right hand). Interestingly, the control group showed comparable performance gains between the Primary and New word sets for all performance variables, despite the New word set not having been practiced by the trained right hand. In contrast, the mirror group showed greater gains for the Primary word set than for the New word set for the primary performance variable CCT. Most notably, the performance gains for the New Word set were comparable between groups. Thus, the performance enhancement under mirror feedback for the practiced movement sequences (Primary word set) was not detected for the novel movement sequences (New word set).

4.2 Mirror visual feedback–mediated performance enhancement

In this study, three performance variables (CCT, PD, and MT) were used to characterize learning-related changes in task performance. Correct Characters Typed (CCT) served as the primary performance measure, as it directly quantifies the task goal of maximizing the number of correctly typed characters within a trial. Movement Time (MT) and Press Duration (PD) served as secondary performance measures. They represent the time intervals associated with two distinct components of task execution—movement and key press—and provide complementary information about learning-related changes accompanying improvements in CCT.

Analysis of these variables revealed significant pre- to post-practice performance improvements in the untrained left hand for CCT, MT, and PD in both groups. Importantly, however, the magnitude of improvement in CCT was significantly greater in the mirror group than in the control group. These findings indicate that while cross-education alone was sufficient to induce performance gains in the untrained left hand, as observed in the control group, the simultaneous combination of cross-education and action observation through mirror visual feedback resulted in greater performance gains. This suggests that the benefits of mirror visual feedback extend even to complex tasks involving fine finger movements.

In contrast to the greater improvement in CCT observed in the mirror group, improvements in the secondary performance variables, PD and MT, were comparable between the mirror and control groups. This apparent dissociation can be understood by examining changes in PD and MT more closely. At the level of group means, both variables showed slightly larger reductions in the mirror group (see Table 1), reflecting marginally faster execution of individual task

components. These small timing advantages likely accumulated across successive key presses within a trial, resulting in a greater overall CCT.

4.3 Positioning the findings within existing MVF literature

The results of the present study add to a limited but growing body of literature demonstrating the benefits of MVF in enhancing motor performance in the untrained hand (Hamzei et al., 2012; Bähr et al., 2018; Ossmy & Mukamel, 2016; Steinberg et al., 2016; Zult et al., 2016; Rjosk et al., 2017; Park & Son, 2022). Notably, the present findings build on those of Ossmy and Mukamel (2016), who reported that MVF produced greater performance gains than either cross-education or action observation. In both studies, MVF was delivered using a virtual reality (VR) headset, and both tasks involved performing sequential finger movements.

However, the task used in the present study was more complex. While Ossmy and Mukamel's task involved repeated execution of a fixed sequence of finger flexion–extension movements, the present task involved execution of spatially targeted sequences of fine finger movements with increased multi-joint and multi-finger coordination demands. In addition, participants practiced multiple distinct movement sequences, with the order of sequence execution randomized within each trial, in contrast to the repeated execution of a single fixed sequence in Ossmy and Mukamel's study. Together, the present study's task had increased demands on coordination, spatial accuracy, and sequence execution, and the results demonstrate that MVF-mediated performance enhancement extends even to complex tasks involving fine finger movements.

4.4 Cross-Education and task design factors

In contrast to the present study, Ossmy and Mukamel (2016) reported no significant performance gains from cross-education alone (i.e., in the normal feedback condition). At first glance, this may seem surprising given the greater complexity of the task used in the present study. However, this can be plausibly explained by differences in experimental design.

In Ossmy and Mukamel's study, during the pre- and post-practice evaluation, participants were instructed to perform the task *as quickly and accurately* as possible. Hence, the participants had to optimize both speed and accuracy while performing the task. Performance was evaluated in accordance with this instruction. Successfully performing an entire movement sequence, which consisted of five sub-components, was considered a 1-point increase in performance score. An error in performing any sub-component resulted in the entire sequence being considered as unsuccessful, even if some sub-components were performed correctly.

In contrast, in the present study, the participants were instructed to perform the task *as quickly as possible* without worrying about potential errors. Hence, the participants could focus on maximizing speed without being constrained by potential errors. Performance was evaluated in accordance with this instruction. Successfully performing each sub-component (i.e., each correctly typed character) of a movement sequence, which consisted of six sub-

components, was considered a 1-point increase in performance score. Any error in performing a sub-component was not penalized. Instead, the participants were required to correctly execute the sub-component before proceeding. Consequently, execution of an entire movement sequence resulted in a cumulative 6-point increase in performance score. Importantly, these differences in task instructions likely had differential effects on how participants performed the task, thereby contributing to differences in cross-education observed between the two studies.

Another key difference between the studies was in the design of the practice session. In Ossmy and Mukamel's study, participants were instructed to perform the *task at their own pace* during the practice trials. In contrast, in the present study, participants were explicitly instructed to improve their performance with each practice trial. Similar instructions have been used in previous MVF studies, where participants were asked to perform the task quickly during the practice session (Hamzei et al., 2012; Steinberg et al., 2016; Rjosk et al., 2017; Bähr et al., 2018). Such instructions may promote greater learning in the trained limb compared to practicing at one's own pace. In the context of cross-education, improvements in the trained limb have been shown to correlate positively with improvements in the untrained limb (Poh et al., 2012; Lee et al., 2010). Therefore, maximizing learning in the trained limb may, in turn, enhance cross-education.

Furthermore, a unique feature of the present study is that the practice session was designed to actively encourage performance improvement both within and across trials. The highest score achieved was continuously displayed, and participants were instructed to beat their previous best performance in each trial. In addition, continuous performance feedback was provided in real time during each trial, rather than only between trials. Additionally, the 5-second mid-trial breaks—originally introduced for another purpose (see Section 2.9: *Trial Format*)—allowed participants to assess their performance at multiple points within a trial. These features may have served both motivational and performance-monitoring functions. The instruction to beat one's previous highest score provided a clear, self-referenced performance goal, while the continuously displayed score provided ongoing information about progress toward that goal. This may have encouraged participants to sustain effort and engagement throughout the Practice session. At the same time, the continuously available performance information and the mid-trial breaks may have enabled participants to monitor their ongoing performance and adjust their typing pace based on this information in an effort to achieve that goal.

Overall, the practice instructions and performance feedback system likely motivated participants to maximize typing speed and, consequently, enhance performance in the trained hand. In turn, this may have increased the magnitude of cross-education, underscoring the importance of carefully designing practice sessions.

4.5 Performance gains for novel movement sequences

Another objective of the present study was to investigate whether there were any performance gains in the untrained left hand for novel movement sequences (i.e., movement sequences not practiced by the trained right hand) and whether the magnitude of any such performance gains differed between the mirror and normal visual feedback conditions. Accordingly, post-practice performance was evaluated in the untrained left hand for both the Primary word set (i.e., the movement sequences practiced with the trained right hand) and the New word set (i.e., novel movement sequences). As described in the Methods section, performance in the Pre-Practice LH Primary word set trial was used as the baseline against which performance in the Post-Practice LH New word set trial was evaluated. The rationale for this approach is described in Section 2.11.6: *Statistical Model – New Word Set Analysis*, and its limitations are discussed in Section 5: *Limitations and Future Work*.

The New word set analysis revealed statistically significant pre- to post-practice improvements in performance for all three performance variables: CCT, PD, and MT. Importantly, the magnitude of these improvements was comparable between groups for all three variables. Thus, the performance enhancement associated with mirror feedback that was detected for the practiced movement sequences (Primary word set) was not detected for the novel movement sequences (New word set).

Additional insights were obtained from within-group comparisons of improvement magnitudes between the two word sets. In the control group, improvements were comparable between the Primary and New word sets for all three performance variables. Notably, these comparable improvements were observed despite the New word set not having been practiced by the trained right hand. In contrast, in the mirror group, improvement in the primary performance variable, CCT, was significantly greater for the Primary word set than for the New word set, while improvements in PD and MT were comparable between the two word sets. These findings also motivate future work aimed at isolating the contribution of action observation to MVF-mediated performance improvements.

4.6 Experimental design characteristics related to performance gains beyond the training context

Another aspect worth discussing is that certain characteristics of the experimental design may have favored performance gains beyond the specific training context. One such characteristic is the duration of practice. The training in the present study was short-term. Previous work has suggested that the magnitude of cross-education may depend on the duration of practice (Clark & Ivry, 2010). Clark and Ivry (2010) noted evidence of cross-education after 1 h of practice, whereas little to no cross-education was observed following 5 weeks of training. They proposed that the early stages of learning may rely more on flexible, abstract representations that can transfer across effectors, whereas prolonged practice may increasingly involve more effector-specific representations. Second, practice incorporated variation across seven different movement sequences presented in randomized order, rather than repeated practice of a single fixed sequence. Previous work has shown that experience

with multiple related task variants can facilitate transfer to novel tasks sharing a common structure (Schmidt, 1975; Braun et al., 2009, 2010). Third, the post-practice assessments retained substantial similarity to the practiced task. For the Primary word set, the same movement sequences practiced with the right hand were subsequently assessed with the left hand, whereas for the New word set, the overall task structure and constituent finger movements were preserved while the movements were arranged into novel sequences. Similarity and shared structure between practiced and subsequently assessed tasks have been identified as important determinants of transfer (Braun et al., 2010). Collectively, these characteristics represent a methodological strength of the present study, as they provided favorable conditions for detecting training-related performance improvements in the untrained hand and strengthened the suitability of the paradigm for comparing the effects of MVF and NVF training.

5. Limitations and Future Work

A limitation of the present study pertains to the New word set analysis, which was conducted to assess performance improvements in the untrained left hand for novel movement sequences and whether these improvements differed between the feedback conditions (refer to Section 2.11.6: *Statistical Model – New Word Set Analysis* for more details). To minimize potential learning effects arising from physical task execution with the left hand, a dedicated trial to determine baseline performance for the New word set was not included in the Pre-Practice session. Instead, the performance in the Pre-Practice LH Primary word set trial was used as a common baseline for both word sets, based on the assumption that the initial task difficulty would be comparable across word sets. However, differences in sequence structure and transition demands between the two word sets may result in unequal baseline difficulty. Furthermore, the same word sets served as the Primary and New word sets for all participants and were not counterbalanced across participants. Consequently, the estimated magnitude of performance improvement for the New word set may not accurately reflect the true magnitude of improvement, which in turn could influence the interpretation of the New word set findings.

In addition, within the Post-Practice session, the Primary word set trial was always performed before the New word set trial for each hand. Consequently, potential order effects cannot be ruled out when interpreting differences in performance improvements between the two word sets. Accordingly, interpretations of the New word set analysis should be treated with caution. Future studies could be designed specifically to investigate whether MVF enhances performance gains for novel movement sequences by assessing performance on the New word set before and after the Practice session, while using the Primary word set only during the Practice session.

A further limitation of the present study is the relatively small sample size (n = 10 per group), which limits the precision with which effect magnitudes can be estimated. Accordingly, the reported effect-size estimates should be interpreted with appropriate caution. For example,

the point estimate of the effect size for the between-group difference in CCT improvement was Hedges' g = 1.13; however, its 95% confidence interval was wide [0.21, 2.12], indicating that the magnitude of the effect was estimated with limited precision. Future studies with larger samples would provide more precise estimates of the magnitude of MVF-related performance enhancement.

A further consideration relates to the statistical sensitivity of the study. A sensitivity analysis in G*Power indicated that, with N = 20, the design could detect Group × Session interaction effects of approximately $f = 0.27$ with 80% power ($\alpha = 0.05$), corresponding to a medium-sized effect. This suggests that the study was primarily sensitive to moderate-to-large effects, and smaller effects may not have been reliably detectable. This consideration is particularly relevant to the non-significant Group × Session interactions observed for the secondary performance variables, PD and MT. Future studies with larger samples would provide greater sensitivity for detecting potential small between-group differences in pre- to post-practice performance improvements in PD and MT.

Further insights may be obtained through additional analyses of the present study's dataset. For example, the pre- to post-practice performance improvement in the trained right hand and the trajectory of right-hand performance across the 12 Practice session trials could be analyzed. These analyses could provide insights into whether the two types of visual feedback differentially affected right-hand performance across the experimental sessions and whether right-hand performance improvements predicted corresponding improvements in the untrained left hand, thereby helping contextualize the observed group-level differences. Additionally, analysis of right-hand performance improvement for the novel movement sequences (i.e., New word set) could provide further context for interpreting the finding that, in the left hand, performance improvements for the New word set were not enhanced in the mirror group beyond those observed in the control group.

Another interesting direction for further analysis concerns the New word set. The design of the Primary and New word sets incorporated variation in the degree of similarity between practiced and novel movement sequences. Specifically, each word in the Primary word set had a corresponding word in the New word set with varying degrees of contiguous letter overlap at corresponding serial positions. For example, the longest contiguous overlap between *honor* and *heros* was one letter, whereas *oaths* and *oasis* shared two consecutive letters (*oa*), *ethos* and *ether* shared three (*eth*), and *risen* and *rises* shared four (*rise*). Similar variation in contiguous overlap was present across the remaining word pairs. Future analyses could examine whether performance improvements for words in the New word set vary as a function of the degree of overlap with their corresponding word from the Primary word set. Such an analysis could provide further insight into the overall performance improvement observed for novel movement sequences (New word set).

Furthermore, analysis of the subcomponents of the movement sequences may reveal patterns that provide insight into the nature of MVF-mediated performance enhancement.

For instance, it remains unclear whether different movement categories, such as vertical and lateral movements, exhibit differential improvements. Another relevant analysis concerns the Exploratory Left-Hand Practice Session conducted as the fourth and final session of the experiment. Analysis of left-hand performance across the five trials of this session could reveal whether the rate of performance improvement due to direct physical practice with the left hand differed between the mirror and control groups following right-hand practice. As this exploratory question falls outside the main objectives of the present paper, the corresponding data will be analyzed and reported separately.

Another relevant direction for future research concerns the number of MVF training sessions. Future studies could examine the effects of multi-session MVF training conducted across multiple days or weeks on untrained-hand performance in the present task. Although some studies have examined the effects of MVF training across multiple days or weeks and reported enhanced performance in the untrained hand relative to their respective non-mirror comparison conditions (Hamzei et al., 2012; Zult et al., 2016; Bähr et al., 2018), such multi-session investigations remain limited. Further work is required to characterize the temporal evolution of MVF-related performance enhancement, including changes in the magnitude of enhancement and the point at which performance plateaus. Furthermore, future studies could examine the persistence of MVF-related performance gains by including delayed retention tests conducted several days or weeks after the completion of training.

A further consideration in the present study concerns the contribution of action observation. The contribution of action observation to the additional performance improvement observed under MVF relative to normal visual feedback cannot be isolated with the present experimental design. To further investigate the role of action observation in MVF-mediated performance improvements in the untrained left hand, a future experiment could use a similar experimental structure to the present study, with the Practice session replaced by an Action Observation session. This Observation session would comprise 12 trials in which participants would observe the virtual left hand performing the typing task with the Primary word set while keeping both real hands stationary. Such an experiment could help determine whether action observation alone produces performance improvements for the Primary word set and whether any such improvements are also evident for the New word set.

Finally, a further issue that warrants investigation is whether MVF-mediated performance enhancement occurs in the opposite direction—namely, whether training with the non-dominant left hand under MVF produces greater performance gains in the untrained dominant right hand than training under NVF. Such investigations could also determine whether the magnitude of MVF-mediated performance enhancement depends on whether the dominant or non-dominant hand is trained. To the best of our knowledge, only one study has explicitly examined the role of hand dominance in MVF-based motor learning. Using a complex two-ball rotation task, Rjosk et al. (2016) reported no differences in MVF-mediated performance improvement between training performed with the dominant and non-

dominant hands. However, for this task, other MVF-based studies have reported inconsistent results (Nojima et al., 2012; Reissig et al., 2015a; Rjosk et al., 2017). Taken together, further studies are needed to investigate whether MVF-mediated performance enhancement is observed when either the dominant or non-dominant hand is trained, and whether the magnitude of such enhancement is influenced by hand dominance.

6. Conclusion

The present study demonstrated that mirror visual feedback (MVF) enhances performance in the untrained, non-dominant left hand for a complex motor sequence learning task involving fine finger movements. This enhancement was relative to the already significant performance improvement due to cross-education alone in the control group, highlighting the advantage of simultaneously combining action observation and cross-education through MVF. Furthermore, although improvements in the secondary performance variables (movement time and press duration) did not differ significantly between groups, the mirror group showed slightly greater performance improvement than the control group. This slightly greater improvement in the mirror group may have had a cumulative effect across the trial, resulting in the greater improvement observed in the primary performance variable, CCT. Collectively, these findings extend prior work by Ossmy and Mukamel by demonstrating MVF-related benefits in a more complex motor sequence learning task.

In addition, the study demonstrated that performance gains in the untrained left hand were also detected for novel movement sequences (i.e., sequences not practiced by the trained right hand) in both groups. However, the magnitude of these performance gains was comparable between groups. Thus, the additional performance enhancement associated with MVF that was detected for movement sequences practiced by the trained right hand was not detected for novel movement sequences.

Furthermore, we identified a few factors that could help maximize MVF-mediated learning in the untrained hand and could be incorporated into the design of future MVF-based studies. These include the following:

i. **Continuous Visual Engagement:** The task should be designed such that the ability to perform the task requires continuous visual guidance. During mirror feedback, this implicitly ensures that the participant's attention remains on observing the illusory movements (provided via a mirror or VR headset) of the untrained hand, thereby leveraging the action observation component of MVF. In contrast, in pure action-observation-based learning, it is hard to ensure that participants maintain sustained attention throughout the observation period.
ii. **Task Variability and Complexity:** In tasks that involve repeated execution of the same movements, expertise can be acquired relatively quickly. In such cases, performance may become largely automatic, reducing reliance on visual feedback. As a result, the contribution of MVF’s action observation component to overall learning may be

diminished. Introducing variability into the task, as implemented in the present study through multiple movement sequences, increases task complexity and delays the onset of automatization. This prolongs reliance on visual feedback, thereby sustaining the contribution of action-observation-based learning to overall performance.

iii. **Practice Task Instructions:** Participants should be explicitly instructed to try to improve their performance throughout the practice session. Studies have demonstrated that performance improvements in the trained hand positively correlate with performance improvements in the untrained hand (Poh et al., 2012; Lee et al., 2010).

iv. **Feedback System:** The continuous performance feedback system, as implemented in the current study, has a two-fold advantage: 1. It implicitly incentivizes participants to improve with each practice session trial, while also serving as a mechanism to ensure adherence to the task instruction of attempting to improve throughout the practice session. 2. Knowledge of results has been shown to facilitate motor performance and learning (Salmoni et al., 1984). Taken together, this feedback system facilitates performance improvement in the trained hand, thereby maximizing cross-education.

v. **Task selection:** Cross-education is task-dependent and can, at times, be asymmetrical (e.g., a given task may show improvement in the untrained non-dominant hand following dominant-hand training, but not vice versa). Therefore, selecting a task that does not exhibit cross-education may limit the extent of performance gains achievable through mirror visual feedback (MVF) in the untrained hand. This underscores the importance of task selection, particularly in rehabilitation contexts, where appropriate task choice can maximize the effectiveness of MVF-based interventions.

In conclusion, this study adds to a growing but still limited body of literature demonstrating that MVF can enhance motor performance in the untrained limb, even for a complex motor sequence learning task. This study also shows that the additional performance enhancement associated with MVF that was detected in the untrained left hand for movement sequences practiced by the trained right hand was not detected for novel movement sequences. Finally, we highlight several considerations that may inform the design of future MVF-based studies aimed at enhancing performance gains in the untrained limb.

CRediT authorship contribution statement

Anurag Gupta: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Resources, Data Curation, Validation, Visualization, Writing – Original Draft, Funding Acquisition. **Varadhan SKM:** Conceptualization, Methodology, Resources, Supervision, Project Administration, Funding Acquisition, Writing – Review & Editing.

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Declaration of competing interest

The authors have no competing interests to declare.

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Data availability

The data collected for the current study will be made available upon reasonable request to the corresponding author.

References

1. Altschuler, E. L., Wisdom, S. B., Stone, L., Foster, C., Galasko, D., Llewellyn, D. M. E., & Ramachandran, V. (1999). Rehabilitation of hemiparesis after stroke with a mirror. *The Lancet*, *353*(9169), 2035–2036. https://doi.org/10.1016/S0140-6736(99)00920-4
2. Bähr, F., Ritter, A., Seidel, G., Puta, C., Gabriel, H. H. W., & Hamzei, F. (2018). Boosting the Motor Outcome of the Untrained Hand by Action Observation: Mirror Visual Feedback, Video Therapy, or Both Combined—What Is More Effective? *Neural Plasticity*, *2018*(1), 8369262. https://doi.org/10.1155/2018/8369262
3. Braun, D. A., Aertsen, A., Wolpert, D. M., & Mehring, C. (2009). Motor Task Variation Induces Structural Learning. *Current Biology*, *19*(4), 352–357. https://doi.org/10.1016/j.cub.2009.01.036
4. Braun, D. A., Mehring, C., & Wolpert, D. M. (2010). Structure learning in action. *Behavioural Brain Research*, *206*(2), 157–165. https://doi.org/10.1016/j.bbr.2009.08.031
5. Broderick, P., Horgan, F., Blake, C., Ehrensberger, M., Simpson, D., & Monaghan, K. (2018). Mirror therapy for improving lower limb motor function and mobility after stroke: A systematic review and meta-analysis. *Gait & Posture*, *63*, 208–220. https://doi.org/10.1016/j.gaitpost.2018.05.017
6. Calvert, G. H. M., & Carson, R. G. (2022). Neural mechanisms mediating cross education: With additional considerations for the ageing brain. *Neuroscience & Biobehavioral Reviews*, *132*, 260–288. https://doi.org/10.1016/j.neubiorev.2021.11.025
7. Carroll, T. J., Herbert, R. D., Munn, J., Lee, M., & Gandevia, S. C. (2006). Contralateral effects of unilateral strength training: Evidence and possible mechanisms. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *101*(5), 1514–1522. https://doi.org/10.1152/japplphysiol.00531.2006
8. Chen, Y., Wang, P., Bai, Y., & Wang, Y. (2019). Effects of mirror training on motor performance in healthy individuals: A systematic review and meta-analysis. *BMJ Open Sport & Exercise Medicine*, *5*(1). https://doi.org/10.1136/bmjsem-2019-000590
9. Clark, D., & Ivry, R. B. (2010). Multiple systems for motor skill learning. *WIREs Cognitive Science*, *1*(4), 461–467. https://doi.org/10.1002/wcs.56
10. Gupta, A., & SKM, V. (2026). A VR-based experimental system for studying mirror visual feedback effects on cross-education. *Scientific Reports*, *16*(1), 12048.

https://doi.org/10.1038/s41598-026-41353-1
11. Hamzei, F., Läppchen, C. H., Glauche, V., Mader, I., Rijntjes, M., & Weiller, C. (2012). Functional Plasticity Induced by Mirror Training: The Mirror as the Element Connecting Both Hands to One Hemisphere. *Neurorehabilitation and Neural Repair*, *26*(5), 484–496. https://doi.org/10.1177/1545968311427917
12. Hoff, M., Kaminski, E., Rjosk, V., Sehm, B., Steele, C. J., Villringer, A., & Ragert, P. (2015). Augmenting mirror visual feedback-induced performance improvements in older adults. *European Journal of Neuroscience*, *41*(11), 1475–1483. https://doi.org/10.1111/ejn.12899
13. Hsieh, Y., Yang, T., Peng, Z., Wang, R., Shih, H., & Yang, Y. (2025). Effects of mirror therapy on motor and functional recovery of the upper extremity in subacute stroke: Systematic review and meta-analysis. *Pm & R*, *17*(5), 567–581. https://doi.org/10.1002/pmrj.13316
14. Kang, W., Pineda Hernández, S., & Mei, J. (2021). Neural Mechanisms of Observational Learning: A Neural Working Model. *Frontiers in Human Neuroscience*, *14*. https://doi.org/10.3389/fnhum.2020.609312
15. Karni, A., Meyer, G., Jezzard, P., Adams, M. M., Turner, R., & Ungerleider, L. G. (1995). Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature*, *377*(6545), 155–158. https://doi.org/10.1038/377155a0
16. Karni, A., Meyer, G., Rey-Hipolito, C., Jezzard, P., Adams, M. M., Turner, R., & Ungerleider, L. G. (1998). The acquisition of skilled motor performance: Fast and slow experience-driven changes in primary motor cortex. *Proceedings of the National Academy of Sciences*, *95*(3), 861–868. https://doi.org/10.1073/pnas.95.3.861
17. Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., & Haith, A. M. (2019). Motor Learning. *Comprehensive Physiology*, *9*(2), 613–663. https://doi.org/10.1002/j.2040-4603.2019.tb00069.x
18. Lee, M., Hinder, M. R., Gandevia, S. C., & Carroll, T. J. (2010). The ipsilateral motor cortex contributes to cross-limb transfer of performance gains after ballistic motor practice. *The Journal of Physiology*, *588*(1), 201–212. https://doi.org/10.1113/jphysiol.2009.183855
19. Lindsay, R. S., Larkin, P., Kittel, A., & Spittle, M. (2023). Mental imagery training programs for developing sport-specific motor skills: A systematic review and meta-analysis. *Physical Education and Sport Pedagogy*, *28*(4), 444–465. https://doi.org/10.1080/17408989.2021.1991297
20. Manca, A., Hortobágyi, T., Carroll, T. J., Enoka, R. M., Farthing, J. P., Gandevia, S. C., Kidgell, D. J., Taylor, J. L., & Deriu, F. (2021). Contralateral Effects of Unilateral Strength and Skill Training: Modified Delphi Consensus to Establish Key Aspects of Cross-Education. *Sports Medicine*, *51*(1), 11–20. https://doi.org/10.1007/s40279-020-01377-7
21. Nojima, I., Mima, T., Koganemaru, S., Thabit, M. N., Fukuyama, H., & Kawamata, T. (2012). Human Motor Plasticity Induced by Mirror Visual Feedback. *Journal of Neuroscience*, *32*(4), 1293–1300. https://doi.org/10.1523/JNEUROSCI.5364-11.2012
22. Norris, T. A., Augenstein, T. E., Rodriguez, K. M., Claflin, E. S., & Krishnan, C. (2024). Shaping corticospinal pathways in virtual reality: Effects of task complexity and sensory feedback during mirror therapy in neurologically intact individuals. *Journal of NeuroEngineering and Rehabilitation*, *21*(1), 154. https://doi.org/10.1186/s12984-024-01454-2
23. Ossmy, O., & Mukamel, R. (2016). Neural Network Underlying Intermanual Skill Transfer

in Humans. *Cell Reports*, *17*(11), 2891–2900. https://doi.org/10.1016/j.celrep.2016.11.009
24. Park, C., & Son, H. (2022). Immediate Effects of Fine-Motor Training on Coordination and Dexterity of the Non-Dominant Hand in Healthy Adults: A Randomized Controlled Trial. *Behavioral Sciences*, *12*(11). https://doi.org/10.3390/bs12110446
25. Pérez-Cruzado, D., Merchán-Baeza, J. A., González-Sánchez, M., & Cuesta-Vargas, A. I. (2017). Systematic review of mirror therapy compared with conventional rehabilitation in upper extremity function in stroke survivors. *Australian Occupational Therapy Journal*, *64*(2), 91–112. https://doi.org/10.1111/1440-1630.12342
26. Poh, E., Riek, S., & Carroll, T. J. (2013). Ipsilateral corticospinal responses to ballistic training are similar for various intensities and timings of TMS. *Acta Physiologica*, *207*(2), 385–396. https://doi.org/10.1111/apha.12032
27. Rachaveti, D. (2019). *Studies of motor sequence learning using finger thumb opposition movements* [Indian Institute of Technology Madras]. http://hdl.handle.net/10603/415006
28. Rachaveti, D., Ranganathan, R., & SKM, V. (2020). *Practice modifies the response to errors during a novel motor sequence learning task* (p. 2020.10.09.334169). bioRxiv. https://doi.org/10.1101/2020.10.09.334169
29. Rachaveti, D., & SKM, V. (2020). Motor sequence learning data collected continuously for fifteen days of practice using a novel glove-based typing device. *Data in Brief*, *29*, 105234. https://doi.org/10.1016/j.dib.2020.105234
30. Ramachandran, V., & Rogers-Ramachandran, D. (1996). Synaesthesia in phantom limbs induced with mirrors. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *263*(1369), 377–386. https://doi.org/10.1098/rspb.1996.0058
31. Reissig, P., Puri, R., Garry, M. I., Summers, J. J., & Hinder, M. R. (2015). The Influence of Mirror-Visual Feedback on Training-Induced Motor Performance Gains in the Untrained Hand. *PLOS ONE*, *10*(10), e0141828. https://doi.org/10.1371/journal.pone.0141828
32. Reissig, P., Stöckel, T., Garry, M. I., Summers, J. J., & Hinder, M. R. (2015). Age-Specific Effects of Mirror-Muscle Activity on Cross-Limb Adaptations Under Mirror and Non-Mirror Visual Feedback Conditions. *Frontiers in Aging Neuroscience*, *7*. https://doi.org/10.3389/fnagi.2015.00222
33. Rjosk, V., Kaminski, E., Hoff, M., Sehm, B., Steele, C. J., Villringer, A., & Ragert, P. (2016). Mirror Visual Feedback-Induced Performance Improvement and the Influence of Hand Dominance. *Frontiers in Human Neuroscience*, *9*. https://doi.org/10.3389/fnhum.2015.00702
34. Rjosk, V., Lepsien, J., Kaminski, E., Hoff, M., Sehm, B., Steele, C. J., Villringer, A., & Ragert, P. (2017). Neural correlates of mirror visual feedback-induced performance improvements: A resting-state fMRI study. *Frontiers in Human Neuroscience*, *11*. https://doi.org/10.3389/fnhum.2017.00054
35. Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin*, *95*(3), 355–386. https://doi.org/10.1037/0033-2909.95.3.355
36. Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82*(4), 225–260. https://doi.org/10.1037/h0076770
37. Schmidt, R. A., Lee, T. D., Winstein, C., Wulf, G., & Zelaznik, H. N. (2018). *Motor Control and Learning: A Behavioral Emphasis*. Human Kinetics.
38. Schuster, C., Hilfiker, R., Amft, O., Scheidhauer, A., Andrews, B., Butler, J., Kischka, U., &

Ettlin, T. (2011). Best practice for motor imagery: A systematic literature review on motor imagery training elements in five different disciplines. *BMC Medicine*, *9*(1), 75. https://doi.org/10.1186/1741-7015-9-75

39. Scripture, E. W., Smith, T. L., & Brown, E. M. (1894). On the education of muscular control and power. *Studies from the Yale Psychological Laboratory*, *2*(5), 114–119.
40. Shea, C. H., Kovacs, A. J., & Panzer, S. (2011). The Coding and Inter-Manual Transfer of Movement Sequences. *Frontiers in Psychology*, *2*. https://doi.org/10.3389/fpsyg.2011.00052
41. Shenoy, P., Gupta, A., & S.K.M., V. (2022). Design and Validation of an IMU Based Full Hand Kinematic Measurement System. *IEEE Access*, *10*, 93812–93830. IEEE Access. https://doi.org/10.1109/ACCESS.2022.3203186
42. Steinberg, F., Pixa, N. H., & Doppelmayr, M. (2016). Mirror Visual Feedback Training Improves Intermanual Transfer in a Sport-Specific Task: A Comparison between Different Skill Levels. *Neural Plasticity*, *2016*, 8628039. https://doi.org/10.1155/2016/8628039
43. Ste-Marie, D. M., Law, B., Rymal, A. M., Jenny, O., Hall, C., & McCullagh, P. (2012). Observation interventions for motor skill learning and performance: An applied model for the use of observation. *International Review of Sport and Exercise Psychology*, *5*(2), 145–176. https://doi.org/10.1080/1750984X.2012.665076
44. Thieme, H., Morkisch, N., Mehrholz, J., Pohl, M., Behrens, J., Borgetto, B., & Dohle, C. (2018). Mirror therapy for improving motor function after stroke. *The Cochrane Database of Systematic Reviews*, *2018*(7), CD008449. https://doi.org/10.1002/14651858.CD008449.pub3
45. Toth, A. J., McNeill, E., Hayes, K., Moran, A. P., & Campbell, M. (2020). Does mental practice *still* enhance performance? A 24 Year follow-up and meta-analytic replication and extension. *Psychology of Sport and Exercise*, *48*, 101672. https://doi.org/10.1016/j.psychsport.2020.101672
46. Veale, J. F. (2014). Edinburgh Handedness Inventory – Short Form: A revised version based on confirmatory factor analysis. *Laterality*, *19*(2), 164–177. https://doi.org/10.1080/1357650X.2013.783045
47. Vogt, S., & Thomaschke, R. (2007). From visuo-motor interactions to imitation learning: Behavioural and brain imaging studies. *Journal of Sports Sciences*, *25*(5), 497–517. https://doi.org/10.1080/02640410600946779
48. Wulf, G., Shea, C., & Lewthwaite, R. (2010). Motor skill learning and performance: A review of influential factors. *Medical Education*, *44*(1), 75–84. https://doi.org/10.1111/j.1365-2923.2009.03421.x
49. Zhou, S. (2000). Chronic Neural Adaptations to Unilateral Exercise: Mechanisms of Cross Education. *Exercise and Sport Sciences Reviews*, *28*(4), 177.
50. Zult, T., Goodall, S., Thomas, K., Solnik, S., Hortobágyi, T., & Howatson, G. (2016). Mirror Training Augments the Cross-education of Strength and Affects Inhibitory Paths. *Medicine & Science in Sports & Exercise*, *48*(6), 1001. https://doi.org/10.1249/MSS.0000000000000871