

The Relationship Between Embodiment Perception and Motor Learning in Virtual Reality-based Interventions

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Virtual reality (VR) is a rapidly evolving technology that offers immersive experiences by simulating realistic environments and interactions. In the context of motor learning and rehabilitation, VR has emerged as a promising tool because of its ability to provide controlled, customizable and engaging training scenarios. A key factor in the effectiveness of VR-based interventions is the sense of embodiment, which refers to the user's perception of being present in the virtual environment and having control over a virtual body. This thesis investigates the influence of different sensory feedback modalities on the sense of embodiment and task performance in VR-based motor learning. Through two studies, we examine how the combination of visual and tactile feedback affects embodiment perception and motor task performance in VR environment. In the first study, we explore the effects of pressure feedback on task performance and embodiment in VR-based mirror therapy. Twenty-two able-bodied participants were divided into two groups, with one group receiving the pressure feedback on their thumb and index fingertips during a pick-and-place task. The results indicate that the group with haptic feedback achieved a 15.07% higher task success rate and reported a 12.80% higher embodiment perception compared to the control group. The second study extends the investigation to the impact of vibrotactile feedback in a ball-and-beam control task. Nineteen participants were exposed to four conditions: No Feedback, Vibrotactile Feedback only, Visual Feedback Only and Both Vibrotactile and Visual Feedback. The condition with Both Vibrotactile and Visual Feedback had a 14.52% improvement in task performance and a higher embodiment perception compared to other conditions. Overall, this thesis contributes to the understanding of how sensory feedback modalities can be effectively integrated into VR systems to enhance embodiment and motor learning, suggesting that incorporating haptic feedback into a visual interaction may be associated with higher embodiment and improved motor task performance. These insights have implications for the design of more effective VR-based interventions for training and rehabilitation purposes, emphasizing the value of multisensory feedback in these contexts.

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Chapter 1

Introduction

Virtual reality (VR) is an evolving technology that has impacted the way we perceive and interact with digital environments by immersing users in a virtual three-dimensional world [3]. In recent years, VR has found a significant application in the field of rehabilitation, offering a safe and controlled environment for patients to practice physical, cognitive, and motor skills without the risk associated with real-world activities [123]. For example, stroke survivors can use VR to engage in virtual exercises that help improve their motor functions and regain lost abilities [127], while individuals with cognitive impairment can participate in virtual scenarios designed to enhance memory, attention, and problem-solving skills [64].

An essential aspect of immersive VR experience is the sense of embodiment, defined as “...the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body, especially in relation to virtual reality applications” by Kilteni et al. [63]. This concept is important for motor learning and rehabilitation, as it influences how users perceive and interact with their virtual environment. Several factors impact the sense of embodiment in VR. First, proprioception, the awareness of body position and movement, is essential for maintaining balance and coordinating movements [67]. Second, visual feedback, such as seeing one’s limbs move, reinforces the connection between the body and self-perception [44]. Third, sensory input from skin, muscles, and joints helps individuals gauge their body’s orientation and movements in space [38]. Lastly, motor control and agency, the ability to initiate and control voluntary movements, further strengthen the sense of embodiment as individuals feel in charge of their physical actions [13].

Despite the advancements in VR technology, several challenges remain unaddressed, particularly in the context of motor learning. One such challenge is the translation of effects or learning from virtual scenarios to real-world tasks. In some cases, individuals

may learn a task in VR and improve their performance within the virtual environment, but this improvement does not necessarily translate to enhanced performance in real-life tasks [49]. This issue could be attributed to a lack of embodiment and Immersion in the VR experience. When users do not feel fully embodied or immersed in the virtual environment, the skills and abilities they develop may not effectively transfer to real-world scenarios.

Motor learning, the process of acquiring and improving motor skills through practice, is a complex process affected by various factors, including sensory feedback [82]. When performing a motor skill, the brain relies on sensory information from the environment and the body itself to refine movements and improve performance. In VR environments, the lack of realistic sensory feedback, particularly tactile feedback, can hinder the effectiveness of motor learning compared to real-world practice [58]. This highlights the importance of investigating the relationship between motor learning and embodiment in VR environments.

In this thesis, we aim to explore how different sensory feedback modalities, including visual representations of hands and tactile feedback, influence the sense of embodiment in VR and how this, in turn, correlates with improvements in task performance in motor learning. We hypothesize that the combination of visual and tactile feedback will lead to a higher sense of embodiment compared to visual feedback alone, thereby enhancing motor learning performance. To address this, we conducted two experiments in a VR environment:

1. VR-based mirror therapy (see [chapter 3](#)): a pick-and-place study (N=22, 11 for each group) where one group (*with haptics*) received haptic feedback (pressure on thumb and index fingertips) with a haptic glove (Weart TouchDIVER, Italy), and the other (*without haptics*) did not.
2. Ball and beam (see [chapter 4](#)): a positional control study (N=19) where participants were exposed to four conditions of No feedback (NHV), Haptic (vibrotactile) feedback (H), Visual feedback (V), and haptic and visual feedback (HV).

By examining the impact of cutaneous haptic feedback on the sense of embodiment and motor task performance, our findings contribute to a deeper understanding of how multisensory feedback can be leveraged to enhance embodiment and motor learning in VR. This research has implications for the design of more effective VR systems for training and rehabilitation purposes, further motivating the exploration of embodiment as a factor in VR-based motor learning.

Chapter 2

Related Work

In this chapter, we review related work in Embodiment Perception, Haptics, and Mirror Therapy, especially as it relates to VR.

2.1 Embodiment Perception in VR

The sense of embodiment in virtual reality (VR) has been extensively studied, with researchers exploring various factors that contribute to this phenomenon. Slater et al. [136] showed that the visual representation of the hands significantly enhances the sense of embodiment in VR. Building on this, Petkova et al. [107] further demonstrated that the perspective from which the virtual body is viewed can influence the strength of the embodiment illusion.

Tactile feedback has been found to reinforce the sense of embodiment by providing congruent multisensory information. For example, Cui [18] highlighted the impact of tactile feedback on improving the realism of hand appearance and the sense of interactivity in VR. Similarly, Richard et al. [118] studied the sense of embodiment in VR shared experiences and found that social presence and co-presence can enhance the feeling of embodiment in a virtual environment.

While these studies provide insights into the factors affecting embodiment, the relationship between embodiment and task performance, particularly in motor learning tasks, remains an area that warrants further exploration. For instance, Iwasaki et al. [59] examined how the level of embodiment affects attention distribution and task performance in

dual-task scenarios, yet the direct link between embodiment and motor learning is still not fully understood.

The influence of locomotion techniques on embodiment and presence in VR has been investigated by Waltemate et al. [147], revealing that different techniques, such as walking in place or using a joystick, can significantly affect the user’s sense of presence and connection to the virtual environment. Similarly, the role of avatar appearance in immersive VR has been studied by Suk and Laine [139] and Gonçalves et al. [39], demonstrating that the visual representation and controllability of the avatar are critical factors in enhancing the sense of embodiment. These studies underscore the importance of carefully designing both movement mechanisms and avatar aesthetics to optimize the user’s immersive experience and sense of self within virtual worlds.

The concept of embodiment extends beyond VR to augmented reality (AR), with studies by Choudhary et al. [15] and Matamala-Gomez et al. [86] exploring its implications for interpersonal distance perception and self-perceived body awareness, respectively. The embodiment of photorealistic avatars and its influence on the perception of body weight in VR has been studied by Wolf et al. [151]. Kokkinara et al. [67] also investigated the effects of visuomotor calibration on perceived space and body in immersive VR. They found that visuomotor adaptation can change the perception of space; for example, adjusting the mapping between real-world movements and their virtual counterparts can make a virtual room appear larger or smaller. However, its effects on the perception of the body differ depending on the type of distortion. For instance, altering the size of the virtual hand can affect how users perceive the size and reach of their own hand, but this perception might not change uniformly across all types of distortions.

Research has expanded our understanding of embodiment in VR across diverse applications, illustrating its significant impact on user experience and performance. Phillips et al. [108] examined the impact of avatar embodiment on distance perception accuracy in non-photorealistic immersive virtual environments used for architectural design. They discovered that avatar embodiment can enhance distance perception accuracy in virtual environments, which is important for accurate architectural design and spatial planning. In the cognitive domain, Kocur et al. [66] found that both self-perception and external perception of avatars can influence task outcomes, suggesting that avatar design should be carefully considered to support cognitive tasks in VR. Additionally, Borrego et al. [9] highlighted the therapeutic potential of embodiment in VR, showing that both healthy individuals and those recovering from stroke can experience enhanced presence and engagement when interacting with virtual tasks, pointing to promising applications in rehabilitation. Together, these studies indicate the various applications of embodiment in VR, from enhancing professional tasks to supporting health and rehabilitation.

The exploration of embodiment in virtual reality (VR) has expanded to various aspects of human perception and interaction, providing insights into the intricate relationship between virtual experiences and our sense of self. Perez-Marcos et al. [105] worked on the neurophysiological correlation of embodiment, and revealed that VR can be a powerful tool in enhancing motor-cognitive neurorehabilitation by leveraging motivational factors and the sense of presence. Pritchard et al. [112] examined the intricate interplay between visual form, touch, and position cues, highlighting their non-hierarchical influence on embodiment, agency, and presence in VR, suggesting that a balanced integration of sensory inputs is essential for a compelling sense of self in virtual environments. Popat [110] discussed the broader implications of embodiment in VR, proposing that it significantly shapes our experience and understanding of virtual spaces, with potential impacts on performance and learning. Vecchiato et al. [146] investigated the neurophysiological reactions to virtual architectural environments, indicating that the sense of embodiment can influence aesthetic appreciation and emotional responses, underscoring the potential of VR in fields beyond gaming, such as architecture and design.

While existing studies have laid a foundation for understanding the factors influencing embodiment in VR, there is a clear gap in understanding how these factors translate to improved task performance and learning outcomes. This gap motivates our work to explore the role of multisensory feedback in enhancing embodiment and its impact on motor learning in VR.

2.2 Haptics in VR

Incorporating haptic feedback into (VR) environments has garnered significant research interest, particularly within the domain of motor skill learning and rehabilitation. Haptic feedback, encompassing both tactile and force feedback modalities, serves as an important element in improving the realism and immersion of VR experiences by providing users with simulated touch sensations [116]. This technology presents promising applications across diverse domains, including training and education, as well as therapeutic and rehabilitative interventions.

Research in this area has explored various aspects of haptic feedback in VR. Marchal-Crespo and Reinkensmeyer [84] investigated the efficacy of haptic guidance in motor learning, showing its potential to facilitate learning through physical assistance during the initial stages. However, they also cautioned against the risk of dependency which could hinder skill acquisition. Cuppone et al. [21] examined the effects of robot-assisted proprioceptive

training with added vibrotactile feedback, finding significant improvements in somatosensory and motor performance. These studies, along with others like the development of the TIKL suit by Lieberman and Breazeal [77], which demonstrated improvements in target motion tasks, further emphasize the importance of haptic feedback in enhancing motor learning and rehabilitation in VR settings.

Technological advancements in haptic feedback systems have led to innovative applications. The TIKL suit, a wearable vibrotactile feedback system developed by Lieberman and Breazeal [77], showed a 27% improvement in accuracy and an accelerated learning rate of 23% for target motion tasks. Holden [53] discussed the potential of VR combined with haptic feedback for neurorehabilitation, highlighting its ability to provide controlled and repeatable training environments. Oagaz et al. [97] developed a VR system for table tennis training that provides real-time feedback, showing significant improvements in posture and technique. Lee and Choi [71] implemented an adaptive haptic guidance system in a VR-based motor learning task, observing improved learning outcomes compared to constant guidance.

While these studies highlight the potential of haptic feedback, challenges remain. [1] reviewed the limitations of current vibrotactile feedback systems, emphasizing the need for improved realism for effective motor learning in VR training. Levac et al. [75] and Poyade [111] echoed these concerns, highlighting the limitations of current haptic technology in replicating real-world interactions and its potential to improve motor skill acquisition. Muresan et al. [93] further emphasized the importance of realism in haptic feedback for effective VR training compared to conventional techniques.

Research is ongoing to optimize haptic feedback for VR training. Morris et al. [92] demonstrated that active haptic guidance in the form of a correcting force enabled effective learning of complex movements. Esen [27], Esen et al. [28] designed a similar active haptic assistance paradigm using a correcting force for learning force patterns. Srimathveeravalli and Thenkurussi [138] presented VR training systems that used active haptic guidance for handwriting, focusing on character shape and exerted pencil pressure. Rodríguez et al. [121] compared the effectiveness of continuous and error-based active haptic assistance, finding no significant difference, suggesting further research is needed in this area.

Lee and Choi [71] proposed the concept of haptic disturbance, where haptic cues interfere with the learner's movements during training. This method, using noise-like forces, showed promise in expediting motor learning. Lontschar et al. [80] investigated the importance and immersion provided by haptic feedback in a VR learning environment, finding correlations that support its effectiveness for specific learning tasks.

Overall, haptic feedback holds significant promise for enhancing motor skill learning and rehabilitation in VR environments. While challenges remain regarding the realism of haptic interaction, ongoing research is exploring methods to optimize its application and effectiveness in VR training.

2.3 Mirror therapy

Mirror therapy (MT) has emerged as a popular rehabilitation technique for hemiparesis, i.e., weakness in moving limbs on one side of the body, for instance, due to stroke [72, 141], upper phantom limb pain [31, 65], or lower phantom limb pain [81]. It also has the potential to help with rehabilitation for hemiplegia [45], the inability to move limbs on one side of the body. At its core, the method leverages the manipulation of visual feedback to induce positive effects on motor function [142]. The aim is to create visual stimuli that imply movement in one limb, while the actual movement is performed by the opposite limb. The main factors involved are the mirror-neuron system, which triggers the motor process associated with moving the amputated limb when observing the phantom’s motion [124, 120], and the increase in the spatial attention to the paretic (i.e., partially paralyzed) limb [91]. Therapists typically achieve this optical illusion by positioning a mirror between the two limbs; participants can observe the active limb’s reflection in the mirror, and the movement of the active limb is overlaid onto the opposite one [130].

The use of a physical apparatus for MT, which we refer to as conventional MT, was initially explored as a treatment for phantom limb pain by Ramachandran and Rogers-Ramachandran [114]. They were able to demonstrate the brain’s malleability by inducing synesthesia in patients; the visual illusion generated kinesthetic sensations in the paretic limb, essentially tricking the brain into perceiving full motor control over the affected extremity. This paved the way for a new approach to pain management. Subsequent studies extended these findings by examining the efficacy of conventional MT in motor rehabilitation for different patient populations. Thieme et al. [142] reviewed the effects of MT on individuals who had a stroke, reporting positive outcomes for upper-extremity motor function for both chronic and acute stroke populations, based on the Fugl-Meyer Assessment [34]. Cacchio et al. [11] studied the effects of MT on upper limb complex regional pain syndrome patients, where they found significant improvements in pain and motor control as well as greater long-term improvements (after a 6-month follow-up). Similarly, Gygax et al. [45] studied MT in the context of hemiplegic children and Tilak et al. [143] on amputees, and showed that MT is able to reduce pain as well as strength enhancement. Overall, the aforementioned experiments have shown that conventional MT has the poten-

tial to enhance motor recovery and alleviate sensory deficits, both for upper [72] and lower limbs [23].

Despite the positive outcomes associated with conventional MT, this method faces several limitations. The visibility of the physical mirror as well as the non-paretic limb may distract patients [54, 89]. This may take away from the intended illusion, reducing the effectiveness of the therapy. A conventional MT setup is also physically constrained in terms of space, which in addition to making it time-consuming to set up and align properly, can restrict patients' movements [5]. Further, it limits the therapists' ability to customize therapy environments [22], which may prevent them from adequately addressing individual patients' needs. To alleviate these issues, researchers have recently been exploring how MT can be modified to leverage new digital technologies such as virtual reality (VR) [145].

VR-based neurorehabilitation methods offer advantages such as enhanced immersion, customization, and the integration of multi-sensory stimulation [105, 4, 76]. Specifically in the context of MT, da Silva Jaques et al. [22] reported similar usability scores for VR-based MT and conventional MT, with study participants feeling less distracted in the VR setup. Other works exploring VR-based MT include Heinrich et al. [48] and Weber et al. [149], where researchers developed immersive VR-based systems and demonstrated potential motor recovery for post-stroke patients. Hsu et al. [55] also developed a VR-based MT system and compared it with conventional MT in sensorimotor performance for chronic stroke patients. Adjacent to this study, Lin et al. [78] performed a comparative evaluation between stroke patients with mild-to-severe hemiparesis and able-bodied participants in VR-based MT. Both works showed that their systems have a potentially positive impact on the upper extremity sensorimotor performance of different populations.

Although both conventional and VR-based MT primarily rely on visual illusions to induce positive motor control effects, the role of haptics in enhancing therapy experiences can be similarly significant. Adding synchronized haptic feedback to MT can form a reinforcement loop that modifies the body schema, utilizing a multi-sensory percept that enhances the perceived realism of the experience, as seen in the rubber hand illusion [61]. Prior research has shown that the inclusion of haptic feedback in MT enables patients to perceive their movements and interactions better due to higher spatial and temporal information processing bandwidth [95]. This facilitates more effective motor learning and neuro-rehabilitation [73]. Even so, few works have explored the effects of including haptic feedback in the context of conventional MT. This may be due to practical reasons such as the disruption of visuals due to extra haptic apparatuses that need to be worn and the limited amount of physical space available within which the visual illusion can be maintained.

Illustrating the utilization of haptic feedback in conventional MT, Lin et al. [79] incorporated a mesh glove and showed significant improvements in the performance of patients with chronic unilateral stroke. In another work, Hung et al. [56] used tactile, thermal, electrical, and vibration stimulation during the therapy, and showed that vibration emerged as the most effective stimulus type for post-stroke sensorimotor recovery. Similarly, Hunter et al. [57] found that vibrotactile feedback on the arm added to the benefits of MT in terms of improving phantom limb awareness. Further, the positive effects of vibration were also supported by [128], where vibration was used in tandem with MT for amputees, and a significant reduction in pain in their limbs was observed.

In a VR environment, where visual immersion is prioritized, the inclusion of tactile feedback can enhance the perception of presence [37] and may lead to more effective motor rehabilitation outcomes [125]. Sense of Embodiment is critical to maintaining immersion in VR applications and is known to depend on Tactile Sensation [85]. Previous studies have explored different modalities of haptic feedback including vibration [24] as well as the texture and shapes of small objects [104] and electrical stimulation [87] in conventional MT. Similarly, vibration has been applied to VR-based MT [119], showing improvements in participants' range of motion. However, none of them have evaluated how haptic feedback may impact embodiment perception in VR-based MT.

The incorporation of haptic feedback in VR-based MT is especially important for replicating the sense of touch and physical interaction, allowing patients to feel the virtual objects they are manipulating. Tactile feedback in the context of VR-based rehabilitation not only enhances immersion but also enables a more realistic representation of physical interactions in line with real-world experiences. This ultimately leads to improved motor learning and functional recovery through enhanced sensory-motor integration [152]. Some examples that have integrated haptics into VR-based MT include [119], where tendon vibration was added to the hand and wrist, showing significantly higher extension in the movements of healthy participants. Closely related to this direction of research, Spiss et al. [137] examined how touch stimuli can influence the proprioceptive cues between the user's virtual and real arms. A theoretical framework for instantiations of sensory illusions was developed by Farrington et al. [29]; this work, done on the unilateral lower limb amputee population, showed that interacting with a haptic slide bar increased the sense of presence for participants' amputated limb, potentially enhancing the effect of mirrored visual feedback through the use of multi-sensory illusions.

Although the potential of MT in rehabilitation has been well-documented, the integration of VR and haptic feedback presents a novel avenue for enhancing the efficacy of MT. This thesis aims to bridge the gap in understanding the impact of cutaneous haptic feedback on the sense of embodiment and motor learning in VR-based MT. Previous

research has predominantly focused on the visual aspects of VR-based MT, with limited exploration of how tactile feedback can augment the sense of embodiment and subsequently influence motor task performance. By investigating the combination of visual and tactile feedback, this research contributes to a deeper understanding of multisensory feedback's role in optimizing VR interventions for rehabilitation. The novelty of this work lies in its comprehensive examination of how different sensory feedback modalities, particularly cutaneous haptic feedback, can enhance embodiment and motor learning, providing insights for the design of more effective VR systems for training and rehabilitation purposes.

2.4 Motor learning in bimanual tasks

Transitioning from unimanual tasks such as mirror therapy, we discuss the bimanual coordination here. Bimanual tasks involve the simultaneous use of both hands and are critical for various daily activities. Our comprehension of bimanual tasks is significantly enhanced by examining how the brain processes sensory feedback during these activities.

Our understanding of bimanual coordination is enriched by studies investigating how the brain processes sensory feedback during these tasks. For example, Nazarahari et al. [94] explored visual feedback in bimanual circle drawing. They discovered that the non-dominant hand's performance improved significantly when it received a combined visual representation of both hands' positions (composite feedback), especially when the dominant hand received normal visual guidance. This suggests that tailored visual feedback strategies hold promise for enhancing bimanual coordination.

However, bimanual coordination is not simply a superposition of two independent hand movements. Studies by Kagerer [60] and Kasuga and Nozaki [62] highlight a phenomenon called "interference." They found that sudden changes in visual feedback for one hand can disrupt the movement of the other hand. This reveals a delicate balance within the nervous system that controls bimanual movements. Interestingly, this interference is not symmetrical; disruptions to the dominant hand tend to have a greater impact on the non-dominant hand, which highlights an asymmetrical nature in bimanual interference.

Further complexity arises from the concept of arm dominance. Dounskaia et al. [25] observed that the non-dominant arm has a reduced capability to control interaction torque, leading to instability in symmetrical movements, especially during asymmetrical tasks. This observation emphasizes the importance of considering individual differences in motor control strategies, and the need to tailor motor control strategies when designing rehabilitation programs.

The underlying neural mechanisms of bimanual coordination are also being explored. Cattaert et al. [14] proposed a neural cross-talk model to explain interference effects in bimanual tasks. Their model suggests that communication between brain hemispheres significantly contributes to the observed interference. Kagerer [60] built upon this by examining how handedness influences interference patterns. He found that left-handers exhibit different interference patterns compared to right-handers, suggesting weaker lateralization in the brain for left-handed individuals.

The importance of hemispheric specialization and integration in motor control is further emphasized by Serrien et al. [131]. Their review highlights the dynamic interplay between the brain’s hemispheres in regulating bimanual behaviour. They propose that both segregation and integration of brain functions are essential for skilled and adaptable motor behaviour.

The existing body of research on bimanual coordination has mainly focused on the impact of visual feedback and its role in synchronizing the movements of both hands. Studies have explored how visual cues can enhance performance, particularly emphasizing the dominant hand’s influence over the non-dominant hand and the intricate neural mechanisms involved in managing coordinated actions. However, this literature predominantly overlooks the potential impacts of multisensory feedback, including tactile sensations and proprioceptive inputs, particularly from the perspective of embodiment in motor tasks. This oversight highlights a significant gap in the current understanding, suggesting that future research should incorporate these elements to provide a more holistic approach to the study of bimanual coordination. Such an approach could lead to more effective rehabilitation techniques that engage the entire sensory apparatus, thereby fostering better integration and functionality of both hands in daily activities.

Chapter 3

The Impact of Pressure Feedback on Task Performance and Embodiment in Virtual Reality-based Mirror Therapy

Based on the concepts discussed in [chapter 2](#), this chapter aims to explore how pressure feedback, as a form of tactile sensation, affects motor task performance and the sense of embodiment in a VR environment. In particular, the objective of this chapter is to see if individuals can improve the performance of their non-dominant hand by observing the dominant hand performing a motor task, and whether the addition of pressure feedback can boost their performance. For this purpose, we employ a pick-and-place task, a common rehabilitation exercise.

A total of twenty-two able-bodied participants were recruited for this study and were divided into two groups: one receiving pressure feedback through haptic gloves and the other serving as a control group without such feedback. The experimental design consisted of three main conditions: Baseline, Training (with mirrored scene), and Testing, allowing for a comprehensive evaluation of the participants' performance and subjective experiences across different stages of the intervention.

The chapter presents a detailed analysis of the task performance, measured through success rates and task completion times, and embodiment perception, assessed through a modified version of the Avatar Embodiment questionnaire ¹.

¹This chapter has been submitted to IEEE Transactions on Haptics and is currently under review.

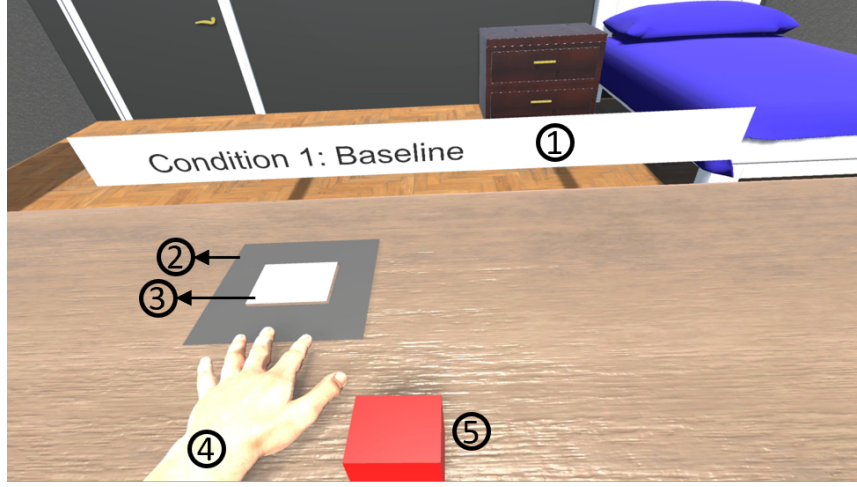


Figure 3.1: Components of the virtual environment: (1) Instruction panel, (2) Trap, (3) Target, (4) Avatar’s visible hand, and (5) Block. Participants were instructed to pick the block with the avatar’s hand and place it on the target. Depending on the condition, whether it was mirrored or not, the participants had to control the avatar’s hand with their dominant or non-dominant hand. Each time the red block was placed on either the target or the trap, the trial was considered finished, the block would reappear at its initial position, and the target and trap were randomly positioned within the participant’s task space.

3.1 Task Environment

For this study, we designed a VR-based pick-and-place task that includes a variety of rehabilitation movements such as elbow flexion and extension as well as grasping and pinching. The virtual environment consisted of a closed room with decorations to simulate a comfortable space. A table was located at the center of the virtual room, with a $3 \times 3 \times 3 \text{ cm}^3$ red block and a $3 \times 3 \text{ cm}^2$ white square target surrounded by a 1 m grey margin as the trap. The experiment consisted of a simple precision-based pick-and-place task (see [Figure 3.1](#)). The task required to pick the red block and place it on the target while avoiding the trap. Once the block is placed on either the target or the trap, the trial is completed and the new trial will be started with the block being reset to the initial position and the target being randomly positioned within the participants’ task space to minimize the memorization effect (see [Figure 3.4](#)).

The task was performed in the virtual reality environment designed in the Unity 3D

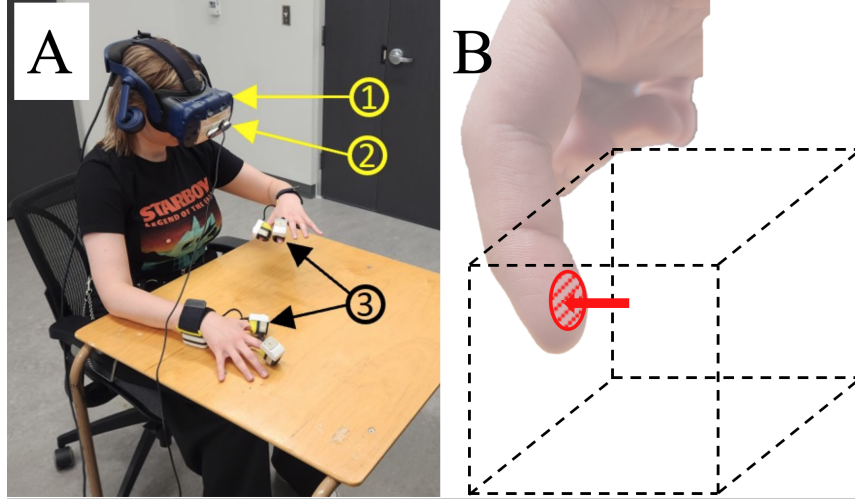


Figure 3.2: (A): Experimental setup: a participant performing the pick-and-place task with (1): Vive pro HMD, (2): Leap Motion Controller 2 and (3): TouchDIVER haptic gloves. (B) The *with haptics* group experienced constant force of 3 N on their thumb and fingertips while touching the virtual block.

game engine (Unity Technologies, Inc., United States), interfaced using a Vive Pro head-mounted display (HMD) (HTC Corp., Taiwan). The real-time visualization of the upper limbs is achieved by using a Leap Motion Controller 2 (Ultraleap Inc., CA, United States) at 120 fps refresh rate mounted to the front of the HMD at 90 fps refresh rate. Additionally, constant force of 3 N on the thumb and index fingertips of the actual non-dominant hand was rendered using the TouchDIVER haptic gloves (Weart, Italy) (see [Figure 3.2-A](#)).

3.2 Participants

Our study included an experiment with details described in [Experimental Procedure](#). Typical studies in this field often involve between 10 and 20 participants, which guided our recruitment of 11 able-bodied participants per group. This was further supported by a power analysis. Anticipating a medium effect size (Cohen’s $d = 0.5$), with a power of 0.8 and a significance level of 0.05, and assuming a standard deviation of the measurements as 0.5, the power analysis suggested that a minimum of 11 participants per group would be required. A total of 22 able-bodied right-handed participants (as a convenient sample size) took part in the study and were divided into two groups. One group experienced constant

force of 3 N on their thumb and index fingertips when these fingers touched the block in the virtual scene (Figure 3.2-B), while the other group did not have haptic feedback rendered on their fingers. We refer to the former as the *with haptics* group and the latter as the *without haptics* group. The *with haptics* group had a mean age of 27.6 years (SD = 4.7) with nine identifying as male and two as female, while the *without haptics* group had a mean age of 26.1 (SD = 2.9), with nine identifying as male and two as female. All participants provided their written informed consent to participate in the study prior to the experiment. Study protocols and procedures were approved by the University of Waterloo Research Ethics Boards (ORE# 45062).

3.3 Experimental Procedure

Figure 3.3 demonstrates the experimental procedure in brief. The experiment was performed in a single-session in-lab visit for each participant. After consenting to participate and providing demographic information, the participants were asked to fill out the handedness questionnaire [99], and they were informed about the virtual environment and their tasks in the experiment. Then, they were asked to wear the HMD and adjust it based on their head size. After the HMD adjustment, the experimenter assisted them in wearing the thimbles on their thumb and index fingertips. Once the devices were worn, the participants were given approximately five minutes to become comfortable with the environment. This familiarization phase lasted until the participants verbally informed they were comfortable with starting the experiment. Then, the experimenter reminded them of their tasks and started the main phase of the experiment.

The experiment consisted of three main conditions: Baseline, Train, and Test.

- **Baseline:** participants would observe their non-dominant hand in the virtual scene and had to control it with their actual non-dominant hand (Figure 3.4-A).
- **Train (mirrored):** participants would see their non-dominant virtual hand, but had to control it with their actual dominant hand (Figure 3.4-B).
- **Test:** similar to Baseline, participants controlled their non-dominant virtual hand with their actual non-dominant hand (Figure 3.4-A).

Each condition consisted of 60 trials. After every 15 trials, participants were given 20 seconds of rest time to minimize the impact of fatigue. Once the 60 trials of each condition were completed, they were given 30 seconds of rest before exposure to the next condition.

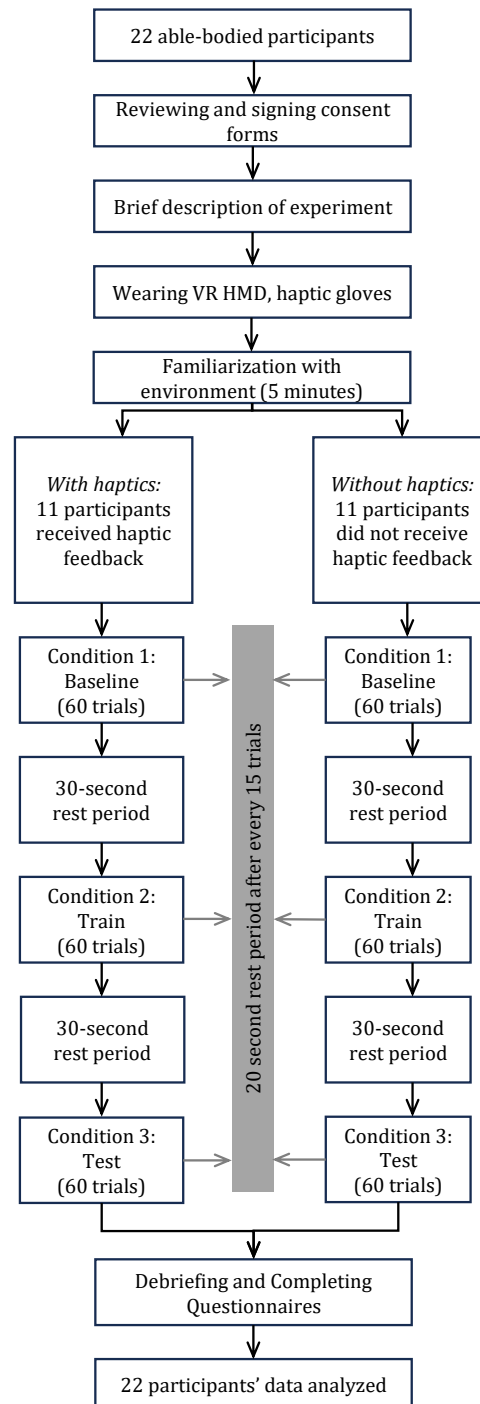


Figure 3.3: A flowchart depicting the stages of the experimental procedure.

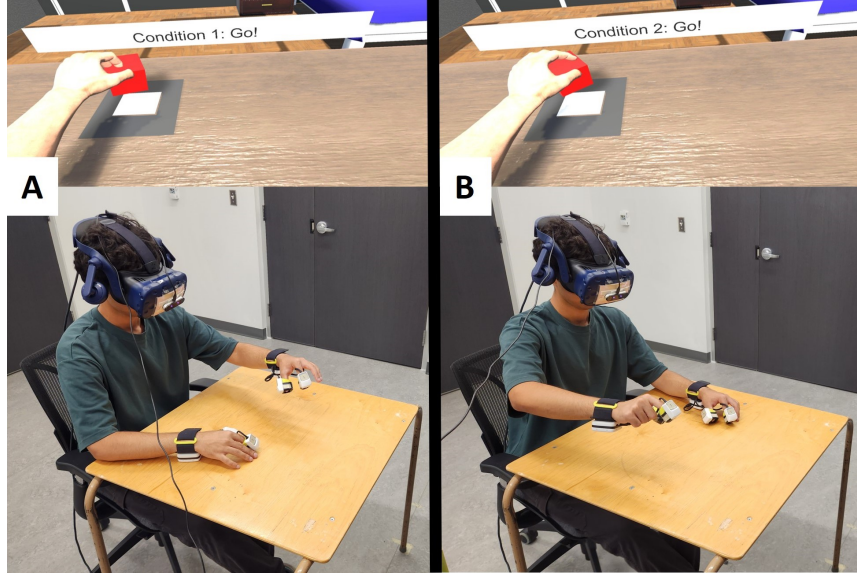


Figure 3.4: Different conditions of the experiment and the participants’ observations in the VR scene (A) Normal, and (B) Mirrored. Normal scene (A) was used in Baseline and Test conditions, and the mirrored scene (B) was used in the Train condition.

Once the three conditions were completed, they were asked to take off the devices and fill out the avatar embodiment and the NASA-TLX questionnaires for every condition. Overall, each participant’s lab visit took between 60 to 75 minutes.

3.4 Measures

In this study, we included four measures which are described as follows:

3.4.1 Success rate

We used the participants’ success rate (i.e., their task scores) as a measure of performance. Throughout the experiment, whenever the block would hit the target, the score was increased by one. Otherwise, the score would remain unchanged. In other words, the scores show the number of successful trials for each participant.

3.4.2 Time

We measured the time of each trial, starting from the instant that the participant picked up the cube, and ending in the instant that the cube hit either the trap or the target. For each condition, we recorded 60 values for time, calculated the mean for each participant over the trials, and then calculated the mean for each group over the participants.

3.4.3 Avatar Embodiment

Participants were asked to respond to the categories of the Avatar Embodiment questionnaire on a 7-point Likert scale varying from -3 to +3 denoting "Strongly disagree", "Disagree", "Somewhat disagree", "Neither agree nor disagree", "Somewhat agree", "Agree" and "Strongly agree", respectively. The categories included Body Ownership, Agency and Motor Control, Tactile Sensation, and Location of the Body. The final embodiment score was derived by normalizing each response to $[0, 1]$, and calculating the sum of the weighted scores for each category. Since we hypothesized that haptic feedback improves task performance, the weights for Body Ownership and Location of the Body were assigned as 20, and the weights for Agency and Motor Control, and Tactile Sensation were set to 30. Subcategories of the questionnaire with the questions and the score calculation are shown in [Table 3.1](#). In this study, the External Appearance category presented in [\[41\]](#) was not a focal point, and consequently, it was excluded from the embodiment questionnaire.

3.4.4 Task Load Index

Participants were asked to respond to the NASA-TLX categories, including Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration, on a scale of 1 to 21. Then, their response was normalized to $[0, 1]$, and the final task load index was obtained by calculating the sum of the weighted scores. The weights for Mental Demand, Physical Demand, Temporal Demand, and Performance are assigned to 20, and the weights for Effort and Frustration are set to 10.

3.5 Results

Here, we present the results of the experiment as well as the participants' responses to the avatar embodiment and the task load index questionnaires in the form of box plots as well

Table 3.1: Modified version of the Avatar Embodiment questionnaire used for the mirror therapy experiment.

Category	Questions	Score
Body Ownership	Q_1 : I felt as if the virtual hand was my hand. Q_2 : I felt as if the virtual hand I saw was someone else. Q_3 : It seemed as if I might have more than one hand.	$s_1 = Q_1 - Q_2 + Q_3$
Agency and Motor Control	Q_1 : It felt like I could control the virtual hand as if it was my own hand. Q_2 : The movements of the virtual hand were caused by my movements. Q_3 : I felt as if the movements of the virtual hand were influencing my own movements. Q_4 : I felt as if the virtual hand was moving by itself.	$s_2 = Q_1 + Q_2 + Q_3 - Q_4$
Tactile Sensations	Q_1 : It seemed as if I felt the touch of the hand in the location where I saw the virtual hand touched. Q_2 : It seemed as if the touch I felt was located somewhere between my physical hand and my virtual hand. Q_3 : It seemed as if the touch I felt was caused by the cube touching the virtual hand. Q_4 : It seemed as if my hand was touching the cube.	$s_3 = Q_1 - Q_2 + Q_3 + Q_4$
Location of the Body	Q_1 : I felt as if my hand was located where I saw the virtual hand. Q_2 : I felt out of my body. Q_3 : I felt as if my real hand was drifting toward the virtual hand or as if the virtual hand was drifting toward my real hand.	$s_4 = Q_1 - Q_2 + Q_3$
Overall		$S = 20s_{1,n} + 30s_{2,n} + 30s_{3,n} + 20s_{4,n}$ $s_{i,n} = \text{normalized } s_i$

as reporting the mean (M) and the standard deviation (SD) for the mirror therapy study. Prior to analyzing the data statistically, we performed the Shapiro-Wilk test and confirmed that the data followed a normal distribution by visually inspecting the Q-Q plots of residuals. We then employed statistical tests to assess the significance of the observed differences by conducting two distinct types of comparisons: (1) within-participant comparisons in fixed groups using one-sample t-test and (2) between-participant comparisons in fixed conditions using two-sample t-test under various conditions. Furthermore, to report the effect size, we adopted robust Cohen’s distance [2].

In analyzing the *Task Performance*, we compare the results of each group individually between their Baseline and Test, as well as comparing the two groups with each other in Test. In analyzing *Avatar Embodiment* and *Task Load Index*, we compare the groups in Train to see the efficacy of the haptic information.

3.5.1 Task Performance

The performance of the participants is shown in Figure 3.5-A. Both groups performed similarly in Baseline, *without haptics* had slightly lower success rate than *with haptics* (*without haptics*: $50.00\% \pm 7.07\%$; *with haptics*: $55.92\% \pm 14.17\%$), and their score dropped in Train (*without haptics*: $33.78\% \pm 11.50\%$; *with haptics*: $36.98\% \pm 15.73\%$). Both groups performed better in Test (*without haptics*: $66.37\% \pm 5.62\%$; *with haptics*: $76.37\% \pm 6.40\%$), and significant differences were observed by comparing each group’s performance between Baseline and Test (One-sample t-test: *with haptics*: $p = .001$, Cohen’s $d = 1.41$; *without haptics*: $p < .001$, Cohen’s $d = 2.01$), and *with haptics* did significantly better than *without haptics* in Test (Two-sample t-test: $p < .001$, Cohen’s $d = 1.38$).

The duration of the task performance for each group is shown in Figure 3.5-B. Both groups performed similarly in Baseline (*with haptics*: $1.32\text{ s} \pm 0.29\text{ s}$; *without haptics*: $1.46\text{ s} \pm 0.31\text{ s}$). In Train, both groups performed slower than Baseline (*with haptics*: $1.79\text{ s} \pm 0.36\text{ s}$; *without haptics*: $1.64\text{ s} \pm 0.21\text{ s}$) but were able to recover and perform faster in Test (*with haptics*: $1.23\text{ s} \pm 0.32\text{ s}$; *without haptics*: $1.31\text{ s} \pm 0.27\text{ s}$). However, one-sample t-test showed no significant differences for each group amongst different conditions. Two-sample t-test did not show any significant difference between the two groups in Test either.

3.5.2 Avatar Embodiment

The score for Body Ownership is shown in Figure 3.6-A. Both groups responded similarly to Baseline (*without haptics*: 4.82 ± 3.87 ; *with haptics*: 5.09 ± 2.34), while their scores

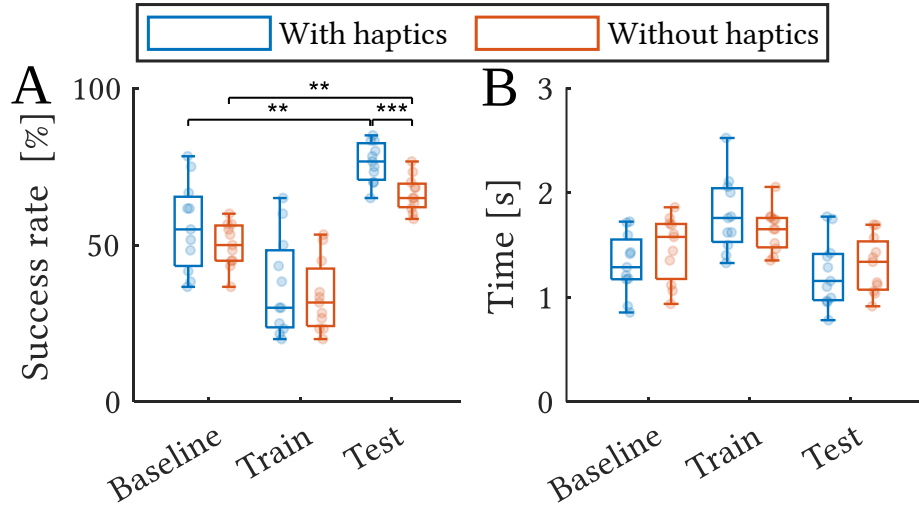


Figure 3.5: Performance of the participants in terms of (A): Success rate which is the number of successful trials reported in percentage, and (B): Task duration. Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Both groups were significantly more successful in their Test compared to their Baseline with ** $p < .05$ for *with haptics* and *** $p < .001$ for *without haptics*, respectively. *With haptics* had higher success rate than *without haptics* during Test with *** $p < .001$.

dropped in Train (*without haptics*: 2.45 ± 4.30 ; *with haptics*: 3.27 ± 2.37). In Test, *with haptics* scored slightly higher than *without haptics* (*without haptics*: 3.45 ± 2.84 ; *with haptics*: 5.00 ± 2.86). Two-sample t-test showed no significant differences between the groups in Train.

Figure 3.6-B depicts the participants' response to Agency and Motor Control. In all conditions, *with haptics* scored slightly higher than *without haptics* (In Baseline: *without haptics*: 3.45 ± 4.23 ; *with haptics*: 5.45 ± 2.88 . In Test: *without haptics*: 3.55 ± 4.03 ; *with haptics*: 5.36 ± 3.53) and in Train they scored the lowest compared to the other conditions (In Train: *without haptics*: 0.82 ± 4.47 ; *with haptics*: 4.45 ± 3.11). Two-sample t-test showed no significant differences between the groups in Train.

The score for Tactile Sensation is illustrated in Figure 3.6-C. *With haptics* scored slightly higher than *without haptics* in Baseline (*without haptics*: -2.27 ± 3.80 ; *with haptics*: 0.91 ± 3.81). Both groups reported lower scores in Train (*without haptics*: -3.82 ± 3.22 ; *with haptics*: 1.09 ± 2.91). However, in Test, the *with haptics* group reported a higher score

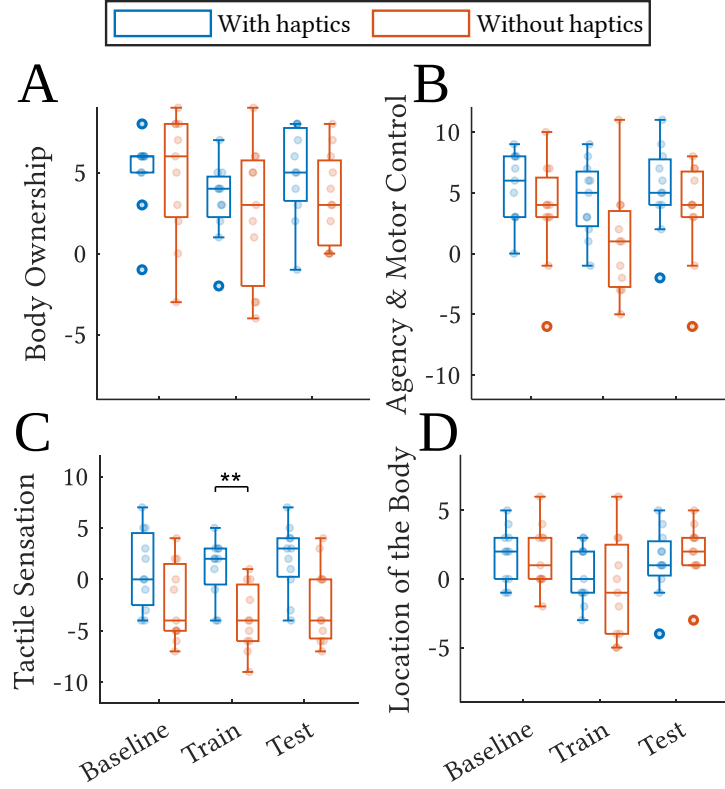


Figure 3.6: Participants' response to different categories of the embodiment perception questionnaire (A): Body Ownership, (B): Agency and Motor Control, (C): Tactile Sensation and (D): Location of the Body. The responses are presented in the form box plots showing the minimum, 25% percentiles, median, 75% percentiles, maximum of each metric and outliers for all conditions. The *with haptics* group scored significantly higher than *without haptics* in Tactile Sensation during Test (with ** $p < .01$).

than Baseline while *without haptics* reported similar to Baseline (*without haptics*: -2.27 ± 3.82 ; *with haptics*: 2.00 ± 3.32), resulting in promising differences between the two groups in the Train (Two-sample t-test: $p = .001$).

The Location of the Body score is represented in Figure 3.6-D. No specific trends were observed for each group between the conditions (In Baseline: *without haptics*: $M = 1.64 \pm 2.34$; *with haptics*: 1.73 ± 2.00 . In Train: *without haptics*: -0.73 ± 3.69 ; *with haptics*: 0.36 ± 2.11 . In Test: *without haptics*: 2.00 ± 2.10 ; *with haptics*: 1.28 ± 2.45). Two-sample t-test showed no significant differences between the groups in each condition.

The overall score of the embodiment is shown in Figure 3.7-A. Based on the figure, the *with haptics* group achieved higher scores than their counterparts in all conditions (In Baseline: *without haptics*: $54.65\% \pm 13.73\%$; *with haptics*: $65.53\% \pm 10.02\%$. In Train: *without haptics*: $48.17\% \pm 14.58\%$; *with haptics*: $60.97\% \pm 7.57\%$. In Test: *without haptics*: $57.65\% \pm 9.55\%$; *with haptics*: $66.17\% \pm 12.07\%$). Even though the score of each group in Train is the least, *with haptics*' was significantly higher than *without haptics*' in this condition (Two-sample t-test: $p = .018$, Cohen's $d = 0.95$).

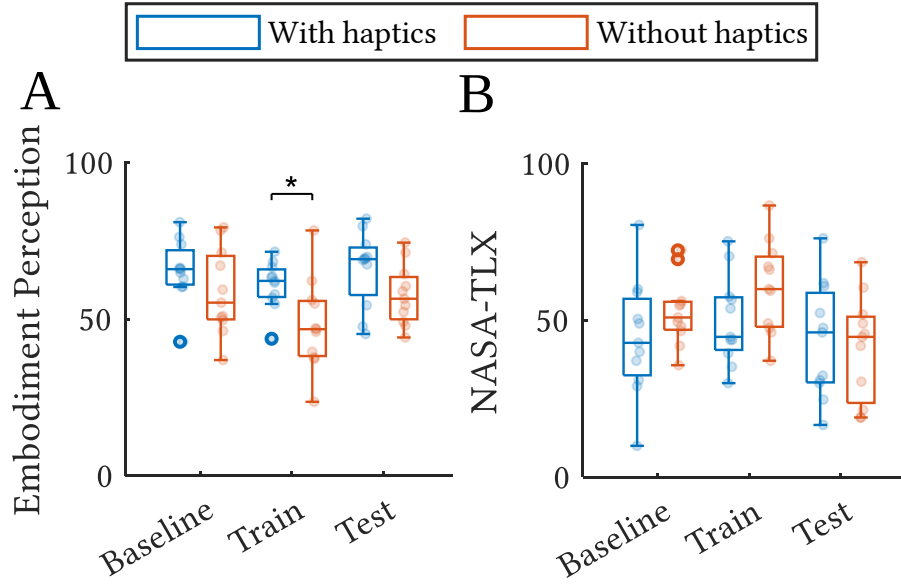


Figure 3.7: Participants' overall score in (A): Embodiment Perception, (B): Task Load Index. The scores are presented in the form box plots showing the minimum, 25% percentiles, median, 75% percentiles, maximum of each metric and outliers for all conditions. The *with haptics* group scored higher in overall embodiment perception than the *without haptics* group during Test (with * $p < .05$).

3.5.3 Task Load Index

The result of the overall NASA-TLX score for the two groups is shown in Figure 3.7-B. In Baseline and Train, the *without haptics* group scored slightly higher than *with haptics* (In Baseline: *without haptics*: 52.81 ± 10.81 ; *with haptics*: 44.46 ± 18.69 . In Train, *without haptics*: 60.65 ± 14.75 ; *with haptics*: 50.09 ± 14.16). Both groups performed similarly in

Test (*without haptics*: 41.13 ± 16.79 ; *with haptics*: 43.64 ± 18.30), and two-sample t-test showed no significant differences between the two groups in Train.

In addition to the overall task load index, the category-wise scores are shown in [Figure 3.8](#). Significant differences between the two groups were observed for the Physical Demand and Temporal Demand categories during the Train condition. The participants in the *with haptics* group reported significantly lower Physical Demand compared to their counterparts (two-sample t-test: $p = .008$). They also found the task to be less temporally demanding than the *without haptics* group (two-sample: $p = .029$). Two-sample t-test showed no significant differences were found between the two groups during the Train condition in other categories.

3.6 Discussion

In this section, we discuss the interpretation of our results from the mirror therapy experiment in terms of [Task Performance](#), [Avatar Embodiment](#), and [Task Load Index](#). Furthermore, we discuss additional insights and acknowledge the limitations of our work.

During Baseline, the two groups exhibited similar task scores ([Figure 3.5-A](#)). The subsequent decline in observed scores for both groups in Train (by 32.43% in *with haptics* and 33.86% in *without haptics*) can be attributed to the fact that the Train condition involved mirroring the scene and participants had to perform the task with their dominant hand while seeing their virtual non-dominant hand in motion. In other words, the misalignment of visual feedback is a plausible explanation for the drop in scores.

The divergent performance observed in Test stands out as a significant aspect of the results. In line with the previous investigations on the potential of the mirror neurons' effect on motor learning [[10](#), [122](#)], in Test, it was expected that both groups would score higher than their previous conditions. However, the *with haptics* group exhibited a substantial improvement from Train and significantly outperformed the *without haptics* group by 15.07%. The *with haptics* also performed the task in the Test condition slightly faster than the *without haptics* group ([Figure 3.5-B](#)). This demonstrates that the improved performance in the *with haptics* group was not attained by sacrificing fast movements, which is known as speed-accuracy trade-off [[30](#)]. The integration of haptic feedback could have affected the motor performance in multiple ways. It might have enabled the *with haptics* group to refine their skills more effectively, resulting in improved scores; the tactile cues might have provided an additional feedback loop for participants to fine-tune their actions, leading to the observed superior performance in Test. The difference observed in

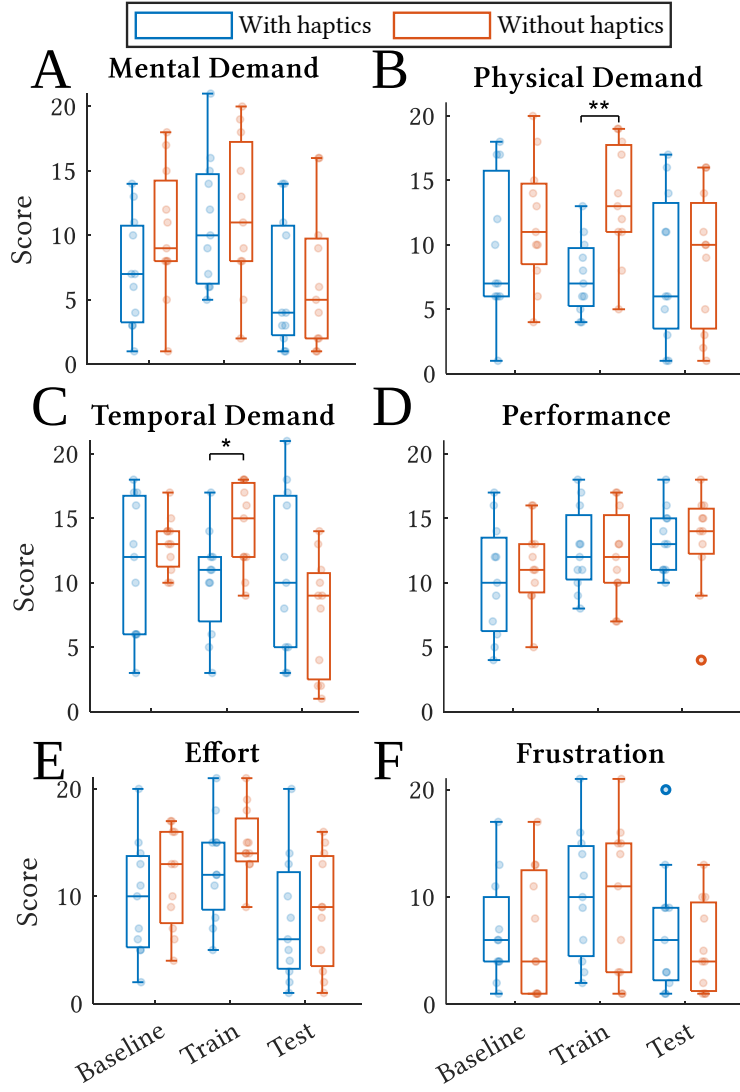


Figure 3.8: Participants' responses to the task load index questionnaire in the categories of (A): Mental Demand, (B) Physical Demand, (C): Temporal Demand, (D): Performance, (E): Effort, and (F) Frustration. The responses are presented in the form of box plots showing the minimum, 25% percentiles, median, 75% percentiles, maximum of each metric and outliers for all conditions. The *with haptics* group responded significantly lower than *without haptics* in Physical Demand (with ** $p < .01$), and Temporal Demand (with * $p < .05$) during Train.

the task accuracy (Figure 3.5-A) between the two groups in the Test condition may also be attributed to differences in cognitive load; haptic feedback could have alleviated cognitive strain by offering direct tactile cues [134]. This reduced cognitive load [150] might have empowered the *with haptics* group to make decisions more swiftly and accurately, contributing to their performance advantage. Furthermore, the observed improvements in task performance is not due to participants adapting to the technology. This is supported by the experimental design, which included a 5-minute familiarization phase and 60 trials of baseline to ensure that participants were well-accustomed to the VR setup before the actual testing began. This setup was intentionally structured to minimize any novelty effects or adaptation to the technology, which could otherwise skew the results.

In terms of Avatar Embodiment, even though the analysis of Body Ownership scores (Figure 3.6-A) did not show any statistically significant differences between the two groups, the *with haptics* group scored slightly higher as compared to the *without haptics* group in Test. This may indicate that tactile feedback did not affect the Body Ownership perception substantially.

For the agency and motor control category (Figure 3.6-B), the *with haptics* group exhibited marginally higher scores than the *without haptics* group even though this difference did not register as statistically significant. This pattern could suggest a trend toward increased agency and motor control perception in the presence of haptic cues. Nonetheless, the absence of a pronounced effect warrants further investigation into the interplay of haptic cues and participants' sense of control over their avatars. Similarly, no significant changes were observed in the Location of the Body (Figure 3.6-D) across conditions and groups.

Out of all categories in Avatar Embodiment, haptic feedback was observed to create the most pronounced impact in the Tactile Sensation category (Figure 3.6-C). The *with haptics* group reported significantly higher scores than the *without haptics* group during the Train condition. This finding highlights the influence of haptic feedback on participants' perception of tactile interactions with their avatars, increasing their awareness of and connection to the virtual experience. Moreover, this result is in line with [57], where an experiment with amputees showed that vibrotactile feedback combined with conventional MT was shown to strengthen awareness of phantom limbs; we thus suggest that pressure feedback may also be effective in terms of improving the learning effects of VR-based MT.

The overall embodiment analysis shows that the *with haptics* group reported increased overall embodiment perception during the Train phase (Figure 3.7-A), and demonstrated markedly improved task performance in the subsequent Test condition (Figure 3.5-A). This suggests that the amplified sense of embodiment experienced during training may

have influenced and positively impacted task execution during the test phase. This agrees with a study on rubber hand illusion by [96] that reported the improvement in single-handed task performance with an enhanced embodiment, as well as a study by Iwasaki et al. [59] that reported similarly on dual-handed task performance. Our study suggests similarly in VR-based MT, that the improvement in embodiment during the Train phase, when the non-dominant arm is inactive, may contribute to the enhanced task performance in the Test phase.

The overall task load index (Figure 3.7-B) shows that *without haptics* found Train slightly more difficult than *with haptics*. Further details of it can be seen in category-wise comparison (Figure 3.8) where the participants answered the questionnaire on a scale of 1 to 21. Both groups found Train slightly more mentally demanding than the other conditions. The Performance category shows that both groups thought they performed slightly better in Test compared to the previous conditions. Interestingly, they thought they were performing slightly better in Train than Baseline, while this is not in line with Figure 3.5-A. Furthermore, *without haptics* exerted slightly more effort in all conditions than their counterpart. No major trend was observed in Frustration, except that both groups scored slightly higher in Train than other conditions. This outcome implies that the absence of haptic cues might lead to a heightened perceived workload in the task.

Considering the overall task load index (Figure 3.7-B), both groups exhibited similar scores, albeit with a slight elevation in the group without haptics. This result indicates that while haptic feedback influenced workload perceptions within specific dimensions, the cumulative effect on overall workload perception was relatively marginal. The implications of this study are relevant for designing virtual environments to optimize user experiences and task performance. Incorporating haptic feedback could be particularly beneficial for tasks involving physical and temporal demands, as it appears to alleviate perceived workload during training. However, the subtle effect on the overall workload score suggests that designers should consider a holistic approach that considers various dimensions of workload perception.

Chapter 4

The Impact of Vibrotactile Feedback on Task Performance and Embodiment in a Motor Task

While [chapter 3](#) focused on the application of pressure feedback in mirror therapy, this chapter explores a different aspect of motor learning through the ball and beam study. This shift in focus is motivated by the need to understand the impact of embodiment and sensory feedback in a broader range of motor tasks. The ball and beam study offers an opportunity to investigate bimanual coordination and the role of embodiment in tasks that require precise control and balance. Unlike mirror therapy, this study involves bimanual interactions, providing insights into how the sense of embodiment influences coordination between both hands.

In this chapter, the main objective is to explore the relationship between the sense of embodiment and the motor learning in a bimanual task. For this purpose, we designed a ball-and-beam control task, where participants were required to balance a virtual ball on a beam by controlling its rotation. Nineteen able-bodied participants were subjected to four experimental conditions in random order: No feedback, Vibrotactile feedback only, Visual feedback only, and both Vibrotactile and Visual feedback. In the study design, we considered that the visual feedback would modify the sense of embodiment, indirectly influencing motor learning. In contrast, the haptic feedback not only alters the embodiment but also provides information directly relevant to the motor task, thereby holding a direct relationship with motor learning. The study measured task performance through kinematic data, muscle activity via electromyography, and subjective responses through embodiment and task load questionnaires.

The results indicated that the presence of vibrotactile feedback, especially when combined with visual feedback, enhanced participants' task performance and sense of embodiment. The findings suggest that multimodal sensory feedback can improve motor control and perceptual integration in VR-based tasks. This research contributes to the understanding of how different sensory feedback modalities can be leveraged to enhance motor learning and embodiment in VR, with potential implications for the design of VR systems for rehabilitation and training purposes.

4.1 Task Environment

For this study, we designed a VR-based ball-and-beam control task. The virtual environment consisted of a beam balanced on a pivot, normal to the frontal plane and located at the centre of the virtual room. Participants were required to hold two controllers with their fingertips (see [Figure 4.1-A](#)), which represented the virtual beam. Ideally, to make the design more realistic, and to minimize the lateral movement of the arms, we thought about connecting the controllers with a rod. However, the vibrotactile feedback rendered from each controller appeared to affect the other controller and in turn, be disruptive throughout piloting. A virtual ball with a radius of 2 cm was placed on the centre of the beam, and the task was to control the rotation of the beam such that the ball would remain on a specified target area, which was a $3 \times 3 \text{ cm}^2$ white square (see [Figure 4.1-B](#)).

On the background of the environment, a grey wall was placed as the instruction panel, on which the state of the experiment was shown, as well as a coloured circle point. The experiment state could be either "Go", "Stop", or "Ready". The experiment would start with a 10-second countdown and the state of the experiment would turn into "Go" and the circle on top of the script would turn into green. In this phase, the target would start moving on a predefined trajectory of $p = A \sin(\omega t)$ (where $A = 0.4m$ is the amplitude and $\omega = 0.2\pi$ is the angular velocity) along the beam, and participants had to control the rotation of the beam to control the position of the ball. After 10 seconds, the experiment state would turn into "Stop" and the state circle would turn red when the participants had to put their hands on their laps and rest for 7 seconds. After the rest time, the experiment state would turn into "Ready", and the state circle would turn yellow. In this state, the participants had to lift their hands, make the beam horizontal and prepare themselves for the next trial. In this state, a horizontal white transparent beam would appear so that the participants could adjust the beam with reference (see [Figure 4.2](#)). This cycle was repeated 50 times for each condition.

The task was performed in the virtual reality environment designed in the Unity 3D

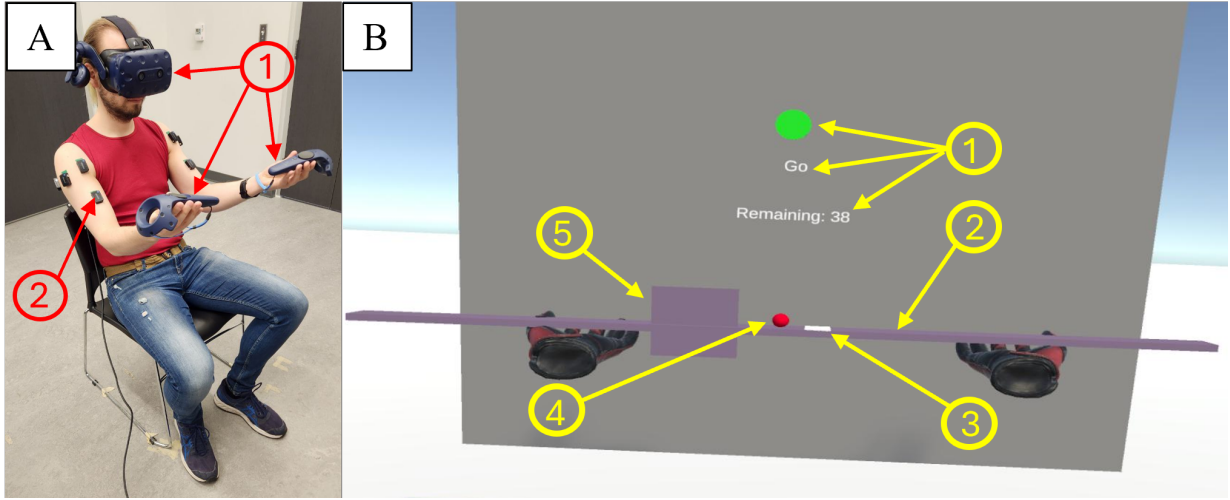


Figure 4.1: (A) Apparatus of the ball and beam experiment including (1): Vive pro HMD and controllers (HTC Corp., Taiwan), and (2) Trigno electromyography sensors (Delsys, UK). (B) Components of the virtual environment in the ball and beam experiment including (1) Instruction panel, showing the experiment state and the remaining trials, (2) Beam, (3) Target, (4) Ball, and (5) Occluder. Participants were instructed to control the rotation of the beam such that the ball would remain on the target. Each trial would last 10 seconds unless the ball would fall out of the beam.

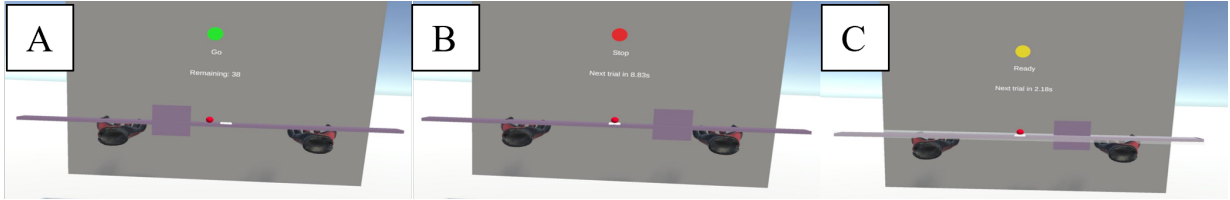


Figure 4.2: States of the ball and beam experiment including (A) Go, where the target would start moving on the beam, and the participants had to control the rotation of the beam to control the position of the ball such that it would follow the target for 10 seconds. (B) Stop, where the participants had to put their hands on their laps and rest their muscles for 7 seconds. (C) Ready, where the participants had to lift their hands, make the beam horizontal, and prepare themselves for the next trial in 3 seconds. In this state, a horizontal white transparent beam would appear as a reference. This cycle was repeated 50 times for each condition of the experiment.

game engine (Unity Technologies, Inc., United States), interfaced using a Vive Pro head-mounted display (HMD) (HTC Corp., Taiwan). Participants sat on a chair during the experiment (see [Figure 4.1-A](#)). Muscle activity was recorded using electromyography (EMG) sensors (Trigno, Delsys, US) at 1,926 Hz (synchronized with Unity). EMG sensors were attached to the biceps brachii, triceps brachii and anterior, middle, and posterior deltoid of each arm. To enhance the quality of the EMG signals, the EMG electrode sites were shaved and cleaned with alcohol swabs prior to attachment.

4.2 Participants

The ball and beam study included an experiment with details described in [Experimental Procedure](#). Typical studies in this field often involve between 10 and 20 participants, which guided our recruitment of 19 able-bodied participants (8/11 females/males, age: 25 ± 3 years). This was further supported by a power analysis. Anticipating a medium effect size (Cohen's $d = 0.5$), with a power of 0.8 and a significance level of 0.05, and assuming a standard deviation of the measurements as 0.8, the power analysis suggested that a minimum of 19 participants would be required. All participants provided their informed written consent to participate in the study before the experiment. The study protocols and procedures were approved by the Research Ethics Boards of the University of Waterloo (ORE # 45062).

4.3 Experimental Procedure

[Figure 4.3](#) demonstrates the experimental procedure. The experiment was performed in a single in-lab session for each participant. After consenting to participate and providing demographic information, participants were informed about the virtual environment and their tasks in the experiment. Then, they were asked to wear the HMD and adjust it based on their head size. After the HMD adjustment, the experimenter assisted them in holding the VR controllers. The participants were then given two trials of each condition to become familiar with the environment. Then, the experimenter reminded them of their tasks and started the experiment. The conditions were exposed to the participants in random order. Unlike the previous study, the selection of within-participant over the between-participant guarantees consistency across conditions for the same individuals, and facilitates a direct comparison of the impact of different feedback modalities on the same individual. After

every condition was finished, the participants were asked to remove the HMD and respond to the Avatar Embodiment and NASA-TLX questionnaires.

The experiment consisted of four main conditions:

- **No feedback (NHV):** Participants only observe the experimental components with neither the virtual representation of the hands nor the haptic sensation (Figure 4.4-A).
- **Haptics only (H):** Participants do not observe the virtual hands but feel the vibration from the controllers (Figure 4.4-A).
- **Visual only (V):** Participants observe virtual hands and do not feel haptic feedback (Figure 4.4-B).
- **Haptics and visual (HV):** Participants observe the virtual hands and feel the haptic feedback (Figure 4.4-B).

For the conditions that contained haptic feedback, vibration was rendered on both VR controllers with the frequency of 50Hz and a logarithmic amplitude representing the ball's position on the beam for tactile funnelling:

$$A_L = 0.2 \log(d_R + 1) \quad (4.1)$$

$$A_R = 0.2 \log(d_L + 1) \quad (4.2)$$

where A_L and A_R are the amplitude of the vibration rendered on the left and right controller, and d_R and d_L are the distance between the ball and the right and left hands, respectively [103]. Similarly, the amplitude of the vibrotactile feedback was fine-tuned through piloting. The selection of a 50 Hz frequency in the VR controllers was informed by preliminary piloting. During the pilot tests, participants expressed a preference for lower frequencies for the feedback, as these frequencies were found to be more indicative of the slow motion of the ball on the beam. This choice was further supported by the fact that such a frequency is within the range that effectively stimulates mechanoreceptors in fingertips, particularly the Meissner corpuscles[109] and Pacinian corpuscle [8].

Each condition consisted of 50 trials of 10 seconds each. Participants were given 7 seconds of rest after each trial to minimize the impact of fatigue and 3 seconds to prepare for the next trial. Once each condition was completed, they were asked to remove the HMD and respond to the embodiment and NASA-TLX questionnaires.

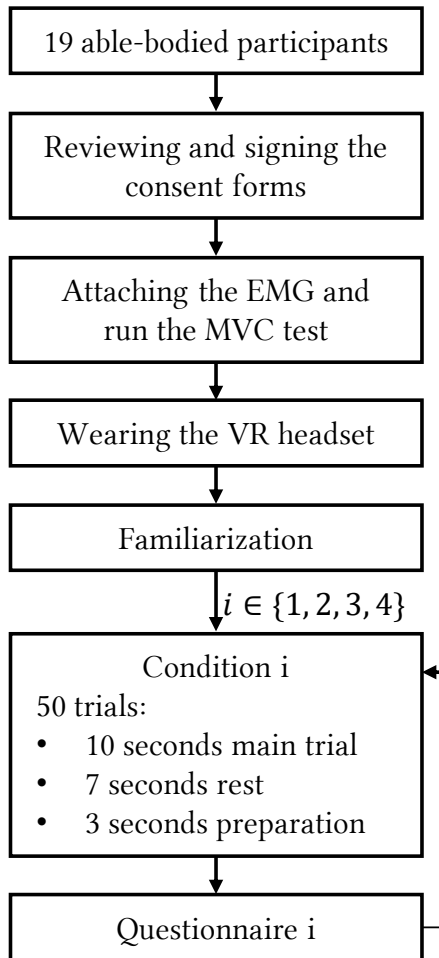


Figure 4.3: A flowchart depicting the ball and beam experimental procedure.

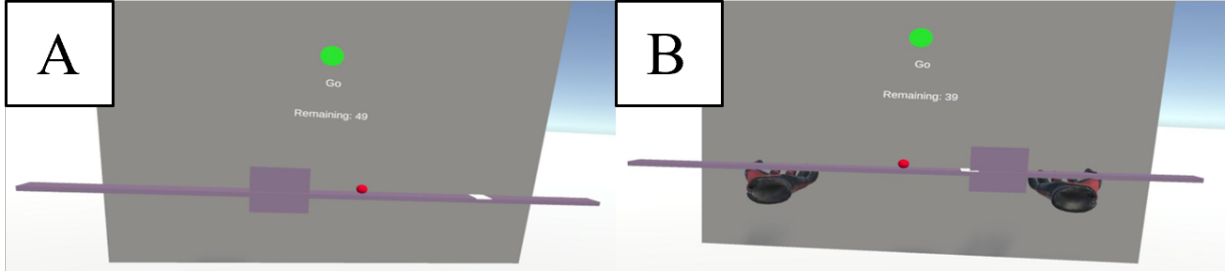


Figure 4.4: Participants observation in the Go state of the ball and beam experiment in (A) No feedback and the Haptic only conditions (B) Visual only and both haptics and visual conditions.

4.4 Measures

In this study, we include four sets of measures that are described as follows:

4.4.1 Kinematic measures

Kinematic data, including the trajectory of the ball, target and controllers were recorded with the HTC Vive pro setup. Then, for each trial, we calculated the following kinematic metrics:

1. Maximum absolute trajectory error: The maximum absolute value of the difference between the trajectory of the target and the trajectory of the ball, similar to [88].
2. Cross-correlation: To quantify the similarity between the target trajectory and the ball trajectory, we employed Pearson cross-correlation coefficient fixed at zero-lag.
3. Zero crossing: The number of times the ball passes the target per trial as a measure of smoothness, reported as the average over the first and the last ten trials.
4. Early and late slopes of the learning curve (maximum absolute error), calculated by averaging the slope of the early and late 10 trials of conditions, which is derived as:

$$S^k = \frac{E^{k+1} - E^k}{(k+1) - (k)}, \quad (4.3)$$

where S^k and E^k are the slope and the maximum absolute error of the trial k .

4.4.2 EMG measures

EMG signals were band-passed filtered (4th order Butterworth, cut-off frequencies of 10 and 500 Hz). Then, each signal was full-wave rectified and smoothed by calculating the root-mean-square of the signal (window length = 50 ms) and normalized by maximum voluntary contraction (MVC) [68]. Preprocessed EMG data were then segmented based on the start/end of each trial. Two metrics were computed for EMG data of each segment:

1. Mean muscle activity: The mean value of the normalized EMG data was calculated for each muscle for each trial [68].
2. Co-contraction of muscles: Coactivation between a pair of muscles (Biceps-Triceps, and Posterior deltoid-Anterior deltoid) was calculated for each trial [94]:

$$C_{ij}^k = \frac{\int_{t_{start}^k}^{t_{end}^k} e_i(t)e_j(t)dt}{t_{end}^k - t_{start}^k} \quad (4.4)$$

We included this metric of to ensure that participants were not stiffening their joints as a strategy to perform the task, which could mask true skill acquisition or adaptation.

4.4.3 Avatar Embodiment

Participants were asked to respond to the categories of the Avatar Embodiment questionnaire on a 7-point Likert scale varying from -3 to +3 denoting "Strongly disagree", "Disagree", "Somewhat disagree", "Neither agree nor disagree", "Somewhat agree", "Agree" and "Strongly agree", respectively. The categories included Body Ownership, Agency and Motor Control, and Tactile Sensation. The final embodiment score was derived by averaging the response of each category, and then calculating the sum of the weighted scores for each category. The weights for all conditions were assigned as 1. Subcategories of the questionnaire with the questions and the score calculation are shown in Table 4.1. In this study, the categories Location of the Body and External Appearance presented in [41] were not a focal point and consequently were excluded from the embodiment questionnaire.

4.4.4 Task Load Index

Similar to the previous study (chapter 3), participants were asked to respond to NASA-TLX categories, including Mental Demand, Physical Demand, Temporal Demand, Performance,

Effort, and Frustration, on a scale of 1 to 21. Then, their response was normalized to $[0, 1]$, and the final task load index was obtained by calculating the sum of the weighted scores. The weights for Mental Demand, Physical Demand, Temporal Demand, and Performance are assigned to 20, and the weights for Effort and Frustration are set to 10.

4.4.5 Embodiment perception and motor learning relationship

For further analyzing the effect of the sense of embodiment on motor learning, we assumed the no-feedback condition as the reference and decided to see the difference between the embodiment score and the kinematic data with the difference. For the motor learning metric, we took the maximum absolute error of the test (last 10 trials) of each condition, normalized it with the baseline (first 10 trials) of the same condition and subtracted them from the same value obtained from the no-feedback condition. We call this ΔError , which is be obtained as:

$$\Delta\text{Error}_i = \frac{\text{Error}_{i,\text{Test}}}{\text{Error}_{i,\text{Baseline}}} - \frac{\text{Error}_{NHV,\text{Test}}}{\text{Error}_{NHV,\text{Baseline}}}, \quad (4.5)$$

where Error_i is the maximum absolute error of the condition i , Baseline is the first ten trials, and Test is the last 10 trials of that condition.

For the embodiment metric, we computed the difference between the embodiment score of each condition with the NHV condition:

$$\Delta\text{Embodiment}_i = \text{Embodiment}_i - \text{Embodiment}_{NHV}. \quad (4.6)$$

We assumed a linear model for the relationship between the embodiment perception and motor learning. To fit lines, we employed robust least squares regression with manual weighting. The weights for the potential outliers were assigned as 0.2, and for the rest of the datapoints were assigned as 1.

To identify statistical difference between the slope of the lines, we employed ANCOVA test with a significance level of 0.05 to test group-level differences. Following the ANCOVA test, we conducted pairwise comparisons, between the lines, using T-test. To account for multiple comparisons between the three lines, we applied the Bonferroni correction.

4.5 Results

Here, we present the results of the experiment as well as the participants' responses to the avatar embodiment and the task load index questionnaires in the form of box plots,

Table 4.1: Modified version of the Avatar Embodiment questionnaire used in the ball and beam experiment.

Category	Questions	Score
Body Ownership	Q_1 : I felt as if the virtual hand was my hand.	$s_1 = Q_1 - Q_2 + Q_3$
	Q_2 : I felt as if the virtual hand I saw was someone else.	$s_1 = s_1/3$
	Q_3 : It seemed as if I might have more than one hand.	
Agency and Motor Control	Q_1 : It felt like I could control the virtual movement of the ball on the beam as if I was manipulating it with my own hands.	$s_2 = Q_1 + Q_2 + Q_3 - Q_4$
	Q_2 : The movements of the ball along the beam were directly influenced by my movements.	$s_2 = s_2/4$
	Q_3 : I felt as if the movements of the ball along the beam influenced the movement of my hands.	
	Q_4 : I felt as if the ball was moving along the beam independent of my movements.	
Tactile Sensations	Q_1 : It seemed as if I could feel the position or movement of the ball on the beam in my hands, corresponding to where I saw it on the beam.	$s_3 = Q_1 - Q_2 + Q_3$
	Q_2 : It seemed as if the sensation of the ball's movement on the beam was felt somewhere between my physical hands and the position of the ball on the virtual beam.	$s_3 = s_3/3$
	Q_3 : It seemed as if the tactile sensations I felt were caused by the ball's movements along the virtual beam.	
Overall		$S = (s_1 + s_2 + s_3)/3$

as well as reporting the mean (M) and the standard deviation (SD) for the ball and beam study. Before statistical analysis of the data, we performed the Shapiro-Wilk test and confirmed that the data followed a normal distribution by visually inspecting the Q-Q plots of residuals. We then employed statistical tests to assess the significance of observed differences by conducting within-participant comparisons in fixed population using one-sample T-test. Furthermore, to report the effect size, we adopted robust Cohen’s d model [2].

4.5.1 Kinematic data

The maximum absolute error between the ball and target positions in the trials is shown in Figure 4.5, and the comparison between the baseline (first 10 trials) and the test (last 10 trials) of each condition is represented in Figure 4.6. According to this figure, all conditions are observed to have a downward trend (Average of the test trials of NHV: 0.90 ± 0.05 ; H: 0.86 ± 0.054 ; V: 0.89 ± 0.05 ; HV: 0.85 ± 0.03). Comparison between the baseline and test with a fixed condition showed significant differences in Haptic only, Visual only, and Haptic and visual feedback conditions (One sample T test: $p_H < .001$, Cohen’s $d = 1.41$; $p_V = .038$, Cohen’s $d = 0.82$; $p_{HV} = .0014$, Cohen’s $d = 2.32$). Comparison between the test trials of different conditions did not show any significant differences.

The cross-correlation coefficient between the ball and the target position in the baseline and test trials of each condition is shown in Figure 4.7. Across conditions, trajectories between the ball and the target showed consistency from baseline to test trials, except the haptic-only condition, which exhibited a statistically significant difference ($H_{Baseline}$: 0.83 ± 0.16 ; H_{Test} : 0.90 ± 0.09 ; One sample T-test: $p_H = .024$, Cohen’s $d = 0.38$).

The number of zero crossings is shown in Figure 4.8. It can be seen that overall, participants were more likely to control the beam such that the ball would pass the target more frequently during the test trials compared to the baseline trials in all conditions except the haptic-only condition. However, one sample T-test did not show any significant differences between the baseline and the test in fixed conditions. The overall zero crossings of each condition can be seen in Figure 4.9. One-sample T-test did not show any significant differences between different conditions.

The average slope of the maximum absolute error between the baseline (first 10 trials) and the test (last 10 trials) of different conditions with the order of exposure to the participants is shown in Figure 4.10. The average slope was significantly lower in the baseline of the first condition compared to the test of the same condition (One-sample T-test: $p = .004$, Cohen’s $d = 1.27$).

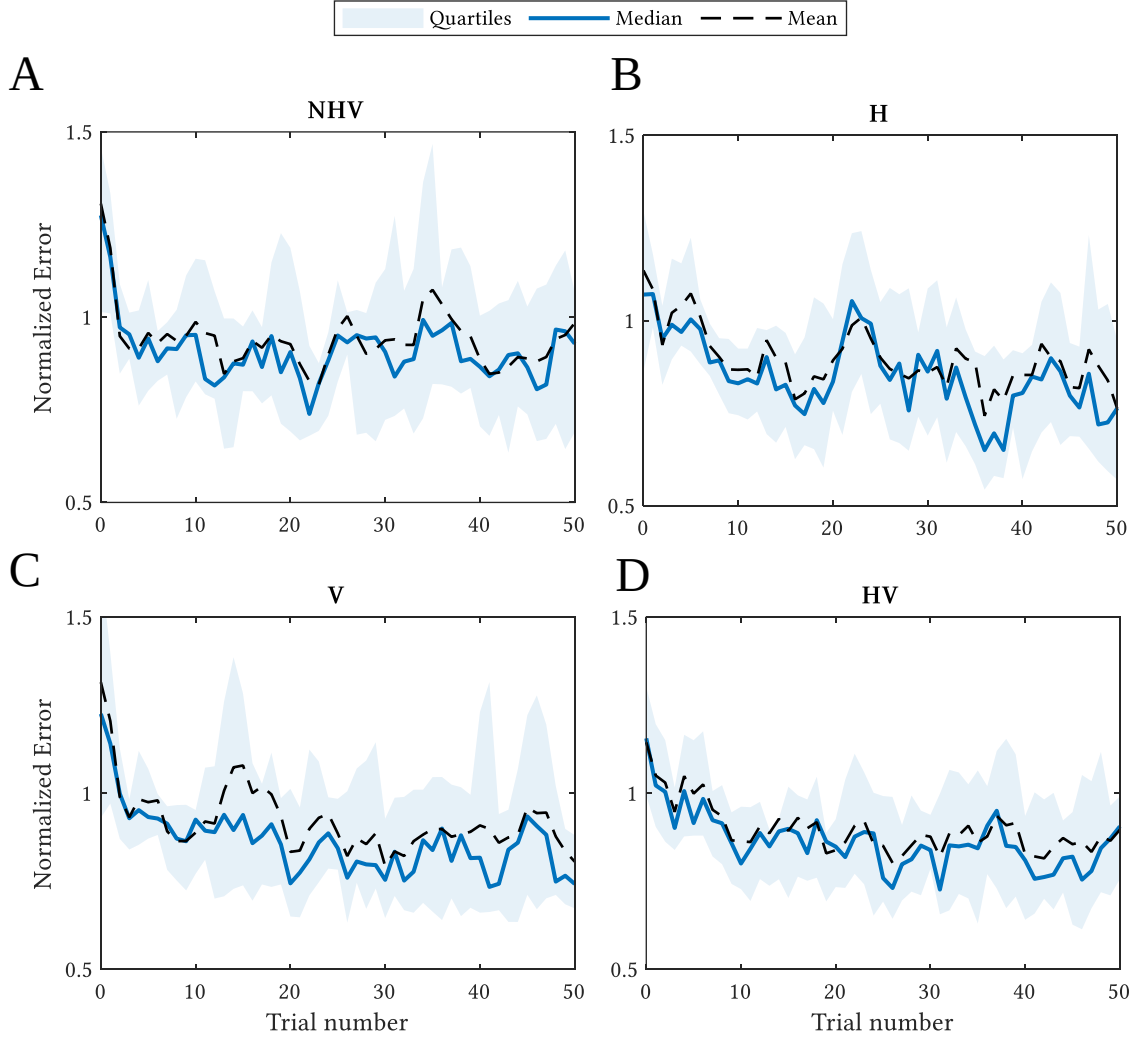


Figure 4.5: Maximum absolute error between the position of the ball and the target over the trials in different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only. HV: haptic and visual feedback).

4.5.2 EMG data

The mean muscle activity of the dominant and the non-dominant hand for each condition is shown in [Figure 4.11](#). Based on the figure, participants activated their non-dominant hand's muscle more than their dominant hand in almost all the measured muscles across all

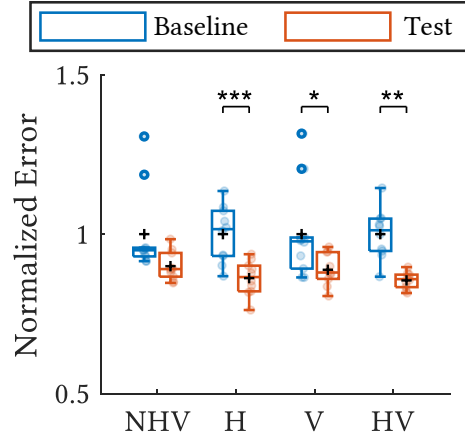


Figure 4.6: The maximum absolute error between the baseline (first 10 trials) and the test (last 10 trials) of different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only. HV: haptic and visual feedback). The values are normalized with the baseline of every condition. Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric. Significant differences were observed between the baseline and the test trials of H, V and HV (with * $p < .05$, ** $p < .01$ and *** $p < 0.001$).

conditions. However, this activation became significant in the anterior deltoid in the visual only and the haptic and visual conditions (One-sample T-test: $p_V = .046$; $p_{HV} = .045$).

The mean muscle activity of the dominant hand for the baseline (first 10 trials) and the test (last 10 trials) of each condition is shown in Figure 4.12. Based on the figure, participants' muscle activations were similar between the first and last trials of each condition, and the Friedman test did not show any significant difference between the baseline and test trials of any conditions. Among the measured activations, the anterior deltoid and the posterior deltoid had the highest and lowest activations under all conditions (average in all conditions: Anterior deltoid: $19.92\% \pm 8.13\%$; Posterior deltoid: $11.53\% \pm 6.29\%$).

The co-contraction of different muscle pairs of the dominant and the non-dominant hand across different conditions are shown in Figure 4.13-A to Figure 4.13-D. Based on the figures, co-contraction of anterior-posterior deltoid of the dominant hand (Figure 4.13-C) is observed to be the lowest (with an average of less than 3% for all conditions), and the co-contraction of the same pair in the non-dominant hand is observed to be the highest (with the average of approximately 4%). One-sample T-test did not show any significant differences across different conditions for fixed agonist-antagonist muscle pairs.

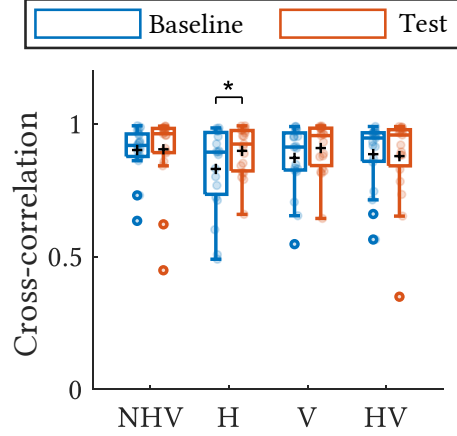


Figure 4.7: Cross-correlation factor between the target and the ball trajectory in baseline (first 10 trials) and the test (last 10 trials) of different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only, HV: haptic and visual feedback). Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric. Baseline and test trials of the H condition were found to be significantly different from each other (with * $p < .05$).

4.5.3 Embodiment perception and task load index

To identify the statistical differences in the subjective questionnaires, we initially employed a Friedman test with a significance level of 0.05 to test condition-level differences. Following the Friedman test, we conducted pairwise comparisons, between the conditions, using the one-sample T-test. To account for multiple comparisons between the HV, we applied the Bonferroni correction.

The overall score of the embodiment is shown in Figure 4.14-A. Based on the figure, the participants scored a higher sense of embodiment in both haptic and visual feedback compared to single feedback and the no-feedback conditions (NHV: ± 0.30 ; H: 0.33 ± 0.47 ; V: 0.08 ± 0.56 ; HV: 0.63 ± 0.43). Significant differences in haptic and visual feedback were observed compared to the other conditions (Friedman: $p < .001$, One-sample T-test: $p_{NHV,HV} < .0003$, Cohen's $d = 1.16$; $p_{H,HV} = .003$, Cohen's $d = 0.50$; $p_{V,HV} = .0004$, Cohen's $d = 1.22$).

The overall task load index is shown in Figure 4.14-B. Participants responded similarly to the NASA-TLX questionnaire under different conditions (NHV: $42.71\% \pm 11.06\%$; H:

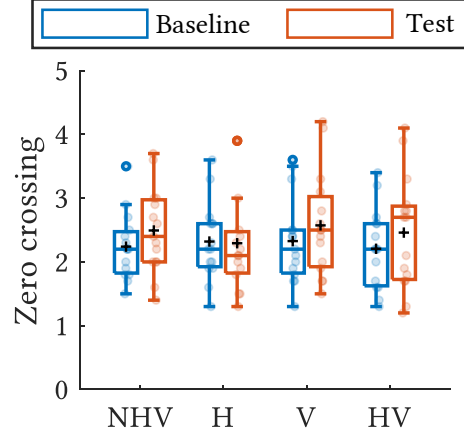


Figure 4.8: Zero crossing between the target and the ball trajectory in baseline (first 10 trials) and the test (last 10 trials) of different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only. HV: haptic and visual feedback). Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric.

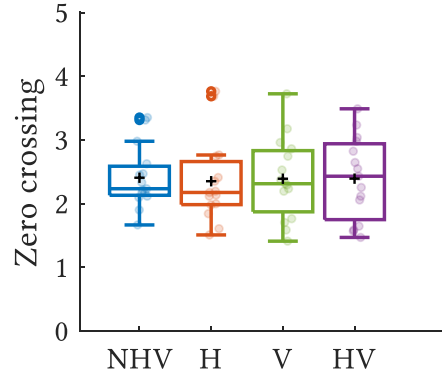


Figure 4.9: The overall zero crossing between the target and the ball trajectory of different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only. HV: haptic and visual feedback). Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric.

44.20% $\pm$ 9.73%; V: 40.51% $\pm$ 9.04%; HV: 43.15% $\pm$ 10.42%), and Friedman did not show any significance in the difference in the overall task-load index between the conditions.

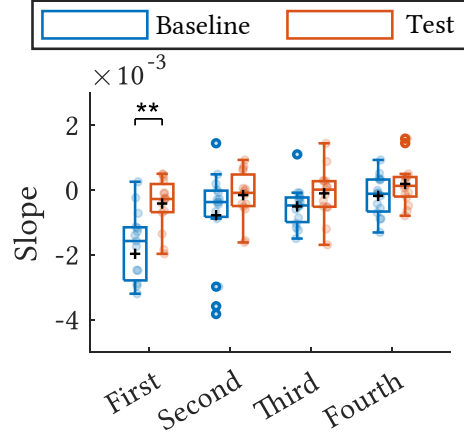


Figure 4.10: The average slope of the maximum absolute error amongst baseline (first 10 trials) and test (last 10 trials) across different conditions. The conditions are sorted with the order of exposure to each participant. Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric. Comparison in the average slope of the baseline and the test of the first condition showed a significant difference (with ** $p < .01$).

4.5.4 Embodiment perception and motor learning

Figure 4.15-A shows data for each participant as well as the fitted lines. The fitted lines parameters are shown in Table 4.2. The comparison between each linear model and the constant model showed significant differences for the Visual only and the Haptic and Visual conditions (F-test, $p_V = .017$; $p_{HV} = .025$). The comparison between the lines showed significant differences between the Haptic only and the Visual only conditions, as well as the Haptic only and the both Visual and Haptic groups (ANCOVA: $p = .012$; T-test: $p_{H,V} = .012$, $p_{H,HV} = .011$).

Figure 4.15-B shows the centroid of each condition, which are obtained by averaging the x and y values of the datapoints from Figure 4.15-A. The centroids coordinates are as follows:

$$C_H = (0.29, -0.06) \quad (4.7)$$

$$C_V = (-0.01, -0.11) \quad (4.8)$$

$$C_{HV} = (0.58, -0.05), \quad (4.9)$$

where $C_i = (x_i, y_i)$ is the centroid of the condition i , x_i and y_i are the Δ Embodiment and the Δ Error for condition i (with respect to the NHV condition), respectively.

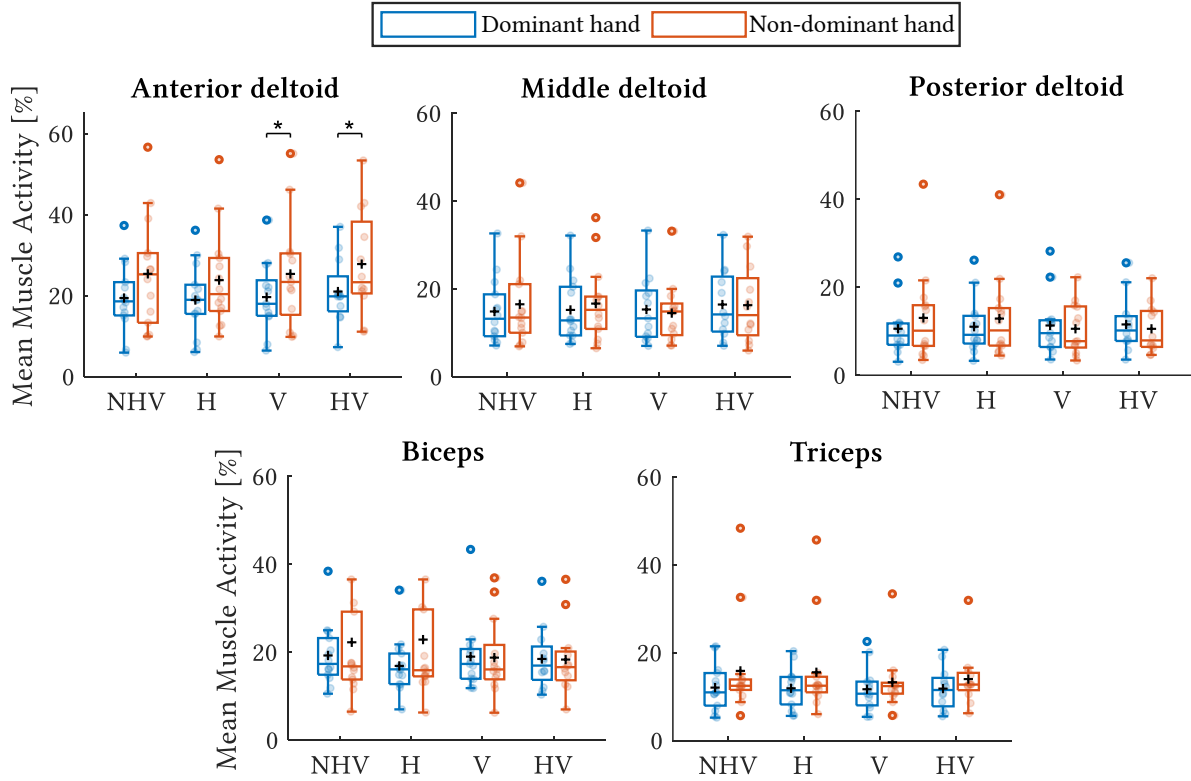


Figure 4.11: The mean muscle activity of the dominant and the non-dominant hand for different muscles across different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only, HV: haptic and visual feedback). Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric. Comparison of the mean activity of the anterior deltoid in V and HV conditions showed significant differences between the dominant and the nondominant hand (with $* p < .05$).

4.6 Discussion

Figure 4.5 and Figure 4.6 present the effect of haptic, visual and combined feedback on the maximum absolute error in performing the task. Initially, we observed in the NHV condition that participants demonstrated a high degree of variability in performance, with no significant reduction in errors over the course of 50 trials (Figure 4.5). This was supported by the lack of improvement between the baseline and test trials shown in Figure 4.6, suggesting that in the absence of feedback, participants were unable to self-correct or improve

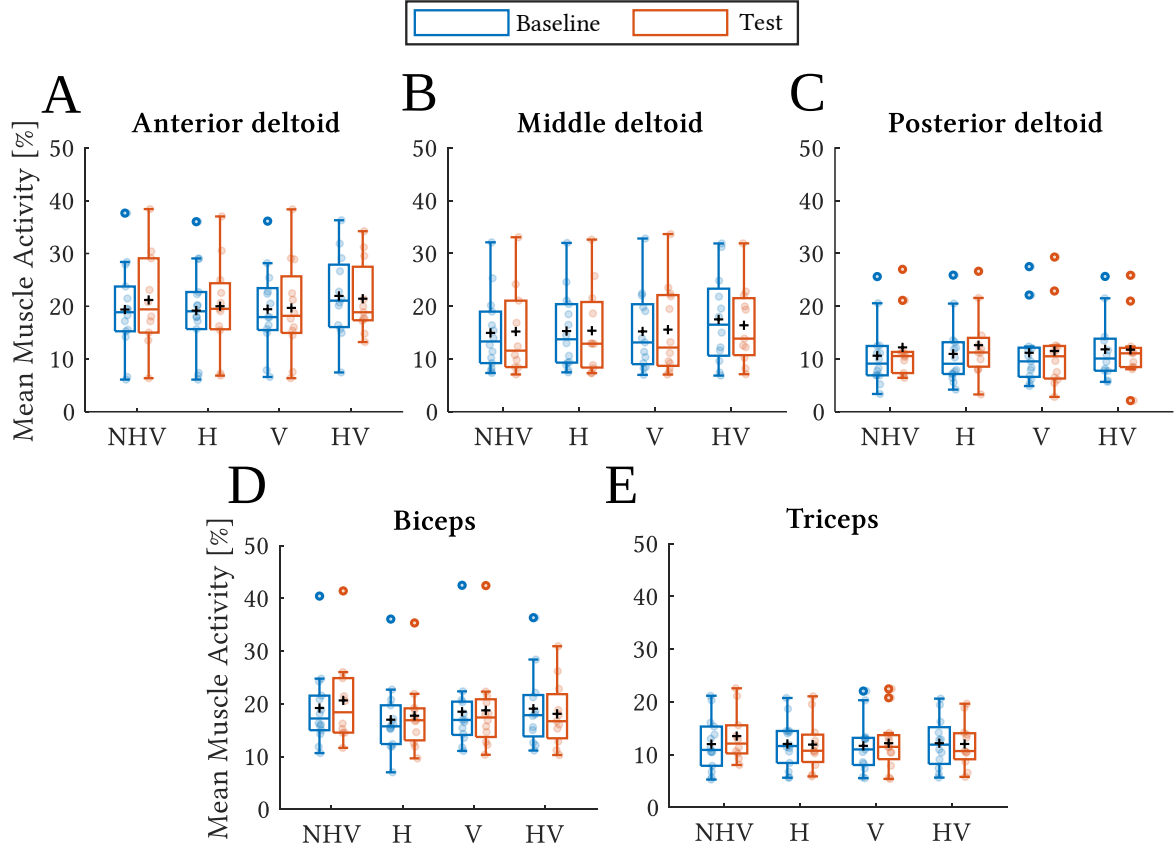


Figure 4.12: Mean muscle activity of the dominant hand between the baseline (first 10 trials) and the test (last 10 trials) for the muscles (A): Anterior deltoid, (B): Middle deltoid, (C): Posterior deltoid, (D): Biceps, (E): Triceps across different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only, HV: haptic and visual feedback). Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric.

their performance effectively, which is in line with prior research done by Sigrist et al. [134].

Figure 4.6 provides a comparative analysis of the normalized error across the four conditions, illustrating a clear trend in error reduction in the haptic-only (H), the visual-only (V) and the combined (HV) feedback conditions. Although both types of feedback individually lead to improvement, the visual condition did not outperform the haptic condition,

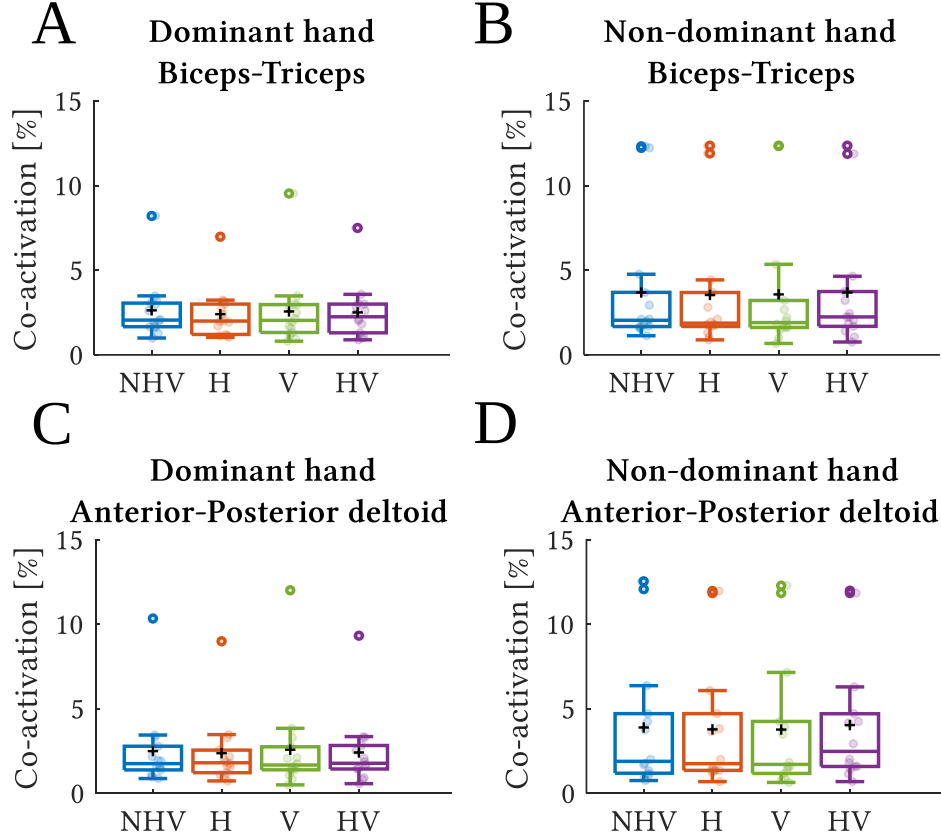


Figure 4.13: Muscle co-activations for Biceps-Triceps of the dominant hand (A), non-dominant hand (B) and Anterior-Posterior deltoid of the dominant hand (C) and non-dominant hand (D) across different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only, HV: haptic and visual feedback).

which could challenge the expected dominance of visual feedback in spatial accuracy tasks [132].

The combined feedback condition (HV) provided evidence of a synergistic effect, resulting in the most substantial error reduction. This is exemplified by statistically significant enhancement from baseline to test trials and the consistently low errors across trials in Figure 4.5. These findings invite a deeper examination of how individual differences in sensory integration may contribute to the effectiveness of feedback modalities, aligning with research exploring the balance between sensory inputs during motor learning [50].

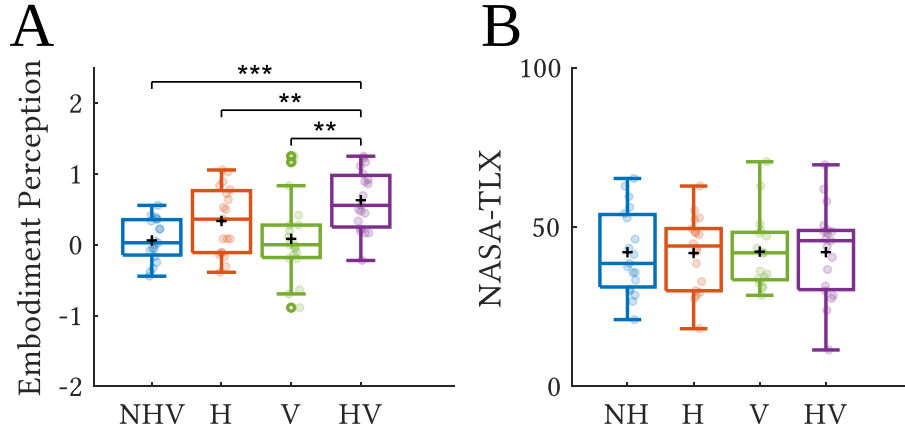


Figure 4.14: Subjective responses to the embodiment perception and the NASA-TLX questionnaires across different conditions (NHV: no feedback, H: haptic feedback only, V: visual feedback only, HV: haptic and visual feedback). Box plots present the minimum, 25% percentiles, median, 75% percentiles and maximum of each metric for all conditions. Also, the + sign shows the mean for each metric. The participants scored a higher sense of embodiment in the HV condition compared to other conditions (with *** $p < .0003$ and ** $p < .003$).

Table 4.2: Fitted lines parameters. The comparison between each line with constant showed significant difference (with * $p < .05$).

Condition	Slope	Intercept	F-test
Haptic only (H)	0.04	-0.13	$p > .05$
Visual only (V)	-0.36	-0.20	* $p = .017$
Haptic and visual (HV)	0.46	0.22	* $p = .025$

Figure 4.7 shows the similarity factor between the ball and the target trajectories in baseline and test trials of each condition. The initial lower performance in the H condition suggests that participants may rely more on visual cues when first learning the task. However, as they receive haptic feedback, they learn to integrate this information effectively, significantly improving their performance during test trials. Another possible scenario is that the exposure to haptic feedback may have initially disrupted participants' performance, resulting in lower proficiency during the baseline trials. As the participants

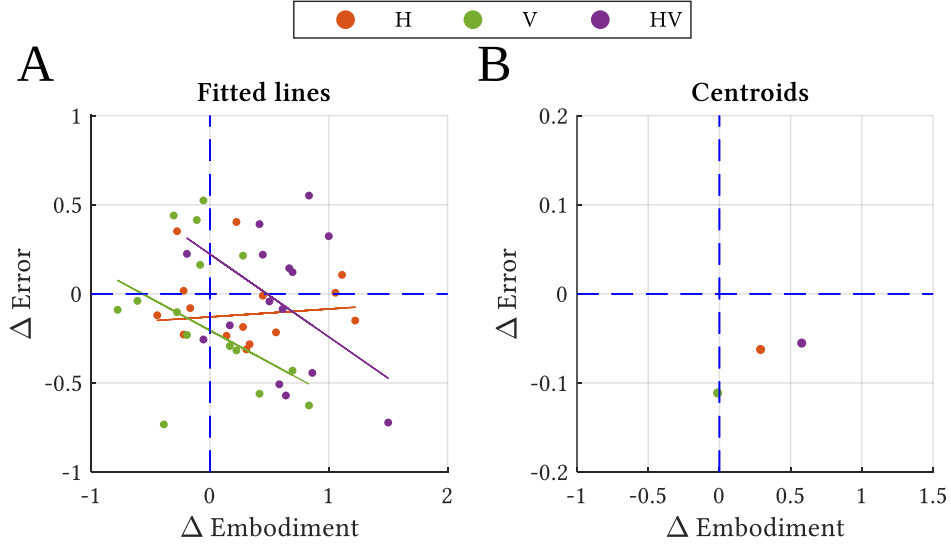


Figure 4.15: Embodiment perception score and the normalized maximum absolute error of each participant with respect to the no-feedback condition. Δ shows the difference of the value with respect to the no-feedback condition, (A) shows the participants as well as the fitted lines for each condition, (B) shows the centroid of each condition (NHV: no feedback, H: haptic feedback only, V: visual feedback only. HV: haptic and visual feedback).

adjusted over time, their performance improved.

The analysis of zero crossings offers an alternative perspective on participants' motor control abilities under various conditions. A lower number of zero crossings in the test trials in the haptic-only condition (Figure 4.8) suggests that participants are learning to anticipate and correct their movements, which results in ball trajectories deviating less frequently from the target path, increasing in the smoothness of the motion. This could imply that participants are becoming more capable of predicting the target's movement and adjusting their actions accordingly.

The analysis of zero crossings across other conditions (Figure 4.8 and Figure 4.9) shows that the presumed advantage of combined feedback in promoting a smooth motion may not be straightforward. Without any feedback (NHV), participants maintained a consistent motion path, showing that even in the absence of external cues, a certain level of intrinsic control was present. When haptic feedback was introduced (the H condition), a noticeable improvement in this intrinsic control was observed, indicating that tactile cues may enhance the precision of movement. Conversely, the high variability observed with the

visual feedback (V) condition suggests that while visual cues were processed and utilized by the participants, they did not consistently result in precise motor control. This could suggest that visual cues in this context were not as important for fine-tuning movements, potentially due to the cognitive demand of processing such feedback or because the cues provided were not directly related to the crucial aspects of the task that influence motion control.

Figure 4.10 shows the average slope of the maximum absolute error across different conditions, aligned with the order of exposure for the participants. The marked improvement in the First condition highlights the effect of initial exposure on learning, often referred to as the early learning effect [36]. This phenomenon reflects the rapid acquisition of skills at the beginning of practice, likely due to the novelty of the task and the steep part of the learning curve that individuals typically experience. However, the negative slope in the following conditions indicates that learning is still occurring, albeit at a slower rate, rather than reaching a plateau with a slope of zero or almost zero. Additionally, the moderate slopes in the test part of the first condition and similar test trials of later conditions suggest that the learning due to novelty does not significantly bleed into the subsequent conditions. This indicates a more isolated impact of the early learning effect, without a substantial carryover into later stages of the experiment. Furthermore, the consistent motor strategy used by participants across different conditions, as learned in the baseline, supports the idea of a sustained learning effect without significant deviation in approach.

Figure 4.11 shows the mean muscle activity of the dominant and non dominant hand of the participants across conditions. A notable observation from the plots is that there is a bilateral representation of muscle activity across all conditions, suggesting that the tasks were not performed unimanually. Indeed, both the dominant and non-dominant hands show varied levels of muscle activity. Specifically, the anterior deltoid in both Visual only and combined feedback (HV) conditions demonstrates significant differences in activity between the dominant and non-dominant hands. This implies that although there may have been a dominant hand that was expected to be more active, the non-dominant hand was also highly engaged during the task, negating the possibility that the task was conducted with one hand only. The balanced engagement across both hands suggests that participants were likely using both hands simultaneously or alternating between them during the task performance, indicating a bimanual coordination rather than a unimanual task execution.

The mean muscle activities of participants across different conditions can be seen in Figure 4.12. This figure suggests that the different feedback conditions do not significantly affect the mean muscle activity in this specific task, as indicated by the relatively stable muscle activation across all conditions and muscles. The lack of variation in muscle activity between the baseline and test phases for each feedback condition indicates that participants

are likely using similar motor strategies throughout the task regardless of the type of feedback received. This uniformity in muscle activation could imply a few possibilities: the task demands are consistent and well within the participants' capabilities; the participants do not modify their motor strategies significantly after feedback is introduced or throughout the trials; or the feedback provided does not require or elicit changes in muscle activation patterns.

The consistent muscle co-activation (Figure 4.13) across different feedback modalities suggests that participants were able to maintain a stable motor strategy throughout the task. Given this stability, it is clear that the observed reduction in error (Figure 4.6), as discussed previously, is likely due to other factors unrelated to muscle co-contraction. Such factors might include improved sensorimotor integration, enhanced cognitive strategies, or better anticipation of the task demands, rather than a change in the fundamental neuromuscular activation patterns.

Figure 4.14 highlights the psychological impact of feedback on task engagement and perception. The significant increase in embodiment perception (Figure 4.14-A) in the HV condition suggests that multimodal feedback can lead to a more immersive and integrated experience for participants, potentially enhancing the quality of interaction and the performance in the task. Also, the lower median and higher variability in the V condition could potentially be attributed to the participants' experience of the avatar hands. Without the tactile confirmation provided by haptic feedback, participants may have found it more difficult to accept the virtual hands as extensions of their own, leading to a weaker sense of embodiment. Visual feedback alone, while informative, may sometimes lack the immersive quality that haptic feedback provides, which can be critical in reinforcing the connection between the user and the avatar or virtual environment.

The absence of a significant difference in NASA-TLX scores (Figure 4.14-B) between conditions indicates that while the type of feedback affects the sense of embodiment, it does not necessarily influence the perceived workload, which aligns the findings in [113]. This could mean that even if participants feel more connected to the task with certain types of feedback, they do not necessarily find it more demanding.

Figure 4.15 provides insights into how different types of feedback influence the participants' sense of embodiment and error rates. While there is individual variability, the general trend in the HV condition suggests that combining haptic and visual feedback may enhance the sense of embodiment and reduce errors more effectively than either type of feedback alone.

The variability shown in Figure 4.15-A indicates that the relationship between embodiment and error reduction is not straightforward. While some participants may experience

increased embodiment alongside reduced errors, this is not a uniform effect across all individuals. The centroids in [Figure 4.15-B](#) provide a clearer picture of the average shifts due to each feedback condition, and here we see a potential advantage for combined feedback in positively influencing both perceived embodiment and performance.

Overall, the absence of feedback led to high variability and no significant improvement in performance, underscoring the essential role of external sensory feedback in motor learning, as supported by previous research Sigrist et al. [[134](#)]. The findings demonstrated that while both haptic and visual feedback individually improved performance, the combined feedback condition resulted in the most significant error reduction and the highest sense of embodiment. This superposition effect suggests that multimodal feedback is superior to unimodal feedback in enhancing both task performance and sensory integration, challenging the expected dominance of visual feedback alone. These outcomes align with existing literature that emphasizes the balance between sensory inputs for effective motor learning [[50](#)], and highlight the potential of combined feedback to create more immersive and integrated virtual experiences, thereby enhancing both the quality of interaction and performance in virtual tasks.

Chapter 5

Conclusion and Outlook

In this thesis, we explored the impact of different sensory feedback modalities, including visual representation of hands and the proposed tactile feedback, on the sense of embodiment in VR and its correlation with improvements in task performance in motor learning. Our findings demonstrate that the combination of visual and tactile feedback leads to a higher sense of embodiment compared to visual feedback alone. This enhanced sense of embodiment correlates with improved task performance in motor learning tasks, as demonstrated in the VR-based mirror therapy and ball-and-beam control task studies. We also observed more improvement in motor learning in the ball and beam task when participants were presented with haptic feedback rather than visual appearance of the hands. This can be partly attributed to the improved embodiment as well as the task relevant information of position of the ball on the beam coded in the haptic feedback. While the appearance of hands on the beam does not have any relevant information to the motor task, but has an embodiment effect.

In the VR-based mirror therapy experiment ([chapter 3](#)), we found that providing pressure feedback on the index and thumb fingertips significantly increased the embodiment perception during training and the task success rate during testing, while also reducing the task load index. These results suggest that tactile feedback (pressure on the fingertips) can enhance the effectiveness of VR-based mirror therapy for motor learning and rehabilitation.

In the ball-and-beam control task study ([chapter 4](#)), we observed that the presence of vibrotactile feedback improved participants' performance in terms of kinematic metrics such as absolute trajectory error and correlation between the ball and the target trajectories. Our muscle activity analysis did not show any change of muscle co-contraction when the participants were presented with additional vibrotactile and/or visual modali-

ties. This suggests that the improved results are not due to adopting a different motor control strategy, e.g., high gain feedback control or increase of joint impedance. Furthermore, participants reported a higher sense of embodiment in the condition with vibrotactile feedback, which supports the notion that adding a tactile dimension can enhance the sense of presence and performance in VR-based motor tasks. While the visual appearance of hands may contribute to a sense of embodiment, it is the tactile feedback that represents a distinct sensory dimension in this study.

Overall, this thesis contributes to the understanding of how cutaneous haptic feedback can be leveraged to enhance embodiment and motor learning in VR. These findings have implications for the design of more effective VR systems for training and rehabilitation purposes, highlighting the potential of incorporating cutaneous haptic feedback to improve user experience and task performance.

5.1 Limitations and Future Work

After summarizing the findings of this thesis, we acknowledge the limitations of our work which offer avenues for future research.

One limitation is the limited demographic of participants used in the studies. Future research should include a more diverse range of participants, encompassing individuals with different motor disabilities, to improve the generalizability of the findings.

Another limitation of this work was a lack of understanding of the participants' prior familiarity of VR environment. Assessing familiarity with VR could provide insight into its potential impact on the outcomes of VR-based interventions. A deeper understanding of how previous exposure to VR affects a user's performance in motor learning tasks and their sense of embodiment could help tailor VR interventions to individual users more effectively.

In the first study ([chapter 3](#)), one of the limitations is that the simplicity of the task may have led to saturation in learning outcomes among able-bodied participants. Although the task was intended to simulate a rehabilitation exercise, the task, which was inspired by [89], might not have been sufficiently challenging to fully test the capabilities and adaptations of individuals without disabilities. Furthermore, the haptic gloves used, while adding realism through pressure feedback on the thumb and index fingertips, also introduced additional weight on the thimbles. This could potentially alter the participants' natural strategies for picking up the cubes, adding an unintended layer of complexity to the task that could

influence performance and perception outcomes in ways not accounted for by the study design.

One of the limitations of the ball and beam study([chapter 4](#)), is the proprioceptive accuracy was challenged due to the configuration of the virtual hands shown to the participants. Although the hands were intended to represent the participant’s own in the VR environment, they may not have perfectly mirrored the natural positioning and movement needed for manipulating the virtual beam. This discrepancy might have affected the users’ proprioceptive integration and their performance on the task, which might have hindered their embodiment scores in the V and the HV conditions. Future studies could aim to optimize the alignment of the virtual hands with the participants’ actual hand positions and movements, thereby enhancing the proprioceptive congruence and potentially improving the effectiveness of the training.

The studies were conducted in short sessions, focusing primarily on early motor learning rather than longer-term skill acquisition and retention. To understand the long-term effects of enhanced embodiment on motor learning and rehabilitation outcomes, longitudinal studies are necessary. These studies should investigate the role of improved embodiment or additional sensory feedback on skill consolidation and retention, assessing the sustainability of the observed effects and their implications for long-term skill transfer. Furthermore, future systems could benefit from incorporating adaptive feedback mechanisms that customize the sensory feedback based on individual user needs, preferences, and progress. Personalized feedback could potentially enhance the effectiveness of VR-based interventions for motor learning and rehabilitation.

Incorporating neuroimaging or electrophysiological techniques, such as electroencephalogram (EEG) or functional magnetic resonance imaging (fMRI), could provide deeper insights into the neural correlates of embodiment and its relationship with motor learning. Understanding the neural mechanisms underlying embodiment could result in designing more effective VR interventions for motor learning. Translating the findings into practical VR applications for specific rehabilitation or training scenarios would be a valuable step forward. Developing and testing VR interventions in real-world settings could facilitate their adoption in clinical and educational environments.

Exploring more sophisticated haptic feedback systems, such as providing force feedback or rendering different textures, could further enhance the sense of embodiment and task performance. Additionally, incorporating sound as a sensory modality in future studies could provide a more immersive experience and potentially improve user engagement and learning outcomes. Investigating the effects of varying levels of haptic complexity and auditory feedback on user experience and learning outcomes could inform the design of

more immersive and effective VR systems. Furthermore, future work could benefit from interdisciplinary collaboration between fields such as neuroscience, psychology, engineering, and education. Such collaboration could lead to innovative approaches to integrating sensory feedback in VR and a deeper understanding of its effects on human cognition and behaviour.

In addition to the aforementioned limitations, it is important to note that in this research, embodiment perception was primarily recorded through subjective data obtained from questionnaires. Although this approach provides valuable insights into the participants' experiences, measuring embodiment perception in real-time using objective methods could offer a deeper understanding of its dynamics and fluctuations during VR interactions. Real-time measurement techniques, such as physiological monitoring or behavioural analysis [46], could provide a more continuous and detailed picture of embodiment, allowing for a deeper exploration of its relationship with motor learning and task performance. Integrating such objective measures in future studies could enhance the precision and richness of the data, leading to more robust conclusions and further advancing VR-based motor learning and rehabilitation.

Moving forward, it would also be beneficial to explore sensory weighting in these studies. This approach investigates how the relative emphasis on different sensory modalities (visual, haptic, auditory) can influence learning outcomes. VR systems have the potential to dynamically adjust the weight given to each sense based on the specific task and user characteristics. For example, a system might prioritize haptic feedback for tasks requiring manipulation like grasping objects, while increasing visual feedback for tasks focused on spatial awareness like navigating a virtual environment. Investigating how to optimize this sensory weighting based on individual needs and learning styles could be a key factor in enhancing the effectiveness of VR interventions for motor learning and rehabilitation.

References

- [1] Alahakone, A. U. and Senanayake, S. A. (2009). Vibrotactile feedback systems: Current trends in rehabilitation, sports and information display. In 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pages 1148–1153. IEEE.
- [2] Algina, J., Keselman, H., and Penfield, R. D. (2005). An alternative to cohen’s standardized mean difference effect size: a robust parameter and confidence interval in the two independent groups case. Psychological methods, 10(3):317.
- [3] Ameen, N., Hosany, S., and Tarhini, A. (2021). Consumer interaction with cutting-edge technologies: Implications for future research. Computers in Human Behavior, 120:106761.
- [4] Anderson, K. R., Woodbury, M. L., Phillips, K., and Gauthier, L. V. (2015). Virtual reality video games to promote movement recovery in stroke rehabilitation: a guide for clinicians. Archives of physical medicine and rehabilitation, 96(5):973–976.
- [5] Augenstein, T. E., Kortemeyer, D., Glista, L., and Krishnan, C. (2022). Enhancing mirror therapy via scaling and shared control: a novel open-source virtual reality platform for stroke rehabilitation. Virtual Reality, 26:1–14.
- [6] Basdogan, C., Kiraz, A., Bukusoglu, I., Varol, A., and Doğanay, S. (2007). Haptic guidance for improved task performance in steering microparticles with optical tweezers. Optics Express, 15(18):11616–11621.
- [7] Basdogan, C. and Srinivasan, M. A. (2002). Haptic rendering in virtual environments. In Handbook of virtual environments, pages 157–174. CRC Press.
- [8] Bolanowski Jr, S. and Zwislocki, J. J. (1984). Intensity and frequency characteristics of pacinian corpuscles. i. action potentials. Journal of neurophysiology, 51(4):793–811.

- [9] Borrego, A., Latorre, J., Alcañiz, M., and Llorens, R. (2019). Embodiment and presence in virtual reality after stroke. a comparative study with healthy subjects. Frontiers in neurology, 10:476598.
- [10] Buccino, G. and Riggio, L. (2006). The role of the mirror neuron system in motor learning. Kinesiology, 38(1.):5–15.
- [11] Cacchio, A., De Blasis, E., De Blasis, V., Santilli, V., and Spacca, G. (2009). Mirror therapy in complex regional pain syndrome type 1 of the upper limb in stroke patients. Neurorehabilitation and neural repair, 23(8):792–799.
- [12] Cameirão, M. S., Pereira, F., and i Badia, S. B. (2017). Virtual reality with customized positive stimuli in a cognitive-motor rehabilitation task. In 2017 international conference on virtual rehabilitation (ICVR), pages 1–7. IEEE.
- [13] Caspar, E. A., Cleeremans, A., and Haggard, P. (2015). The relationship between human agency and embodiment. Consciousness and cognition, 33:226–236.
- [14] Cattaert, D., Semjen, A., and Summers, J. (1999). Simulating a neural cross-talk model for between-hand interference during bimanual circle drawing. Biological cybernetics, 81(4):343–358.
- [15] Choudhary, Z., Gottsacker, M., Kim, K., Schubert, R., Stefanucci, J., Bruder, G., and Welch, G. F. (2021). Revisiting distance perception with scaled embodied cues in social virtual reality. In 2021 IEEE Virtual Reality and 3D User Interfaces (VR), pages 788–797. IEEE.
- [16] Chung, W. and Barnett-Cowan, M. (2023). Sensory reweighting: a common mechanism for subjective visual vertical and cybersickness susceptibility. Virtual Reality, 27(3):2029–2041.
- [17] Cohen, A. R., Lohani, S., Manjila, S., Natsupakpong, S., Brown, N., and Cavusoglu, M. C. (2013). Virtual reality simulation: basic concepts and use in endoscopic neurosurgery training. Child’s Nervous System, 29:1235–1244.
- [18] Cui, D. (2022). The effect of out-of-body experience and tactile feedback on the sense of embodiment in virtual reality. In 2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), pages 919–922. IEEE.
- [19] Cui, D. and Mousas, C. (2021). An on-site and remote study during the covid-19 pandemic on virtual hand appearance and tactile feedback. Behaviour & Information Technology, 40(12):1278–1291.

- [20] Cui, X., Jeter, C. B., Yang, D., Montague, P. R., and Eagleman, D. M. (2007). Vividness of mental imagery: Individual variability can be measured objectively. Vision research, 47(4):474–478.
- [21] Cuppone, A. V., Squeri, V., Semprini, M., Masia, L., and Konczak, J. (2016). Robot-assisted proprioceptive training with added vibro-tactile feedback enhances somatosensory and motor performance. PloS one, 11(10):e0164511.
- [22] da Silva Jaques, E., Figueiredo, A. I., Schiavo, A., Loss, B. P., da Silveira, G. H., Sangalli, V. A., da Silva Melo, D. A., Xavier, L. L., Pinho, M. S., Mestriner, R. G., et al. (2023). Conventional mirror therapy versus immersive virtual reality mirror therapy: The perceived usability after stroke. Stroke Research and Treatment, 2023.
- [23] Darnall, B. D. (2009). Self-delivered home-based mirror therapy for lower limb phantom pain. American journal of physical medicine & rehabilitation/Association of Academic Physiatrists, 88(1):78.
- [24] Ding, L., He, J., Yao, L., Zhuang, J., Chen, S., Wang, H., Jiang, N., and Jia, J. (2020). Mirror visual feedback combining vibrotactile stimulation promotes embodiment perception: an electroencephalogram (eeg) pilot study. Frontiers in Bioengineering and Biotechnology, 8:553270.
- [25] Dounskaia, N., Nogueira, K. G., Swinnen, S. P., and Drummond, E. (2010). Limitations on coupling of bimanual movements caused by arm dominance: when the muscle homology principle fails. Journal of neurophysiology, 103(4):2027–2038.
- [26] Elsayed, H., Barrera Machuca, M. D., Schaarschmidt, C., Marky, K., Müller, F., Riemann, J., Matviienko, A., Schmitz, M., Weigel, M., and Mühlhäuser, M. (2020). Vrs-ketchpen: unconstrained haptic assistance for sketching in virtual 3d environments. In Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology, pages 1–11.
- [27] Esen, H. (2007). Training in virtual environments via a hybrid dynamic trainer model. PhD thesis, Technische Universität München.
- [28] Esen, H., Yano, K., and Buss, M. (2008). Bone drilling medical training system. The Sense of Touch and its Rendering: Progress in Haptics Research, pages 245–278.
- [29] Farrington, M. W., Gerling, G. J., Kohan, L. R., and Johnson, S. L. (2012). A multisensory illusion with haptic interaction to treat phantom limb pain. In 2012 IEEE Haptics Symposium (HAPTICS), pages 217–222, Vancouver, BC, Canada. IEEE, IEEE.

- [30] Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of experimental psychology, 47(6):381.
- [31] Foell, J., Bekrater-Bodmann, R., Diers, M., and Flor, H. (2014). Mirror therapy for phantom limb pain: brain changes and the role of body representation. European journal of pain, 18(5):729–739.
- [32] French, B., Thomas, L. H., Coupe, J., McMahon, N. E., Connell, L., Harrison, J., Sutton, C. J., Tishkovskaya, S., and Watkins, C. L. (2016). Repetitive task training for improving functional ability after stroke. Cochrane database of systematic reviews, (11).
- [33] Fritz, C. O., Morris, P. E., and Richler, J. J. (2012). Effect size estimates: current use, calculations, and interpretation. Journal of experimental psychology: General, 141(1):2.
- [34] Fugl-Meyer, A., Jääskö, L., and Norlin, V. (1975). The post-stroke hemiplegic patient. ii. incidence, mortality, and vocational return in göteborg, sweden with a review of the literature. Scandinavian journal of rehabilitation medicine, 7(2):73–83.
- [35] Fukumura, K., Sugawara, K., Tanabe, S., Ushiba, J., and Tomita, Y. (2007). Influence of mirror therapy on human motor cortex. International Journal of Neuroscience, 117(7):1039–1048.
- [36] Ghorbani, S. and Bund, A. (2017). Throwing skills: Analysis of movement phases in early motor learning. Perceptual and motor skills, 124(2):502–513.
- [37] Gibbs, J. K., Gillies, M., and Pan, X. (2022). A comparison of the effects of haptic and visual feedback on presence in virtual reality. International Journal of Human-Computer Studies, 157:102717.
- [38] Giummarra, M. J., Gibson, S. J., Georgiou-Karistianis, N., and Bradshaw, J. L. (2008). Mechanisms underlying embodiment, disembodiment and loss of embodiment. Neuroscience & Biobehavioral Reviews, 32(1):143–160.
- [39] Gonçalves, G., Melo, M., Barbosa, L., Vasconcelos-Raposo, J., and Bessa, M. (2022). Evaluation of the impact of different levels of self-representation and body tracking on the sense of presence and embodiment in immersive vr. Virtual Reality, 26(1):1–14.
- [40] Gonzalez-Franco, M. and Lanier, J. (2017). Model of illusions and virtual reality. Frontiers in psychology, 8:273943.
- [41] Gonzalez-Franco, M. and Peck, T. C. (2018). Avatar embodiment. towards a standardized questionnaire. Frontiers in Robotics and AI, 5:74.

- [42] Guo, W., Ni, W., Chen, I.-M., Ding, Z. Q., and Yeo, S. H. (2009). Intuitive vibrotactile feedback for human body movement guidance. In 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), pages 135–140. IEEE.
- [43] Gutierrez, T., Rodriguez, J., Velaz, Y., Casado, S., Suescun, A., and Sanchez, E. J. (2010). Ima-vr: A multimodal virtual training system for skills transfer in industrial maintenance and assembly tasks. In 19th International Symposium in Robot and Human Interactive Communication, pages 428–433. IEEE.
- [44] Guy, M., Normand, J.-M., Jeunet-Kelway, C., and Moreau, G. (2023). The sense of embodiment in virtual reality and its assessment methods. Frontiers in Virtual Reality, 4:1141683.
- [45] Gygax, M. J., Schneider, P., and Newman, C. J. (2011). Mirror therapy in children with hemiplegia: a pilot study. Developmental Medicine & Child Neurology, 53(5):473–476.
- [46] Halbig, A. and Latoschik, M. E. (2021). A systematic review of physiological measurements, factors, methods, and applications in virtual reality. Frontiers in Virtual Reality, 2:694567.
- [47] Hart, S. G. and Staveland, L. E. (1988). Development of nasa-tlx (task load index): Results of empirical and theoretical research. In Advances in psychology, volume 52, pages 139–183. Elsevier, North-Holland.
- [48] Heinrich, C., Morkisch, N., Langlotz, T., Regenbrecht, H., and Dohle, C. (2022). Feasibility and psychophysical effects of immersive virtual reality-based mirror therapy. Journal of NeuroEngineering and Rehabilitation, 19(1):1–20.
- [49] Hejtmanek, L., Starrett, M., Ferrer, E., and Ekstrom, A. D. (2020). How much of what we learn in virtual reality transfers to real-world navigation? Multisensory Research, 33(4-5):479–503.
- [50] Henriques, D. Y. and Cressman, E. K. (2012). Visuomotor adaptation and proprioceptive recalibration. Journal of motor behavior, 44(6):435–444.
- [51] Heyes, C. (2010). Where do mirror neurons come from? Neuroscience & Biobehavioral Reviews, 34(4):575–583.
- [52] Hirano, M., Sakurada, M., and Furuya, S. (2020). Overcoming the ceiling effects of experts’ motor expertise through active haptic training. Science advances, 6(47):eabd2558.

- [53] Holden, M. K. (2005). Virtual environments for motor rehabilitation. Cyberpsychology & behavior, 8(3):187–211.
- [54] Horne, M., Thomas, N., McCabe, C., Selles, R., Vail, A., Tyrrell, P., and Tyson, S. (2015). Patient-directed therapy during in-patient stroke rehabilitation: stroke survivors’ views of feasibility and acceptability. Disability and Rehabilitation, 37(25):2344–2349.
- [55] Hsu, H.-Y., Kuo, L.-C., Lin, Y.-C., Su, F.-C., Yang, T.-H., and Lin, C.-W. (2022). Effects of a virtual reality-based mirror therapy program on improving sensorimotor function of hands in chronic stroke patients: a randomized controlled trial. Neurorehabilitation and Neural Repair, 36(6):335–345.
- [56] Hung, Y.-H., Lai, H.-Y., and Shih, C.-H. (2015). Study of multi-sensory stimulation for the design of hand rehabilitation equipment for stroke patients. Journal of Industrial and Production Engineering, 32(7):425–431.
- [57] Hunter, J. P., Katz, J., and Davis, K. D. (2003). The effect of tactile and visual sensory inputs on phantom limb awareness. Brain, 126(3):579–589.
- [58] Islam, M. S. and Lim, S. (2022). Vibrotactile feedback in virtual motor learning: A systematic review. Applied Ergonomics, 101:103694.
- [59] Iwasaki, Y., Navarro, B., Iwata, H., and Ganesh, G. (2022). Embodiment modifies attention allotment for the benefit of dual task performance. Communications biology, 5(1):701.
- [60] Kagerer, F. A. (2016). Asymmetric interference in left-handers during bimanual movements reflects switch in lateralized control characteristics. Experimental brain research, 234:1545–1553.
- [61] Kammers, M. P., de Vignemont, F., Verhagen, L., and Dijkerman, H. C. (2009). The rubber hand illusion in action. Neuropsychologia, 47(1):204–211.
- [62] Kasuga, S. and Nozaki, D. (2011). Cross talk in implicit assignment of error information during bimanual visuomotor learning. Journal of neurophysiology, 106(3):1218–1226.
- [63] Kilteni, K., Groten, R., and Slater, M. (2012). The sense of embodiment in virtual reality. Presence: Teleoperators and Virtual Environments, 21(4):373–387.

- [64] Kim, O., Pang, Y., and Kim, J.-H. (2019). The effectiveness of virtual reality for people with mild cognitive impairment or dementia: a meta-analysis. BMC psychiatry, 19:1–10.
- [65] Kim, S. Y. and Kim, Y. Y. (2012). Mirror therapy for phantom limb pain. The Korean journal of pain, 25(4):272–274.
- [66] Kocur, M., Schauhuber, P., Schwind, V., Wolff, C., and Henze, N. (2020). The effects of self-and external perception of avatars on cognitive task performance in virtual reality. In Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology, pages 1–11.
- [67] Kokkinara, E., Slater, M., and López-Moliner, J. (2015). The effects of visuomotor calibration to the perceived space and body, through embodiment in immersive virtual reality. ACM Transactions on Applied Perception (TAP), 13(1):1–22.
- [68] Konrad, P. (2022). The abc of emg: A practical introduction to kinesiological electromyography. <http://www.noraxon.com/wp-content/uploads/2014/12/ABC-EMG-ISBN.pdf>. Accessed: 2024-02.
- [69] Koritnik, T., Koenig, A., Bajd, T., Riener, R., and Munih, M. (2010). Comparison of visual and haptic feedback during training of lower extremities. Gait & posture, 32(4):540–546.
- [70] Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., and Haith, A. M. (2019). Motor learning. Compr Physiol, 9(2):613–663.
- [71] Lee, J. and Choi, S. (2010). Effects of haptic guidance and disturbance on motor learning: Potential advantage of haptic disturbance. In 2010 IEEE Haptics Symposium, pages 335–342. IEEE.
- [72] Lee, M. M., Cho, H.-y., and Song, C. H. (2012). The mirror therapy program enhances upper-limb motor recovery and motor function in acute stroke patients. American journal of physical medicine & rehabilitation, 91(8):689–700.
- [73] Lee, Y.-y., Lin, K.-c., Wu, C.-y., Liao, C.-h., Lin, J.-c., and Chen, C.-l. (2015). Combining afferent stimulation and mirror therapy for improving muscular, sensorimotor, and daily functions after chronic stroke: a randomized, placebo-controlled study. American journal of physical medicine & rehabilitation, 94(10S):859–868.

- [74] Levac, D., Glegg, S. M., Sveistrup, H., Colquhoun, H., Miller, P. A., Finestone, H., DePaul, V., Harris, J. E., and Velikonja, D. (2016). A knowledge translation intervention to enhance clinical application of a virtual reality system in stroke rehabilitation. BMC health services research, 16:1–11.
- [75] Levac, D. E., Huber, M. E., and Sternad, D. (2019). Learning and transfer of complex motor skills in virtual reality: a perspective review. Journal of neuroengineering and rehabilitation, 16:1–15.
- [76] Lewis, G. N. and Rosie, J. A. (2012). Virtual reality games for movement rehabilitation in neurological conditions: how do we meet the needs and expectations of the users? Disability and rehabilitation, 34(22):1880–1886.
- [77] Lieberman, J. and Breazeal, C. (2007). Tikl: Development of a wearable vibrotactile feedback suit for improved human motor learning. IEEE Transactions on Robotics, 23(5):919–926.
- [78] Lin, C.-W., Kuo, L.-C., Lin, Y.-C., Su, F.-C., Lin, Y.-A., and Hsu, H.-Y. (2021). Development and testing of a virtual reality mirror therapy system for the sensorimotor performance of upper extremity: A pilot randomized controlled trial. IEEE Access, 9:14725–14734.
- [79] Lin, K.-C., Chen, Y.-T., Huang, P.-C., Wu, C.-Y., Huang, W.-L., Yang, H.-W., Lai, H.-T., and Lu, H.-J. (2014). Effect of mirror therapy combined with somatosensory stimulation on motor recovery and daily function in stroke patients: A pilot study. Journal of the Formosan Medical Association, 113(7):422–428.
- [80] Lontschar, S., Deegan, D., Humer, I., Pietroszek, K., and Eckhardt, C. (2020). Analysis of haptic feedback and its influences in virtual reality learning environments. In 2020 6th International Conference of the Immersive Learning Research Network (iLRN), pages 171–177. IEEE.
- [81] MacLachlan, M., McDonald, D., and Waloch, J. (2004). Mirror treatment of lower limb phantom pain: a case study. Disability and rehabilitation, 26(14-15):901–904.
- [82] Magill, R. and Anderson, D. I. (2010). Motor learning and control. McGraw-Hill Publishing New York.
- [83] Magnenat-Thalmann, N. and Bonanni, U. (2006). Haptics in virtual reality and multimedia. IEEE MultiMedia, 13(3):6–11.

- [84] Marchal-Crespo, L. and Reinkensmeyer, D. J. (2009). Review of control strategies for robotic movement training after neurologic injury. Journal of neuroengineering and rehabilitation, 6:1–15.
- [85] Maselli, A. and Slater, M. (2013). The building blocks of the full body ownership illusion. Frontiers in human neuroscience, 7:83.
- [86] Matamala-Gomez, M., Donegan, T., Bottiroli, S., Sandrini, G., Sanchez-Vives, M. V., and Tassorelli, C. (2019). Immersive virtual reality and virtual embodiment for pain relief. Frontiers in human neuroscience, 13:279.
- [87] Mathieson, S., Parsons, J., Kaplan, M., and Parsons, M. (2018). Combining functional electrical stimulation and mirror therapy for upper limb motor recovery following stroke: a randomised trial. European Journal of Physiotherapy, 20(4):244–249.
- [88] Matsuda, N. and Abe, M. O. (2023). Error size shape relationships between motor variability and implicit motor adaptation. Biology, 12(3):404.
- [89] Mazzola, S., Prado, A., and Agrawal, S. K. (2020). An upper limb mirror therapy environment with hand tracking in virtual reality. In 2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob), pages 752–758, New York, NY, USA. IEEE, IEEE.
- [90] Medina, J., Khurana, P., and Coslett, H. B. (2015). The influence of embodiment on multisensory integration using the mirror box illusion. Consciousness and cognition, 37:71–82.
- [91] Michielsen, M. E., Smits, M., Ribbers, G. M., Stam, H. J., van Der Geest, J. N., Bussmann, J. B., and Selles, R. W. (2011). The neuronal correlates of mirror therapy: an fmri study on mirror induced visual illusions in patients with stroke. Journal of neurology, neurosurgery & psychiatry, 82(4):393–398.
- [92] Morris, D., Tan, H., Barbagli, F., Chang, T., and Salisbury, K. (2007). Haptic feedback enhances force skill learning. In Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC’07), pages 21–26. IEEE.
- [93] Muresan, A., McIntosh, J., and Hornbæk, K. (2023). Using feedforward to reveal interaction possibilities in virtual reality. ACM Transactions on Computer-Human Interaction, 30(6):1–47.

- [94] Nazarahari, M., Ajami, S., Jeon, S., and Arami, A. (2023). Visual feedback decoding during bimanual circle drawing. Journal of Neurophysiology, 130(5):1200–1213.
- [95] Nesbitt, K. et al. (2003). Designing multi-sensory displays for abstract data. PhD thesis, University of Sydney.
- [96] Newport, R., Pearce, R., and Preston, C. (2010). Fake hands in action: embodiment and control of supernumerary limbs. Experimental brain research, 204:385–395.
- [97] Oagaz, H., Schoun, B., and Choi, M.-H. (2022). Real-time posture feedback for effective motor learning in table tennis in virtual reality. International Journal of Human-Computer Studies, 158:102731.
- [98] Okamura, A. M. (2004). Methods for haptic feedback in teleoperated robot-assisted surgery. Industrial Robot: An International Journal, 31(6):499–508.
- [99] Oldfield, R. C. (1971). The assessment and analysis of handedness: the edinburgh inventory. Neuropsychologia, 9(1):97–113.
- [100] Orozco, M., Silva, J., El Saddik, A., and Petriu, E. (2012). The role of haptics in games. Haptics rendering and applications, pages 217–234.
- [101] Pacchierotti, C., Abayazid, M., Misra, S., and Prattichizzo, D. (2014). Steering of flexible needles combining kinesthetic and vibratory force feedback. In 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 1202–1207. IEEE.
- [102] Paravati, G., Spataro, V. M., Lamberti, F., Sanna, A., and Demartini, C. G. (2017). A customizable virtual reality framework for the rehabilitation of cognitive functions. In Recent Advances in Technologies for Inclusive Well-Being: From Worn to Off-body Sensing, Virtual Worlds, and Games for Serious Applications, pages 61–85. Springer.
- [103] Patel, P., Ray, R. K., and Manivannan, M. (2019). Power law based “out of body” tactile funneling for mobile haptics. IEEE transactions on haptics, 12(3):307–318.
- [104] Paula, M. H., Barbosa, R. I., Marcolino, A. M., Elui, V., Rosén, B., and Fonseca, M. C. (2016). Early sensory re-education of the hand after peripheral nerve repair based on mirror therapy: a randomized controlled trial. Brazilian Journal of Physical Therapy, 20:58–65.
- [105] Perez-Marcos, D., Bieler-Aeschlimann, M., and Serino, A. (2018). Virtual reality as a vehicle to empower motor-cognitive neurorehabilitation. Frontiers in psychology, 9:2120.

- [106] Petkova, V. I. and Ehrsson, H. H. (2008). If i were you: perceptual illusion of body swapping. PloS one, 3(12):e3832.
- [107] Petkova, V. I., Khoshnevis, M., and Ehrsson, H. H. (2011). The perspective matters! multisensory integration in ego-centric reference frames determines full-body ownership. Frontiers in psychology, 2:8981.
- [108] Phillips, L., Ries, B., Kaeding, M., and Interrante, V. (2010). Avatar self-embodiment enhances distance perception accuracy in non-photorealistic immersive virtual environments. In 2010 IEEE virtual reality conference (VR), pages 115–1148. IEEE.
- [109] Piccinin, M. A., Miao, J. H., and Schwartz, J. (2018). Histology, meissner corpuscle.
- [110] Popat, S. (2016). Missing in action: Embodied experience and virtual reality. Theatre Journal, pages 357–378.
- [111] Poyade, M. (2013). Motor skill training using virtual reality and haptic interaction—a case study in industrial maintenance. MÁLAGA.
- [112] Pritchard, S. C., Zopf, R., Polito, V., Kaplan, D. M., and Williams, M. A. (2016). Non-hierarchical influence of visual form, touch, and position cues on embodiment, agency, and presence in virtual reality. Frontiers in psychology, 7:221627.
- [113] Radhakrishnan, U., Kuang, L., Koumaditis, K., Chinello, F., and Pacchierotti, C. (2023). Haptic feedback, performance and arousal: A comparison study in an immersive vr motor skill training task. IEEE Transactions on Haptics.
- [114] Ramachandran, V. S. and 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.
- [115] Ramachandran, V. S., Rogers-Ramachandran, D., and Stewart, M. (1992). Perceptual correlates of massive cortical reorganization. Science, 258(5085):1159–1160.
- [116] Ramsamy, P., Haffeege, A., Jamieson, R., and Alexandrov, V. (2006). Using haptics to improve immersion in virtual environments. In Computational Science–ICCS 2006: 6th International Conference, Reading, UK, May 28–31, 2006. Proceedings, Part II 6, pages 603–609. Springer.
- [117] Ramstein, C. and Hayward, V. (1994). The pantograph: a large workspace haptic device for multimodal human computer interaction. In Conference companion on Human factors in computing systems, pages 57–58.

- [118] Richard, G., Pietrzak, T., Argelaguet, F., Lécuyer, A., and Casiez, G. (2021). Studying the role of haptic feedback on virtual embodiment in a drawing task. Frontiers in Virtual Reality, 1:573167.
- [119] Rinderknecht, M. D., Kim, Y., Santos-Carreras, L., Bleuler, H., and Gassert, R. (2013). Combined tendon vibration and virtual reality for post-stroke hand rehabilitation. In 2013 World Haptics Conference (WHC), pages 277–282, Daejeon, Korea (South). IEEE, IEEE.
- [120] Rizzolatti, G. and Craighero, L. (2004). The mirror-neuron system. Annu. Rev. Neurosci., 27:169–192.
- [121] Rodríguez, A., Basanez, L., Colgate, J. E., and Faulring, E. L. (2010). A framework for the simulation and haptic display of dynamic systems subject to holonomic constraints. The International Journal of Robotics Research, 29(4):336–352.
- [122] Rodríguez, Á. L., Cheeran, B., Koch, G., Hortobágyi, T., and del Olmo, M. Á. F. (2014). The role of mirror neurons in observational motor learning: an integrative review. European Journal of Human Movement, 32:82–103.
- [123] Rose, T., Nam, C. S., and Chen, K. B. (2018). Immersion of virtual reality for rehabilitation-review. Applied ergonomics, 69:153–161.
- [124] Rossi, S., Tecchio, F., Pasqualetti, P., Ulivelli, M., Pizzella, V., Romani, G., Passero, S., Battistini, N., and Rossini, P. (2002). Somatosensory processing during movement observation in humans. Clinical neurophysiology, 113(1):16–24.
- [125] Sadihov, D., Migge, B., Gassert, R., and Kim, Y. (2013). Prototype of a vr upper-limb rehabilitation system enhanced with motion-based tactile feedback. In 2013 World Haptics Conference (WHC), pages 449–454, Daejeon, Korea (South). IEEE, IEEE.
- [126] Saga, S., Kawakami, N., and Tachi, S. (2005). Haptic teaching using opposite force presentation. Proc. of the World Haptics, pages 18–20.
- [127] Saposnik, G., Levin, M., and Group, S. O. R. C. S. W. (2011). Virtual reality in stroke rehabilitation: a meta-analysis and implications for clinicians. Stroke, 42(5):1380–1386.
- [128] Schmalzl, L., Ragnö, C., and Ehrsson, H. H. (2013). An alternative to traditional mirror therapy: illusory touch can reduce phantom pain when illusory movement does not. The Clinical journal of pain, 29(10):e10–e18.

- [129] Seidler, R. D. (2010). Neural correlates of motor learning, transfer of learning, and learning to learn. Exercise and sport sciences reviews, 38(1):3–9.
- [130] Selles, R. W., Michielsen, M. E., Bussmann, J. B., Stam, H. J., Hurkmans, H. L., Heijnen, I., De Groot, D., and Ribbers, G. M. (2014). Effects of a mirror-induced visual illusion on a reaching task in stroke patients: implications for mirror therapy training. Neurorehabilitation and Neural Repair, 28(7):652–659.
- [131] Serrien, D. J., Ivry, R. B., and Swinnen, S. P. (2006). Dynamics of hemispheric specialization and integration in the context of motor control. Nature Reviews Neuroscience, 7(2):160–166.
- [132] Shin, Y., Lim, J., Kim, Y., Seo, D.-G., and Ihm, J. (2022). Effects of virtual body-representation on motor skill learning. Scientific Reports, 12(1):15283.
- [133] Shushtari, M., Takagi, A., Lee, J., Burdet, E., and Arami, A. (2022). Balance strategy in hoverboard control. Scientific reports, 12(1):4509.
- [134] Sigrist, R., Rauter, G., Riener, R., and Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. Psychonomic bulletin & review, 20:21–53.
- [135] Slater, M., Pérez Marcos, D., Ehrsson, H., and Sanchez-Vives, M. V. (2008). Towards a digital body: the virtual arm illusion. Frontiers in human neuroscience, 2:181.
- [136] Slater, M., Spanlang, B., Sanchez-Vives, M. V., and Blanke, O. (2010). First person experience of body transfer in virtual reality. PloS one, 5(5):e10564.
- [137] Spiss, S., Siess, M., Kim, Y., and Harders, M. (2018). Effect of touch stimuli on proprioceptive recalibration during upper-limb rotation in virtual reality mirror therapy. In 2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob), pages 279–284, Enschede, Netherlands. IEEE, IEEE.
- [138] Srimathveeravalli, G. and Thenkurussi, K. (2005). Motor skill training assistance using haptic attributes. In First joint eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems. World haptics conference, pages 452–457. IEEE.
- [139] Suk, H. and Laine, T. H. (2023). Influence of avatar facial appearance on users’ perceived embodiment and presence in immersive virtual reality. Electronics, 12(3):583.

- [140] Swinnen, S. P., Dounskaia, N., Levin, O., and Duysens, J. (2001). Constraints during bimanual coordination: the role of direction in relation to amplitude and force requirements. Behavioural Brain Research, 123(2):201–218.
- [141] Thieme, H., Mehrholz, J., Pohl, M., Behrens, J., and Dohle, C. (2013). Mirror therapy for improving motor function after stroke. Stroke, 44(1):e1–e2.
- [142] Thieme, H., Morkisch, N., Mehrholz, J., Pohl, M., Behrens, J., Borgetto, B., and Dohle, C. (2018). Mirror therapy for improving motor function after stroke. Cochrane database of systematic reviews, 2018(7).
- [143] Tilak, M., Isaac, S. A., Fletcher, J., Vasanthan, L. T., Subbaiah, R. S., Babu, A., Bhide, R., and Tharion, G. (2016). Mirror therapy and transcutaneous electrical nerve stimulation for management of phantom limb pain in amputees—a single blinded randomized controlled trial. Physiotherapy research international, 21(2):109–115.
- [144] Van der Meijden, O. A. and Schijven, M. P. (2009). The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. Surgical endoscopy, 23:1180–1190.
- [145] Vasantachart, A. Y., Yeo, E., and Chau, B. (2022). Virtual and augmented reality-based treatments for phantom limb pain: A systematic review. Innovations in Clinical Neuroscience, 19(10-12):48.
- [146] Vecchiato, G., Jelic, A., Tieri, G., Maglione, A. G., De Matteis, F., and Babiloni, F. (2015). Neurophysiological correlates of embodiment and motivational factors during the perception of virtual architectural environments. Cognitive processing, 16:425–429.
- [147] Waltemate, T., Gall, D., Roth, D., Botsch, M., and Latoschik, M. E. (2018). The impact of avatar personalization and immersion on virtual body ownership, presence, and emotional response. IEEE transactions on visualization and computer graphics, 24(4):1643–1652.
- [148] Wang, H., Fang, X.-Y., and Yao, J. (2023). Synergic effect of the combination of mirror therapy and electrical stimulation for lower extremity motor function recovery in stroke survivors: a meta-analysis of randomized controlled trials. Topics in Stroke Rehabilitation, 30(1):73–83.
- [149] Weber, L. M., Nilsen, D. M., Gillen, G., Yoon, J., and Stein, J. (2019). Immersive virtual reality mirror therapy for upper limb recovery following stroke: A pilot study. American journal of physical medicine & rehabilitation, 98(9):783.

- [150] Wickens, C. D. (2002). Multiple resources and performance prediction. Theoretical issues in ergonomics science, 3(2):159–177.
- [151] Wolf, E., Merdan, N., Dölinger, N., Mal, D., Wienrich, C., Botsch, M., and Latoschik, M. E. (2021). The embodiment of photorealistic avatars influences female body weight perception in virtual reality. In 2021 IEEE Virtual Reality and 3D User Interfaces (VR), pages 65–74. IEEE.
- [152] Yeh, S.-C., Lee, S.-H., Chan, R.-C., Wu, Y., Zheng, L.-R., Flynn, S., et al. (2017). The efficacy of a haptic-enhanced virtual reality system for precision grasp acquisition in stroke rehabilitation. Journal of healthcare engineering, 2017.