EXPLORING THE EFFECT OF HAND APPEARANCE AND TACTILE FEEDBACK ON THE VIRTUAL HAND ILLUSION

by

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ABSTRACT

Current virtual reality (VR) technologies allow users to not only observe virtual environments but also interact within them by performing a variety of tasks more efficiently and intuitively. In addition, humans experience VR content not only through their visual and auditory systems but also through the somatosensory system. Therefore, we decided to perform three different studies regarding Virtual Hand Illusion (VHI).

We conducted our first 3 x 2 study (abstract, mannequin, and realistic x tactile and no tactile) both in our lab setting and remotely to investigate the effects of virtual hand appearance and tactile feedback on ownership, external appearance, and tactile sensation embodiment dimensions when participants were instructed to perform an assembly task in a virtual environment. As a result, we observed that the mannequin hand had a greater effect size on ownership, and the realistic hand had a greater effect size on tactile sensation and external appearance. We also found that the tactile feedback condition had a greater effect size on external appearance than the no-tactile feedback condition, and the realistic hand appearance in conjunction with the tactile feedback had a significant effect size on the perceived tactile sensation. Participants in the lab setting rated the external appearance of the realistic hand model higher than the remote participants.

We conducted a second virtual reality study to explore the virtual hand illusion through three levels of appearance (Appearance dimension: realistic vs. pixelated vs. toon hand appearances) and two levels of tactile feedback (Tactile dimension: no tactile vs. tactile feedback using another virtual assembly task. We asked the participants to provide self-reported ratings on a survey that captured presence and five embodiment dimensions (hand ownership, touch sensation, agency and motor control, external appearance, and response to external stimuli). The results of our study indicated that (1) tactile feedback was associated with a stronger sense of presence, touch sensation, and response to external stimuli; (2) pixelated hand appearance was associated with the least hand ownership and external appearance; and (3) in the presence of the pixelated hand, prior virtual reality experience of participants was associated with their agency and motor control and their response to external stimuli ratings.

For our third study, we conducted a VR study to further explore the just noticeable difference (JND) of tactile feedback to understand humans' perceptions of tactile stimuli. Our VR study examined the JND in terms of the intensity, duration, and frequency of tactile feedback

provided through commercially available vibrotactile motion controllers, the Oculus Quest 2 controllers. We instructed participants to report whether they perceived a difference between a reference (variation) and a testing stimulus at each point in the experiment for a different property (intensity, duration, and frequency) of tactile feedback. We report both positive and negative JND values for the three properties of tactile feedback. We discuss our findings and limitations at the end of each chapter and provide future study directions in the final chapter.

In the end of the dissertation, we list out our contributions of all three studies in two different directions. One is regarding the design considerations in VR assembly applications. We consider specific hand models, hand and finger animations and assembly task indicators should be applied. The other direction is virtual hand design guideline. We suggest specific rendering style, activation of tactile feedback and JND values for adjustment in VR applications should be developed for stronger sense of embodiment.

CHAPTER 1. INTRODUCTION

1.1 Motivation

Hands are vital for daily life tasks, and the same applies to virtual reality (VR). "Virtual hand illusion" (VHI) describes the illusion of ownership of virtual hands [130]. It refers to the observation that VR users perceive "body ownership" if a virtual hand moves or senses feedback in a virtual environment. VHI studies have explored the effects of different hand model geometries (e.g., realistic hand shape, mannequin hand shape, low-poly blocks, and mini-sphere dots). They found that the actual hand shape generated more substantial ownership than the other geometries [76][77]. In addition, studies in the past found the importance of virtual hand appearance, indicating that with the existence of virtual hand models, the VR environment became more appealing to users [52][64][91]. Further understanding of VHI would provide more detailed design principles for virtual hand models and methods to aid task performance [44][51][56].

Current virtual reality (VR) technologies allow users to not only observe virtual environments but also interact within them by performing a variety of tasks more efficiently and intuitively. Many virtual reality devices enable users to control 3D hand models and interact with virtual objects through using virtual reality controllers. Virtual hands are essential for both forceful and manipulation tasks [110]. In previous VR studies, the inclusion of virtual hands was associated with better task performance for object interaction [109]. Moreover, the existence of virtual hands seems to improve visual cognition, due to increases in short-term memory [107], and enhances cognitive control [108]. It has been observed that when users observe virtual hand models, the virtual reality experience becomes more appealing to them [11][52][64][69]. In modern VR applications, the integration of virtual hands has become an essential design principle [27].

VR developers can also import somatosensory cues in VR by activating the tactile feedback. Tactile feedback refers to the physical response on a device from user input, simulating the sensation of touching and tapping. The use of such technology makes it possible to apply tactile feedback to the feet [169], upper body (chest and back) [170][137], fingertips [171], hands [172][79], and arms [173]. Tactile feedback has been widely applied in different areas, such as mobile interaction [174], social interaction [7][137][138][139], augmented reality [175], surgery [176], and games [82]. The presence of vibrotactile feedback in virtual reality applications provides users with a more realistic interacting experience in virtual environment, and it has become an important factor in fortifying the sense of embodiment in immersive environments [165][166][167][168]. A previously conducted study showed that vibrotactile feedback can enhance the sense of immersion and interactivity for VR users [86]. Moreover, recent studies have shown that the vibrotactile feedback of VR controllers could increase the perceived realism of the appearance of the virtual hands [79], as well as the sense of presence and involvement [112] of VR users. Based on the previous results tactile feedback was in relation to virtual hand illusion as it provided the sense of touch and feel of virtual hands in immersive environments.

In the past, psychophysics studies [153][154][155][156] have explored how humans differentiate tactile feedback in terms of intensity and frequency, which provides a better understanding of how humans perceive tactile feedback. Researchers have used self-made haptic devices such as wearable controllers [177], fingertip vibrators [147], and vibration chairs [156]. To the authors' knowledge, no studies have been conducted so far on estimating the just noticeable difference (JND) value—in psychophysics, which is a branch of experimental psychology, a JND is the amount a stimulus must be changed in order for a difference to be noticeable, detectable at least half the time (absolute threshold)[1] — for virtual reality (VR) controllers' tactile feedback.

JND can help people understand differences and assist with measuring subjective sensitivity to the variation of vibrotactile feedback [192]. Application of JND is essential for cases that require special attention to detail. In the case of VR training applications, VR developers might need to create training scenarios that require trainees to pay attention to specific complex actions by providing the least noticeable tactile feedback. For example, in engineering training applications such as maintenance of induction motors [195], workbench assembly and failure detection can be complex and challenging, requiring extreme caution, and thus more appealing differences of vibration feedback comparing to other responses are essential. Developers can also apply JND values for tactile feedback parameter calibration in user interface [197]. Other cases like surgical simulator and virtual prototyping [198] can also be applicable cases that require additional caution. In case of VR training application, VR developers might need to create training scenarios that require trainees to pay attention to specific complex actions by providing the least noticeable tactile feedback. Thus, knowing how people perceive JND of tactile feedback could

[1] Weber's Law of Just Noticeable Difference. University of South Dakota http://apps.usd.edu/coglab/WebersLaw.html

help developers more specially informing the users for different situations. Furthermore, applying JND as different conditions of tactile feedback can be an interesting approach to see how variations of external stimulus can affect the virtual hand illusion and the sense of embodiment.

Overall, the main purpose of this dissertation is to explore the relationship between hand appearance, tactile sensation, and virtual hand illusion. We have taken into account previous research which indicates that identifying the design principles of avatars is a requirement [44] and that tactile feedback seems to aid task performance in immersive environments [50][51]. Therefore, we conducted three studies to find the impact of hand appearances in terms of hand model and hand shaders, and tactile feedback in terms of JND of different properties.

1.2 Scope

Virtual hand illusion refers to the illusion of ownership of virtual hands. Therefore, it is important to consider how participants perceive their virtual hands in the virtual environment. In this dissertation, we focused on two aspects of the virtual hand: appearance and tactile perception.

In order to create an immersive and realistic virtual environment, there are several aspects that need to be taken under consideration: interaction task design, virtual environment model, VR hardware setup and player control. Moreover, typical virtual hand studies include different characteristics (model appearance, size, rendering style, etc.) [76][77][230]. We decided to follow the methodology from previous studies [76][77][78] to design two sets of different hand appearances. The first set of hands have different models in terms of fidelity (Figure 1). We designed an abstract hand, a mannequin hand, and a realistic hand for the first study.

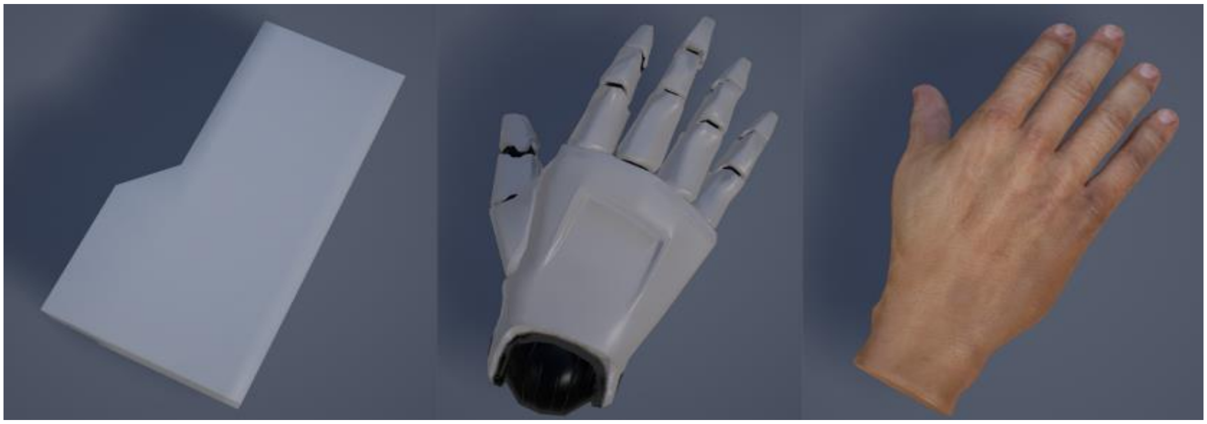

Figure 1. The three different hands used in the first study. From the left: abstract hand, mannequin hand, realistic hand.

For our second study, we were focusing on more detail in the effect of shaders on embodiment. We knew previous studies [76][77] compared the difference between hand models with a larger scale (differences and gap in between rendering style), and therefore we decided to use smaller manipulation in terms of shaders to study in more detail about whether such appearance difference can affect embodiment. Moreover, studies in the past already applied similar shaders and have found significant results in human perception [140][141]. In fact, less detailed shaders like pixilation and toon were found to be more likeable [142]. Having more detail on virtual agents would cause the perceived eeriness to decrease [141]. Therefore, we designed three shaders (Figure 2) for our realistic hand appearance.

Figure 2. The three different hand shaders used in the second study. From the left: realistic, pixelated and toon hand appearance.

For our third study, we needed to consider the different properties of tactile feedback in order to find the JND. These properties of tactile feedback include intensity, duration, and frequency. For all three properties, it was important to find a reference value to compare with. In addition, we also designed both positive and negative values with the same difference for comparison.

1.3 Contribution

This thesis investigated the effect of hand appearance on virtual hand illusion. Moreover, we further explored more details on how people perceive minimal differences for each property of tactile feedback to learn more about human experience. To fulfill this purpose, we conducted three individual VR studies.

The first study utilizes knowledge from previous studies and extends upon them by investigating the effects of virtual hand appearance and tactile sensation on ownership, tactile sensation, and external appearance dimensions of embodiment. We conducted a 3 x 2 study (abstract, mannequin, and realistic hand models x tactile and no tactile feedback) study to determine the key factors contributing to the three above-mentioned embodiment dimensions. We think that our results contribute to further understanding how hand appearance and tactile sensations will affect most participants.

Based on the results of the first study, it was necessary to explore the realistic appearances of virtual hands to understand the potential effects on VHI. Thus, this study utilized knowledge from previously published research and built upon it. We conducted a 3 x 2 (Appearance (Shaders) x 2 (Tactile) study to examine the key factors contributing to the sense of presence and the five abovementioned body ownership dimensions.

Besides hand appearance, we found that it was also essential to study on tactile feedback properties. The third study examined the JND in terms of the intensity, duration, and frequency of tactile feedback provided through commercially available vibrotactile motion controllers, the Oculus Quest 2 controllers. We instructed participants to report whether they perceived a difference between a reference (variation) and a testing stimulus at each point in the experiment for a different property (intensity, duration, and frequency) of tactile feedback. We reported both positive and negative JND values for the three properties of tactile feedback.

In conclusion, the findings of the above studies can be valuable resources for VR application development where hand interaction with tactile feedback is required. These results can be used as an essential design consideration for future virtual reality assembly-related virtual reality applications. Moreover, the knowledge obtained from this study can help the research community develop more efficient VR assembly applications that involve virtual hand appearance and tactile feedback. Developers can create a more realistic VR training environment without the safety risks in the real world.

1.4 Overview of the Thesis

Chapter 1 is an introductory chapter. We introduce our motivation and scope of this dissertation. We also described the three studies conducted that fulfilled our research purpose. In the end, we discussed the contribution of our findings to VR development.

Chapter 2 is the literature review chapter. We review the state-of-the-art in four major sections: embodiment, virtual hand illusion, tactile feedback, and perception. More specifically, perception and body ownership, the effect of virtual hand appearance and tactile feedback, and human perception of tactile feedback is presented. Analysis of each topic is also shown at the end of each section.

Chapter 3 is the methodology review chapter. We provide the current situation of VR training applications. Specifically, we discuss our decision on selecting assembly application as the base for our VR study methodology. Moreover, we also present our basic design decisions and interaction mechanics for all three studies' applications.

Chapter 4 contains the study details of our first VR study. We conducted a study to investigate the effects of virtual hand appearance and tactile feedback on ownership, external appearance, and tactile sensation embodiment dimensions when participants were instructed to perform an assembly task in a virtual environment. Six experimental conditions that combine hand appearances (Appearance dimension: abstract vs. mannequin vs. realistic) and tactile feedback (Tactile dimension: no tactile vs. tactile) levels were examined. We discussed our results at the end of the chapter.

Chapter 5 contains the study details of our second VR study. We conducted another virtual reality study to explore virtual hand illusion through three levels of appearance (Appearance dimension: realistic vs. pixelated vs. toon hand appearances) and two levels of tactile feedback

(Tactile dimension: no tactile vs. tactile feedback). We instructed our participants to complete a different virtual assembly task in this study. This chapter ends with our thoughts and discussion about hand appearance's effect.

Chapter 6 contains the study details of our third VR study. We decided to conduct one more virtual reality study to explore the just noticeable difference (JND) of tactile feedback to further understand humans' perceptions of tactile stimuli. We explored the JND in terms of intensity, duration, and frequency of tactile feedback provided through the Oculus Touch controllers. We instructed participants to report whether they perceived a difference between a reference (variation) and testing stimulus at each point in the experiment for a different property (intensity, duration, and frequency) of tactile feedback. We report both positive and negative JND values for the three properties of tactile feedback.

Chapter 7 is the concluding chapter. We presented our results and future direction in this chapter. Specifically, we pointed out the following questions and directions for future studies: a) discovering aspects of full virtual body affects the sense of embodiment; b) how Oculus Quest's built-in hand interaction model affects VHI; c) what other factors can affect JND of tactile feedback; d) a study using determined JND as conditions to discover the effect of hand vibrotactile feedback on VHI.

CHAPTER 2. LITERATURE REVIEW

2.1 Embodiment

The sense of embodiment is the phenomenon that we feel of our own body by receiving a flow of information related to vision, touch, proprioception, and neural system [199]. Gonzales-Franco and Peck [1] proposed six different embodiment dimensions: body ownership, agency and motor control, tactile sensations, location of the body, external appearance, and response to external stimuli. The sense of embodiment has been studied in many different aspects, including the effects of self-motion artifacts [32] and visuomotor calibration [16], the effects of tactile sensation [7], and the effects of external appearance [2][69]. Additionally, studies that explore the effects on users' embodiment in serious game [15] or training [13] and learning [12] domains have also been conducted. Although there are a number of elements (embodiment dimensions) that could affect self-avatar embodiment in virtual environments [1], it is important to understand what these elements are and how they interact with each other.

2.1.1 Perception

2.1.1.1 Multisensory Information

Among the properties we perceive from our body, one of the most important aspects was the information of body in-space. This information was received through visual, somesthetic (bodily felt) and vestibular sensory inputs; the motion from the head and body limbs with strong motivational projections from the limbic system [200]. This information was then "coded" into the posterior parietal cortex (PPC) and premotor cortex to generate space information with reference to the individual [201][202]. Some general examples of these references include eye, head and body [203][204]. Figure 1 shows how PPC transforms information from our brain to body coordinates.

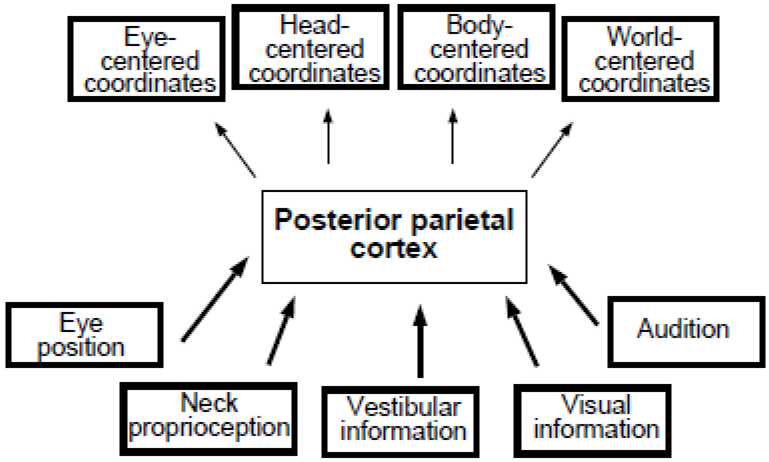

Figure 3. The information transformation through the PPC [204].

2.1.1.2 Proprioception

Proprioception was derived from the Latin word “proprius” meaning “one’s own” and “perception”, referring to the sense of the position of body parts, especially the limbs [205]. Feldman and Latash [206] proposed that proprioception provide feedback regarding efferent information of the body (effort, force, and balance). According to Kammers et al. [207], proprioception information was received by receptors in muscles, tendons, joints, and skin. Then the information was processed by multimodal neurons in PPC [207]. In a study related to perception of movements using muscles, Proske et al. [208] found that movement detection threshold in muscles was higher in active movement comparing to passive movement.

Proprioception was further explored in immersive environment studies. Hong et al. [209] reported reduced ability to integrate sensations for stroke patients. In their study using VR upper limb motor assessment system, they found that excessive reliance on vision hindered stroke patients on reaching accuracy, which approved the function of proprioception [209]. Cho et al. [210] performed a study with proprioception training of Hemiplegia patients. By manipulating visual feedback, they found that VR was a successful tool for training, reaching movement and enhancing proprioception, which aligned with the previous findings [208]. Figure 4 shows the training environment.

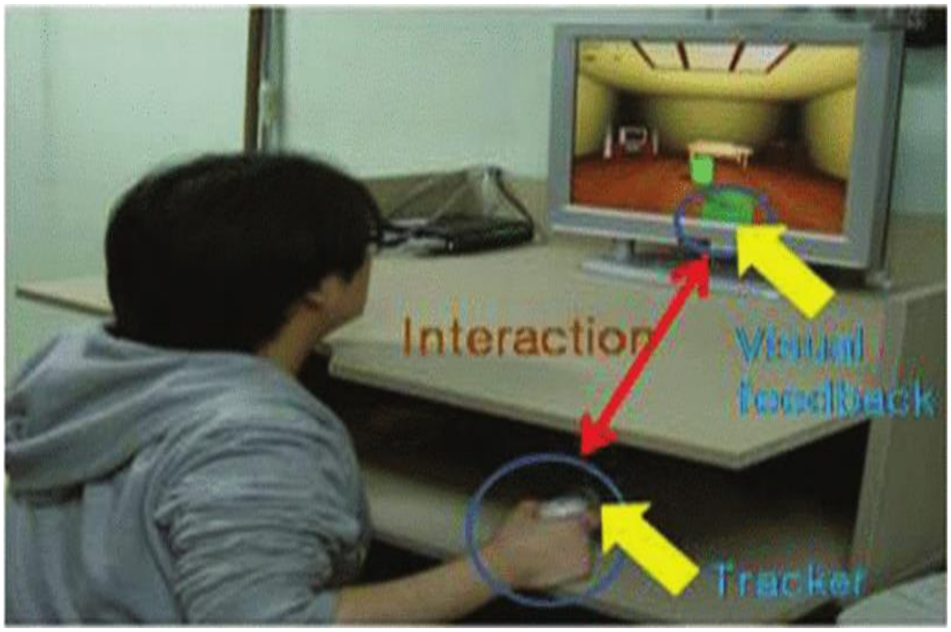

Figure 4. The training environment of Proprioception Training system using VR [210].

Furthermore, a phenomenon that vibration induces limb position illusion was found. Many studies found that applying vibration to limbs would cause out-of-body illusion by losing the association in between perceived location and the effort required to achieve that location [211][212]. Moreover, vibration also caused illusory displace of the limb into anatomically impossible locations. In Craske's study [213], participants felt their hand being bent back to the forearm with vibration. In modern approaches, this phenomenon was confirmed by others. Kiguchi and Honda [214] did a study regarding the effect of frequency in vibration stimulation. Results from their study indicated that the amount of elbow joint motion change increases with the increase of frequency [214]. In addition, they also performed the same study with knee joints [215]. Again, the same results were found: lower-limb motion change could be generated with vibration stimulation [215].

2.1.1.3 Visual Perception

The phenomenon, visual capture, refers to the dominance of the information perceived visually over the information from all other perception cues. Interestingly, in many cases, people favor visual inputs over proprioceptive input [205]. This phenomenon was demonstrated in different studies. Gross and Melzack [216] observed a drift on the proprioceptive input onto the fake limb when the actual limbs were hidden. Botvinick [88] found a similar phenomenon on the limbs under passive movements (Figure 5). Graziano [217] proposed that, under correct circumstances, visual input affect conscious bodily experience.

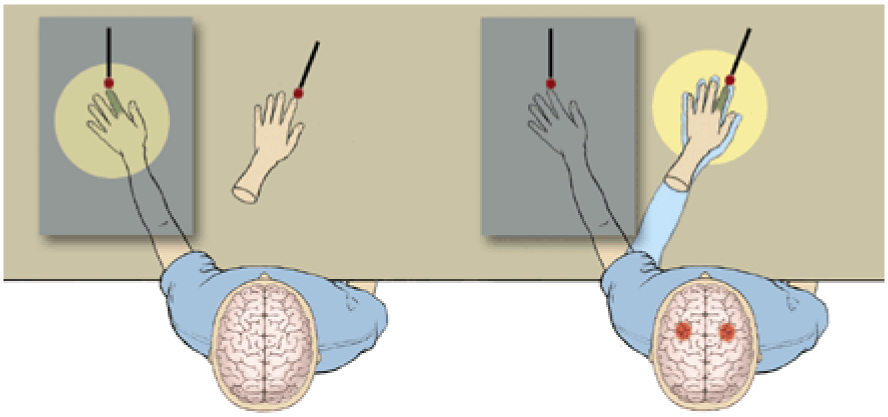

Figure 5. In Botvinick's study, both the artificial limb (hand on the outside) and the real hand (hidden under view) are stroked. The right image shows that the participant experiencing the illusion feels that the rubber hand is his own hand. The red spots in the premotor cortex refers to the tactile and visual receptive fields [88].

In the immersive environment, the visual dominance was studied using VR. Burns et al. [218] conducted a study regarding visual dominance. Participants were able to control a virtual hand in a VR application to "penetrate" objects. As a result, participants were much less sensitive to visual-proprioceptive conflict than visual interpenetration [218]. Alshaer et al. [219] adopted/opted for a more interactive approach using a virtual driving application. They tested out different input devices for driving from high-end simulation software to low-end gaming joysticks. In conclusion, they reported significance for visual dominance effects on driving performance regardless of the input devices [219].

2.1.2 Body Ownership

2.1.2.1 Body Schema and Body Image

Bodily experience contained two important components: the automatic, bottom-up sensory and organizational processes (body schema) and the higher-order, top-down bodily and perceptual representations (body image) [207][220]. Kammers et al. [207] proposed body schema as a representation of spatial and biomechanical properties of the body. This concept was often referred to "an active operative performance of the body rather than a copy, image, global model or conception of the existing part of the body" [221]. In addition, the body image referred to the "owned, but abstract and disintegrated" body representation [221]. In Gallagher and Cole 's study [222], three key points were provided for body image: (1) perceptual experience of own body; (2) conceptual understanding of general body; (3) emotional attitude toward own body.

Similar approaches were utilized in VR regarding embodiment in virtual bodies. Body-image studies were done mainly on the appearance of virtual body (parts). Kilteni et al. [41] explored the effect of human skin color on virtual embodiment (Figure 6). It was found that full body ownership illusions can cause substantial behavior and possible cognitive changes [41] which aligned with the key points of body image [222]. Lin and Jorg [76] did a study on the effect of hand appearance on virtual hand illusion. Their findings indicated that non-anthropomorphic block model generated the strongest for hand illusion [76].

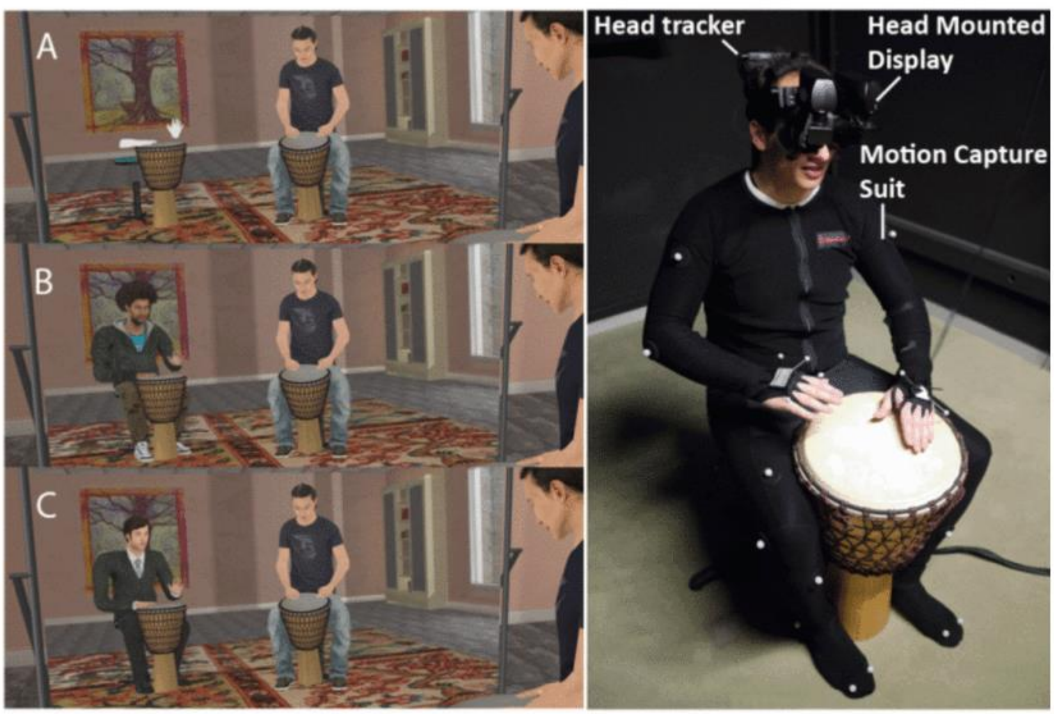

Figure 6. Left: the three conditions of the experiment: (A) White hand only. (B) Casual Dark-Skinned avatar. (C) Formal Light-Skinned avatar. Right: The setup for the participant with HMD, motion capture suit and tracker [41].

On the other hand, body schema was done more on the tactile feedback and interaction of virtual body (parts). Moore et al. [98] explored the effect of haptic feedback for artificial limbs. As a result, vibrotactile feedback generated embodiment in grasping tasks, indicating that a significant proprioceptive drift happened to the virtual hand [98]. Eubanks et al. [135] performed a study about the effect of different tracking fidelities on embodiment of an IK character. Their result indicated that tracking the head, hands and feet significantly increase the sense of embodiment and the sense of spatial presence [135] because those three body parts provided the most accurate spatial and biomechanical information of the entire body.

2.1.2.2 Phantom Limbs

Phantom limb is the illusion of perceiving a limb that does not exist in the body. This phenomenon was widely studied in clinical cases. Phantom limbs were usually perceived by those who had limb amputation, deafferentation or spinal cord injury [205]. Phantom limbs could affect embodiment in different ways. Conomy [223] found that phantom limbs could assist patients with SCI to recover the feeling of knees and ankles. Bors [224] found that patients with SCI could be experiencing unrealistic and unnatural postures, such as “twisted”, “crossed” or “blown up” legs.

Advanced techniques were used in modern approaches in studying the phantom limb phenomenon. An intriguing study was done on healthy participants. Thogersen and Petrini [225] removed participants’ own limb using Mixed Reality while still probing body perception and thermal sensitivity. In their study, participants reported that they felt a retraction or telescoping of their limb proximally, indicating the change of body perception [225]. In a different method, Wake et al. [226] designed a VR rehabilitation application with tactile feedback to relieve phantom pain. By applying tactile feedback on the intact limb, patients reported significant decrease on phantom pain. This study proved the effect of mirror visual feedback and tactile feedback in reducing the phantom limb phenomenon. The findings also provided better understanding in embodiment in immersive environments. Figure 7 shows the VR rehabilitation system structure.

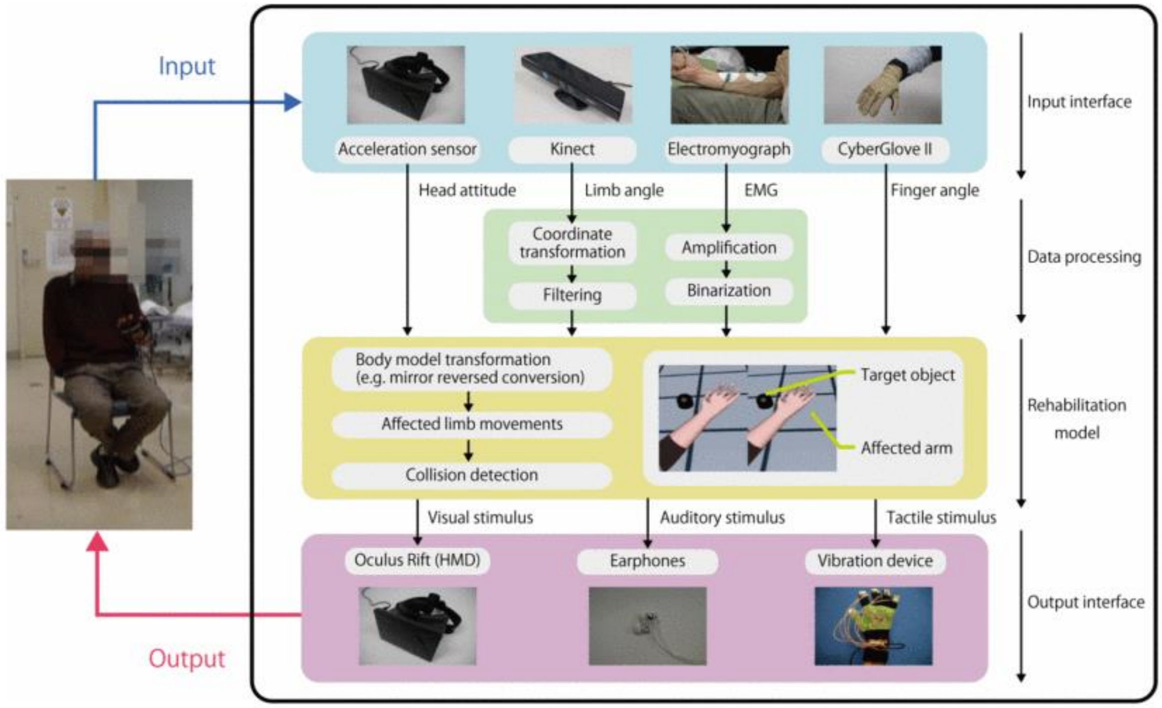

Figure 7. The system structure for the VR rehabilitation application to relieve phantom pain. The system provides motion tracking, tactile feedback to the virtual arm [226].

2.1.2.3 Rubber Hand Illusion

Botvinick and Cohen [18] introduced the "Rubber Hand Illusion" (RHI) for healthy populations. In their study, they indicated that limb ownership can be manipulated through illusory embedment of a rubber limb. Participants tend to feel the fake rubber arm as the real arm [18]. In a later study by Ehrsson et al. [100], it was confirmed that this phenomenon was depending on multiple sensory inputs, including vision, touch, and proprioception. Armel and Ramachandran [227] also found that pain and movement can be perceived in an embodied rubber limb.

Prior to the studies in VR, many psychology studies had been done on revisiting the RHI. In Ehrsson [100]'s study, participants only saw the rubber hand being stroked while their hidden left hand was also stroked. Under coordinated stimulation on both the real hand and the rubber hand, the MRI scanner showed that the premotor cortex was activated, which facilitated showing the transition of hand ownership from the real hand to the rubber hand [100]. In a further study done by Tsakiris and Haggard [19], the study with four experiments was revisited to understand the phenomenological content of RHI. In experiments, they controlled the factors with different rubber hand angles, different rubber hand representation (wooden stick), congruent and incongruent rubber hand representation, mode of stroking (synchronous and asynchronous) and parts of stroking (different fingers), they found that the RHI was more related to the body than the stimulation (Figure 8). The shift of ownership was an adaption of mislocalization of the stimulated body part [19]. Moreover, Dummer et al. [114] also replicated the RHI study with hand movement in the horizontal direction. In their study both the real hand and the fake hand were moving horizontally in the same direction with a wooden stick poking the side of the hand. Similar to the previous studies, synchronous condition was compared to the asynchronous condition. In addition, passive movement was compared to active movement. As a result, synchronous visual and proprioceptive information yielded higher score of RHI [114]. Active movement participants also reported greater RHI [114].

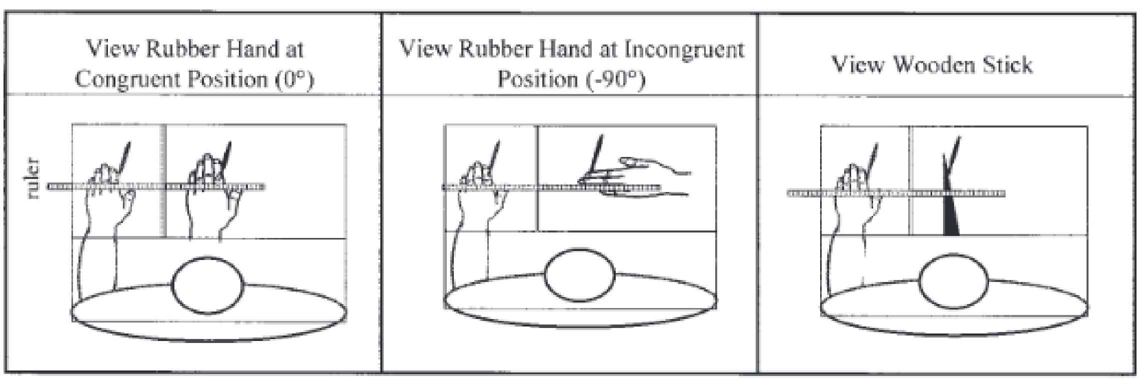

Figure 8. The experiment setup for Tsakiris and Haggard's study [19]. Participants saw different objects in different conditions while the left hand was hidden.

The RHI experiments were replicated in VR to under the effect of different factors on embodiment. In Lin and Jorg (2016)'s study, they asked the participants to get used to the virtual hands first, then they performed a knife cut on the virtual hands. Similar approach was done by Argelaguet et al. [2], in which they included virtual hand interaction with various objects (brick, barbed wire/fire and spinning saw). They reported that less realistic hand generated stronger sense of agency [2]. A different approach was taken by Kondo et al. [27], where they tried to remap a right thumb to a virtual right arm by applying synchronous movements of the thumb and the arm.

As a result, participants felt their own right thumb became the virtual right arm, and illusory body ownership was induced by synchronizing different body parts [27].

Extending upon the RHI, studies have been conducted to investigate the participants' ownership of other body parts, including the brain system [23][24], skin color and temperature [25][26], and foot movements [27]. Lopez et al. [23] found that performing caloric and galvanic vestibular stimulations on healthy subjects generated a strong sense of ownership. Ehrsson et al. [24] suggested that body ownership is formed throughout fast and continuously occurring activities in the cerebellar area. Farmer et al. [25] investigated the effect of embodying different skin colors and found that embodying black skin increased embodiment and lowered racial bias. Finally, Haans et al. [26] claimed that skin colors that do not resemble human skin decreased the perception of RHI.

Besides the partial embodiment induced through RHI, studies investigating the whole body have also been conducted [21][28]. Lurgin et al. [21] investigated the effect of self-avatar appearance on ownership. They found that robot- and cartoon-like avatars elicited a stronger sense of ownership from their participants than human-like avatars (Figure 9). Maselli and Slater [28] also studied full-body illusion. In their immersive VR study on identifying the building blocks of this ownership illusion, they asserted that the first-person perspective was essential in experiencing a sense of ownership.

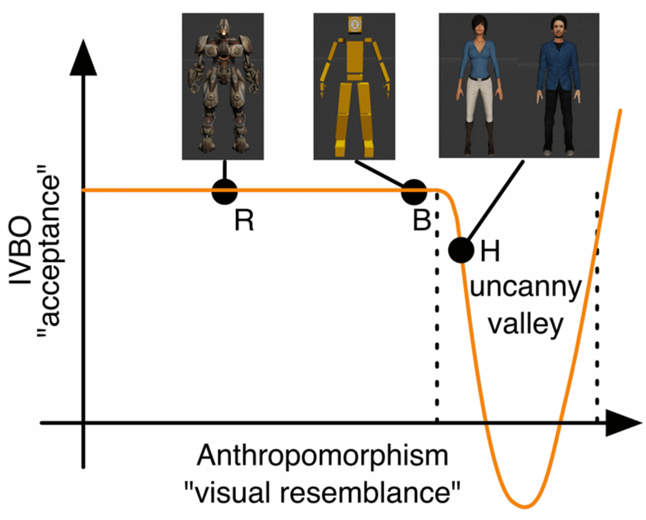

Figure 9. The strength of Illusion of Virtual Body Ownership (IVBO) on different virtual body representation [21].

In immersive environments, it is important to design a realistic body appearance in order to achieve the highest sense of ownership [35]. Body appearance may affect embodiment in many ways, including racial, gender, age, and even cultural factors [37][38][39]. The level of body ownership illusion varies among different study participants and different situations. For example, embodying a black avatar reduces racial bias [40], while embodying a man/woman wearing a suit can lead to substantial behavioral changes [41].

Overall, RHI is the phenomenon that people are perceiving a virtual limb as their actual part of the body. It is related to synchronization of perceived information and body sensation. All approaches brought out significant understanding of RHI about the phenomenon explanation. Tsakiris and Haggard [19]'s approach was a vanguard for controlling hand appearance and feedback location. Dummer et al. [114]'s study also proved previous findings that actions, and sensory components together can generate a sense of body awareness. Moreover, active movement of the body part can generate stronger illusion. According to the previous studies, RHI can be used to "fake out" the sensation of real body parts and can provide realistic tactile feedback experience or help with rehabilitation of damaged limb [225][226]. Therefore, more studies should be done on RHI to understand the reason behind the phenomenon and the methods to generate stronger illusion.

2.1.2.4 Out-of-body Experience

Besides embodiment, disembodiment was also studied to understand central and peripheral dysfunction. Out-of-body experiences (OBE) were the most widely reported of the autoscopic phenomena [205]. Blanke and Arzy [243] defined OBE as heautoscopic (seeing one's own body from a distant) disembodiment and seeing the world at a distant. It was confirmed that OBE could happen in both healthy and unhealthy populations [243]. According to the past studies, OBE was resulted in asynchronous perception from three sources: vestibular, central representations of one's own image and somatosensory and proprioceptive inputs [244][245].

In VR studies, OBE was applied more as a methodology to study other variables and factors. Bourdin et al. [246] did a virtual out-of-body experiment using a mirror in the virtual environment (Figure 10). They achieved OBE on the participants by adjusting the viewport. As a result, they reported the fear of death was found to be lower in the OBE condition, thus indicating out-of-body experience reduces the feat of death [246]. In another study, van Heugten-can der Koloet et al.

[247] explored the effect out-of-body experience on acute dissociation. As a result, they found a significant increase in acute dissociation after VR exposure [247]. This study pioneered the path of investigation dissociation in VR.

Figure 10. Left: the in-body condition. Right: the out-of-body condition [246].

2.2 Virtual hand Illusion

Virtual hand illusion is a common research topic for VR studies. Starting from the rubber hand illusion (RHI) studies, researchers believe that body ownership happens when manipulation of the visual prospective of the object occurs and when sensory signals related to that object is supplied. Users can perceive their virtual hands using either explicit (actively assessing body size and shape, e.g., “How long is my hand?”) [116] or implicit methods (finding landmarks on specific body parts, e.g., “Where is my wrist?”) [118]. In VR, these methods correspond to visual and haptic methods [115]. Studies in VR have found both ways to be effective, by providing realistic hand appearance for VR hand models [76][77][80] and tactile feedback for participants to locate their hands and landmarks [79]. In the past years, studies had been mainly focusing on the effect of different hand appearance (realism, style, size, and skin color) [76][77][80][230] and tactile feedback (feedback patterns and feedback locations) [116][117][118] of the realistic hand. Some had a different approach such as using continuity between hand and body as a factor. In this section, different approaches of exploring VHI will be discussed.

2.2.1 Virtual Hand Appearance

Most studies were done on the realism of virtual hand appearance to seek the effect on VHI. Past studies focused on appearance realism, size of the hand and skin color’s effect on hand illusion.

Lin and Jorg [76] did a between-group study to find how different hand appearances affect virtual hand illusion. Six different appearances (realistic, toony, very toony, zombie, robot, and wooden block) were used (Figure 11). Participants took time to get used to their virtual hands and played two games using the hands: one was blocking virtual spheres, and the other was taking hit from a knife with blood effect (Figure 10.). As a result, VHI happened for all models. However, the effect was perceived weakest for the block model and strongest for the realistic human hand model [76]. Schwind et al. [77] also worked with different hand models and discovered the effect of hand appearance on visual haptic integration. The study combined different and models with haptic feedback on a 3D printed surface so that participant would feel their hand touching the surface. Five appearances were used in the study (realistic human hand, mechanical robot hand, cartoon hand, abstract hand and invisible hand). Significances were found for hand appearance on visual-haptic integration and virtual limb ownership. In addition to changing different models, Kilteni et al. [41] performed a drumming study using different skin colors (white, casual dark-skinned, formal light-skinned) on the virtual hand. In their experiment, participants experienced full-body immersion with a mirror in the environment. Participants were asked to play the drum following a virtual character in the scene. Results indicated that casual dark-skin condition showed stronger movement patterns [41]. Thus, participants embodied in casual dark-skin felt stronger body ownership. Other studies done by Heinrich et al. [96], Pyasik et al. [42] and Argelaguet et al. [2] performed similar approaches by using different hand appearances as conditions and performed either mere hand observation or object manipulation with obstacles using the hands. They mentioned that detailed hand appearance could be an essential factor contributing to VHI [42].

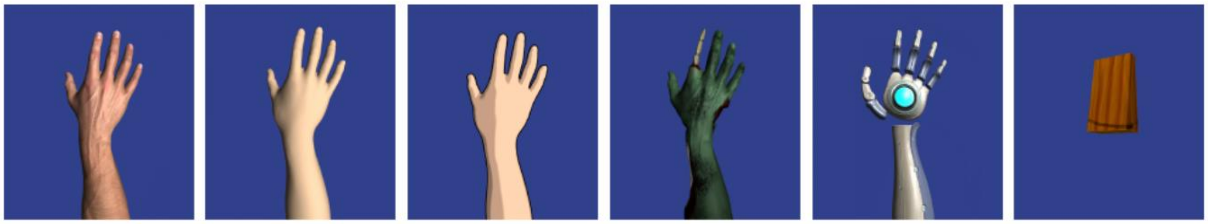

Figure 11. The six geometries used in the hand appearance study [76].

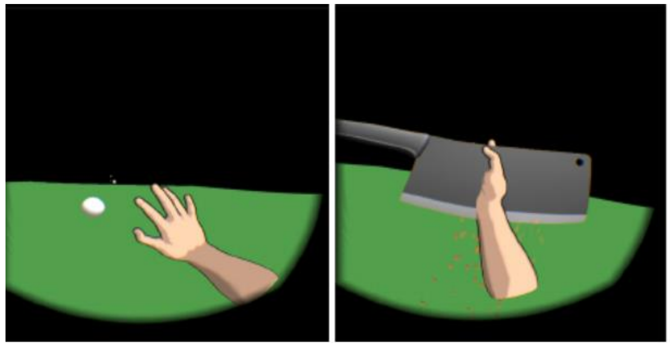

Figure 12. Left: The ball game as the condition phase of the study. Right: The knife hitting the model [76].

Hand appearance has a significant effect on virtual hand illusion. Realistic hand and darker skin both generate stronger VHI and body ownership. From the previous research, VHI can provide users realistic experience and stronger body ownership in VR environment, thus it is worth continuing studying in this direction to understand more about hand appearance's effect. Although there are many studies on the effect of different hand models, little knowledge was available to understand the impact of a hand's realistic appearance on VHI. A previous study showed that appearance fidelity was highly related to 3D rendering quality [103], which is considered an important design element, similar to audio and video quality [101][102]. Rendering style was the most popular technique to determine the rendering output of a 3D environment [93]. Many VR studies used different rendering styles to explore the impact of realistic appearance [103][104][105]. In conclusion, realistic appearance had a significant effect on the quality of experience and task completion time [103], change of emotional state [104], and perception of human expression [105]. Overall, hand appearance was widely studied by many researchers and was proved to be an effective method for exploring virtual hand illusion.

2.2.2 Size perception

Size estimation tasks with a variations of hand models, hand sizes and object sizes were also frequently used to find the factors that could affect VHI [92][230]. It was crucial to find the appropriate design guideline for the virtual models in order to provide stronger VHI to the users. In previous literatures, it was indicated that size cues in immersive environment were reasonably supported by user's own body, when rich familiar size cues presented [228][229]. This means that if high virtual hand illusion was achieved, the size perception would be more précised. A size-perception approach was done by Ogawa et al. [92]. In their study, the effect of virtual hand appearance on object size perception was explored. Ogawa et al. used three different hand models (realistic, iconic, and abstract) with two sizes (large and small) to find differences in between perceived size and actual size of a cube (Figure 13). Participants started by manipulating the cubes and then manually adjusted the size of the cube under different conditions. In Ogawa et al.'s finding, only realistic hand's sizes affected object size perception. And therefore, they indicated that realism had significance effect on the sense of embodiment [92]. Ogawa et al. [230] did a follow up study focusing merely on hand realism's effect on size perception. Like the previous study, both large and small sizes were used. For the hands, they only used realistic hands with different textures for this study as the realism condition. As a result, larger realistic hands caused smaller object size perception, which aligned with their previous study results [230]. Furthermore, Jung et al. [78] did a similar study on size perception comparing personalized hand and generic hand. In their study, they asked the participants to identify the cubes in the real world, and then adjusted the size in the virtual world. In the end, personalized hand had greater effect on body ownership and spatial presence, and better supported on size estimation [78]. Since our study utilizes an assembly application as methodology (see chapter 3), we can use previous study designs regarding sizes of the hand and objects to eliminate potential effects of incorrect size perception during the experiment.

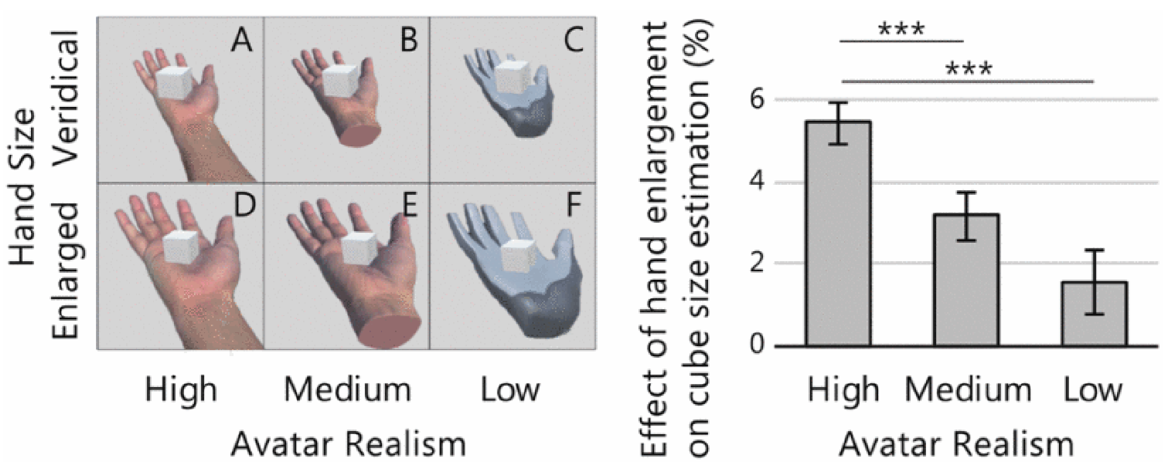

Figure 13. Left: The avatar hands used in the experiment. Right: The ratio of average size estimation in enlarged hand size condition (D-F on the left) [92].

2.2.3 Tactile Feedback on VHI

Besides virtual hand appearance, integrating tactile feedback on the hand was also an effective method to generate VHI. Ehrsson et al. [100]'s rubber hand study included synchronous stroke on both the actual hand and the fake limb. Studies in VR started to duplicate and implement their own version of tactile feedback to find the relationship.

Major studies focused on tactile feedback patterns. Frohner et al. [231] performed a study on wearable haptic devices to find the effect on the embodiment of virtual limbs. They used a wearable hand haptic device and designed a virtual touching experiment with tactile feedback conditions (force feedback, vibrotactile feedback and no feedback (Figure 14). As a result, vibrotactile feedback had significant improvement for embodiment of a virtual hand. While on the other hand, force feedback had stronger responses to certain subscales of subjective embodiment [231]. Moore et al. [98] also did a study regarding different tactile feedback patterns. In their study, five different tactile feedback patterns were used (natural, natural & local vibratory, local vibratory, proximal vibratory and no tactile feedback). Participants were asked to do a cube manipulation task with tactile feedback integrated. As a result, conditions with feedback all generated VHI. Furthermore, switching from natural feedback to proximal feedback did not negatively impacted embodiment [98]. A different approach was done by Richard et al. [99], which was tactile feedback study on a drawing task. They had the same tactile feedback pattern conditions as Frohner et al.'s study. Participants were asked to perform a drawing task in the virtual environment. The haptic device phantom desktop was used to provide tactile feedback. In conclusion, force feedback provided a stronger sense of body ownership than the vibrotactile feedback, which was a different finding from the previous studies [99].

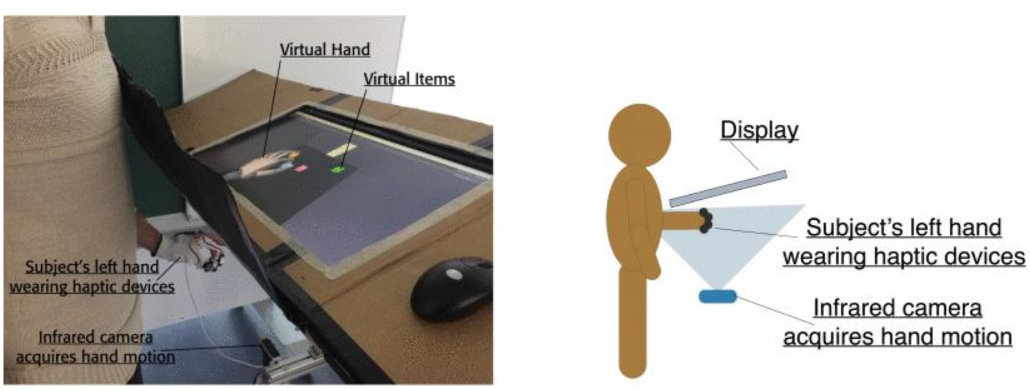

Figure 14. The experimental setup for the virtual touching experiment [231].

As a result, tactile feedback generates stronger VHI comparing to no feedback. Among all the different tactile feedback patterns, studies have contradictory result regarding the effect of force feedback and vibrotactile feedback. Because tactile feedback can be used to improve body ownership and as an effective study method, it is worth exploring both the effect and optimization as a methodology in the future studies. More details regarding tactile feedback will be discussed in the following sections.

2.3 History of Tactile Feedback

Tactile feedback refers to the physical response to the user, simulating the sensation of touch and tap. Tactile feedback technology provides users with realistic experience while interacting in virtual environments, and it has become an important factor in fortifying sense of embodiment in immersive environments [166] [167] [168]. The use of such technology made it possible to apply tactile feedback to the feet [169], back [170], fingertips [171], hands [172], and arms [173]. Tactile feedback has been widely applied in different areas, such as mobile interaction [174], augmented reality [175], surgery [176], and computer animation [7]. One major area of tactile feedback application is virtual reality (VR) gaming using VR controllers' actuators.

The earliest application in tactile technology was in aviation. Aircrafts imported servomechanism systems to generate vibrations in pilots' control to warn about stalls so that pilots can work around the obstacles [262]. Later on, tactile feedback technology was applied to smaller devices such as laptops, mobile devices, and wearables. One example was the trackpad of laptop that used electromagnetic motor to trick finger into feelings things like button clicks [263]. Furthermore, wearables and mobile phones started to import vibrations for alerts and notifications [263]. On the next wave of haptic technology development, researchers tried implementing tactile feedback to media content. Delazio et al. [264] developed the "Force Jacket" to provide full body vibration for different feel effects in VR such as punch, hug, and snake moving across the body. As a development trend, more wearable tactile devices will appear in the future to assist our senses in both the real world and the virtual world.

Back in the 1990s, tactile feedback was implemented in game controllers [232] and arcade game machines [160]. Game consoles such as PlayStation 4, Nintendo Wii, and Xbox One, already featured native controller tactile feedback in many of the major titles. Along with the development of tactile suits and vests, real-time tactile feedback brought revolution to VR applications. Studies about the effect of tactile feedback on user's presence in immersive environments [9], rehabilitation [127], and training [128] have been done using VR games. In addition, tactile feedback has improved the gaming experience of participants [9][223] and the overall user experience [45][139]. Many studies have proved that tactile sensation is a factor contributing to embodiment [8][14]. Kilteni et al. [14] reviewed the factors that could enhance the sense of embodiment. Throughout their research, they found that synchronous tactile sensation enhanced the sense of self-location when a tactile event was seen visually on the self-avatar's body from a first-person perspective. This strengthened the participants' sense of self-location, which was considered a subcomponent of embodiment. It has also been found that the tactile feedback of a virtual hand increases individuals' sense of hand and arm ownership [126]; Fossataro et al., 2018), the touching of the self-body augmented the sense of embodiment (Gonzalez- Franco and Berger 2019), and the vibration sensations associated with specific stimuli on body parts promoted an even a higher sense of embodiment when making contact or interacting with objects (D'Alonzo et al., 2014).

Due to increasing popularity in VR applications and greater support for tactile feedback, it has become essential to understand the effect of tactile feedback on user experience and sense of embodiment in order to provide the industry and academia standards for VR application design. The following sections will review the studies in two different dimensions: The effect of tactile feedback on user experience and embodiment, and innovative methods related to delivering tactile feedback in virtual environments.

2.3.1 Effect of Tactile Feedback

Researchers have been working hard on exploring the effect of tactile feedback. In many studies, it was found that tactile feedback had close relationship to the sense of embodiment; therefore, major studies were focusing on the effect of tactile on different body parts.

Pamungkas and Word [86] developed an electro-tactile feedback system for the hand. The system implemented electrodes in a glove for the participants to wear and a transmitter from the computer (Figure 15). Participants experienced tactile feedback from a VR bouncing ball application. In conclusion, they found that electro-tactile feedback enhanced both the sense of immersion and interactivity for VR users [86]. Richard et al. [99] studied the role of tactile feedback on virtual embodiment through a drawing task. Tactile feedback was provided using the

Phantom Desktop hardware. Participants were asked to draw with their virtual hands in a VR application. As a result, tactile feedback had significant effect on embodiment compared to no feedback for manipulation tasks in VR.

Figure 15. User using the electro-tactile feedback system with Oculus Rift, Leap Motion hand tracker and the haptic feedback device [86].

Full body tactile feedback effect on VR was also explored. Krogmeier et al. [139] performed a study comparing tactile and no tactile feedback with character bumps in an immersive environment. Different tactile feedback intensities were set as conditions. Participants wore the haptic vest and experienced tactile feedback when colliding with virtual characters in the scene. They found significant differences in embodiment, realism of virtual character interaction and haptic feedback realism [139]. Koilias et al. [138] did a similar study in crowd simulation. The scenario was street crossing with many virtual characters around. Participants were asked to cross the street while experiencing tactile feedback from the crowd. Different tactile feedback conditions were used (no tactile, side tactile, back tactile, front tactile, accurate tactile and random tactile). The result indicated that tactile feedback conditions affected participants movement behavior [138]. In addition, in high-density crowd simulation, participants became more sensitive to tactile feedback [138].

The study of tactile feedback was done in VR games. Khamis et al. [112] implemented Electric Muscle Stimulation (EMS) in in-game cinematics in VR games. In the cutscene, users experienced passive tactile feedback were compared with controller-based vibrotactile feedback and no tactile feedback. The feedback was applied to arm muscles. Their results revealed that the EMS approach delivered highly immersive and realistic cutscenes. Users had a higher sense of realism, involvement, and presence [112]. Another study was done by Cui and Mousas [82] using haptic vest for a VR fighting game; the study had two experiments exploring the effect of active tactile feedback and passive tactile feedback in different feedback pattern conditions. Players were asked to wear the haptic suit and fight a virtual boss with various attacks (punches and kicks) (Figure 16). Results showed that tactile feedback had significant effect on presence, tactile sensation, technology adoption and usability [82]. Also, passive tactile feedback had higher rating on tactile sensation and usability [82].

Figure 16. Left: Participant playing the fighting game with the haptic vest. Right: The in-game boss players need to fight [82].

Tactile feedback is effective in generating embodiment for VR users. The use of tactile feedback is successful in both single-user and multi-user scenarios. All the previous studies pointed out that tactile feedback was essential for VR applications. Moreover, in cases of social interaction in immersive environments, studies related to tactile feedback also provided information on how people would interact with each other under specific circumstances. From previous research, tactile feedback provides rich feedback (e.g., realistic feedback from enemy attacks; object interaction feedback following the shape) to generate realistic experience for users in VR games and cinematics, and it is worth studying towards this direction because there are more things to explore and understand in the future. Tactile feedback studies provided design principles for the VR industry regarding application development.

2.3.2 Delivery of Tactile Feedback

Tactile feedback was a key concept for haptic feedback. Haptic feedback referred to sensorial modality in virtual reality interactions [85]. Haptics included both force feedback (object hardiness, weight, and inertia) and tactile feedback (surface contact geometry, smoothness, slippage and temperature) [85]. Traditional haptic devices include wearable computers (e.g., haptic vest), novel actuators (e.g., vibro-tactile controllers), and haptic toolkits. Burdea [85] proposed more usage of tactile feedback in future VR simulations with the improved technology of various devices that could provide tactile feedback. Studies had been trying to create and develop their own innovative tactile feedback devices to deliver the most realistic feedback to users.

The most common type of the tactile devices in VR were hand-held controllers as it delivers vibrotactile feedback to the palm. Choi et al. [161] developed a multifunctional handheld haptic controller for hand movements in VR that was called “CLAW” (Figure 17). This controller provided spatial vibrational feedback to fingertips. It also included actuators that could deliver feedback to the palm. As a result, the device enabled tactile renderings for hand interactions (grasping, touching, and triggering). Users also rated high in usability [161]. In their study Choi et al. [161] developed three different prototypes: chain, layer-hinge, and ratchet-hinge. In conclusion, Haptic Links had the potential to improve haptic rendering of two-handed objects and interactions in VR. All three designs could be used for rendering different object interactions. In a different approach, Stransnick et al. [126] presented Haptic Links, which was an electro-mechanically actuated connection in between two VR controllers. Players could use this device to lock controllers to perform tactile simulation of two-handed objects.

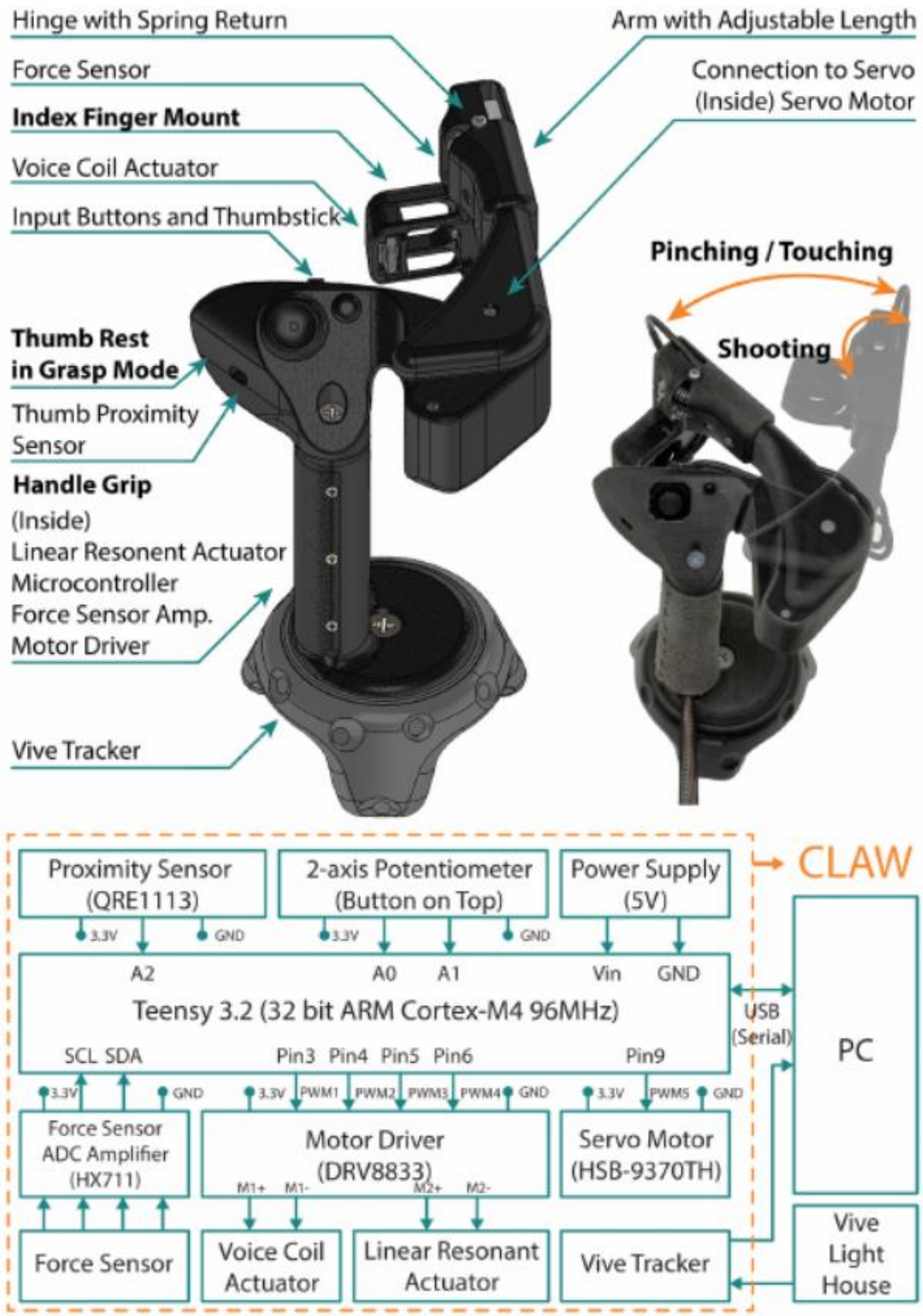

Figure 17. The overall system of CLAW [161], including the actual shape, motion range, and mechatronics components block diagram with detailed information.

In addition to modifying VR controllers, many other haptic devices were created that could deliver tactile feedback directly to user's body. Schorr and Okamura [171] developed a fingertip tactile device that could deform the skin to convey cutaneous force information from object manipulation (Figure 18). The device could simulate object interactions such as grasping, squeezing, pressing, lifting and stroking without using traditional haptic device or pre-determined passive objects [171]. As a result, participants in their study were able to perceive and identify object properties. In a rather passive setting, Cheng et al. [91] proposed a system that tactile feedback used a set of geometric primitives. They created a hemispherical prop as an example. With the feedback from the haptic gloves when touching, participants could sense the detailed geometry of an object in the immersive environment. The system was demonstrated in two virtual scenes: a flight cockpit and a room [91]. In the end, Cheng et al. [91] found that their system simplified proxy and space for passive tactile feedback. It enabled users to perform a rich set of interactions. Different from the other two studies, Araujo et al. [234] went with the traditional method of simulating tactile feedback of virtual objects: a robotic arm (Snake Charmer) spatially aligning an object to map the virtual object that the user was touching. Moreover, Snake Charmer was also capable of matching one or more of the object's shape, texture and temperature. In this study, different objects from simple cube to touch screen were simulated. This system allowed users to easily abstract and sense the virtual objects. A more innovative approach was done by Georgiou et al. [233]. In their study, they developed a touchless haptic system for VR rhythm games using the UHDK5 device and LEAP motion controller. The UHDK5 device generated ultrasound to the user's hand during the gameplay. According to Georgiou et al. [233], this was the world's first mid-air haptic system in VR. The tactile feedback was provided seaminglessly along the game.

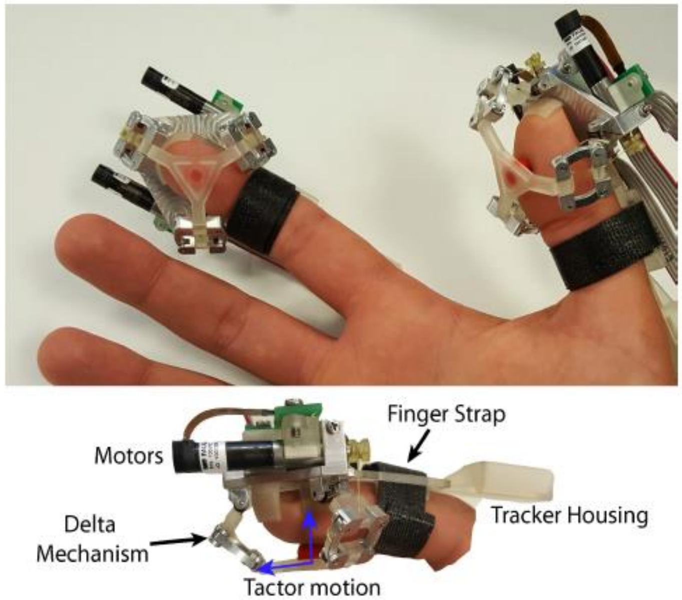

Figure 18. The fingertip haptic device developed by Schorr and Okamura. Each device tactor can move in 3-DoF against the finger pad [171].

Besides hands, there were other attempts to simulate tactile feedback to different parts of the body. Lopes et al. [173] presented impacto, a device designed to render tactile sensation of hitting and being hit in VR. Impacto was designed in bracelet shape with electrical muscle stimulation and electrode (Figure 19). In their studies, three experiments were done by applying this device on different parts of the body: the first experiment was done using a boxing simulation, where participants experienced the feedback by putting the device on the arm; the second experiment was done using a soccer simulation, where participants experienced the feedback by putting the device on the leg and foot; the third experiment was done using a baseball simulation, where participants experienced the feedback by putting the device on the elbow and forearm. As a result, Impacto was proved capable of rendering both active and passive tactile feedback [173]. Using another approach, Israr et al. [235] proposed an upper-body tactile feedback simulation using their Surround Haptics system. A set of vibrating transducers following a pattern in a pad was mounted on a gaming chair. Along with this system, Israr et al. developed a driving simulation game to test out the tactile feedback. They found enhanced spatial tactile strokes for various events, such as collision, tire traction, skidding, acceleration and breaking [235]. As an extension of their previous work, Ismar et al. [170] developed a VR 360-degree video player with haptic feedback playback. They developed a system called "haptic chair" which was available for different tactile patterns. In addition, the subwoofers below the chair could provide motion cues to the chair to provide tactile feedback from the back and the base of the chair. When users were watching VR videos, certain parts of the media triggers haptic messages and generates tactile feedback with line effect, location effect, rumble effect, rain effect and rumble effect. The system overall allowed creation of moving sensory illusions on and around the body [170].

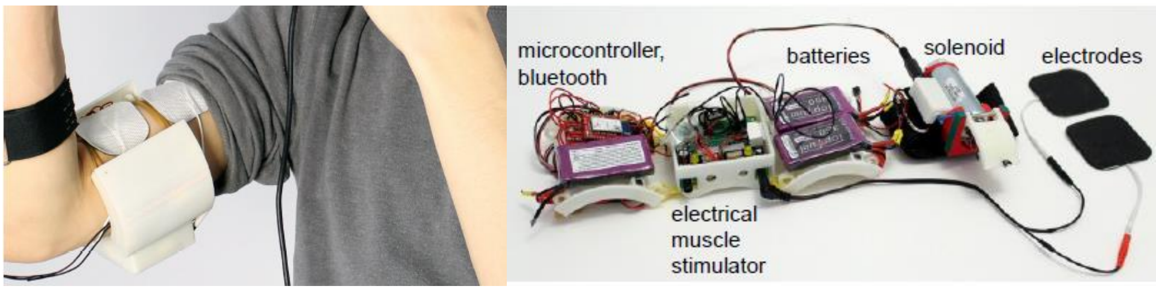

Figure 19. Left: A participant wearing the muscle stimulation component. Right: The Impacto bracelet component [173].

From all the tactile feedback delivery studies, many challenges were overcome. Many studies solved the problems of traditional methods of simulating tactile feedback, which included realistic objects or having oversized haptic devices that needed to be carried onto users' body. The solution to those problems was to either optimize the traditional system by providing more detailed information of object interaction or develop a new device that simulates tactile feedback by specifically focusing on different body parts. In all the methods for tactile feedback delivery, it is now possible to provide feedback on certain body parts based on the need of users and studies with various devices. Tactile feedback can be done by devices equipped on the body (e.g., haptic vest, finger sensors) and out-of-body devices (e.g., chair). Even with the native controllers from the VR system, users can sense rich tactile feedback from interactions in applications. Furthermore, tactile feedback can be delivered individually or combined with other cues such as visual cues and audio cues. Based on the previous research, it is not yet possible to generate tactile feedback on every part of the body and therefore it is worth continuing the development on different tactile feedback devices.

2.4 Tactile Feedback Perception

In the past, many studies were done related to tactile feedback to fully understand how human would perceive tactile feedback. Various areas were explored including sensation area, age and gender, energy integration (temporal summation), frequency discrimination and differential sensitivity (Just noticeable different frequency (JNDF) and just noticeable different levels (JNDL)), adaptation and fatigue, and location discrimination [124]. Each area's studies generated theories about human tactile feedback perception mechanisms.

This section will discuss about the past studies that discovered tactile feedback perception mechanisms in the above categories. Furthermore, modern approaches, either extending the past studies or seeking a new direction for psychophysics studies will be addressed. In addition, contributions, existing problems, and limitations of these studies will also be mentioned.

2.4.1 Sensation area

The way to feel tactile feedback is through human skin. Studies were done to understand how different part of the body could have different threshold for vibro-tactile feedback. Lo and Johansson [123] did a study on the finding regional differences in sensitivity of vibration in the glabrous skin of the hand. In their experiment, there were seven test points on the hand (Figure 20). They used a single test method that yielded a continuous sine wave between 0.8 Hz and 400 Hz in 6 minutes. Subjects' threshold of perception was recorded. As a result, the highest threshold was obtained at the lowest frequencies, and the threshold was minimal at 200-300 Hz [123]. Moreover, at frequencies above 40-60 Hz regional differences were perceived less. The most pronounced frequency range was 12-60 Hz [123]. As a result, sensitivity depended on the distribution and density of the mechanoreceptors (the body organ that senses mechanical stimulus such as pressure) [123]. Verrillo et al. [181] also performed a study related to the subjective magnitude of vibrotactile feedback. A vibrator was placed in the platen of a drill press assembly and provided vibration to the participants' thenar eminence. Ten frequencies (25, 40, 64, 100, 150, 200, 250, 350, 500, and 700Hz) were present and the participants were asked to match the subjective intensity of the test frequency using a variable attenuator. As a conclusion, the subjective magnitude function for vibration was a power function with a slope of about 0.89 for frequencies up to 350 Hz, and the slope value may increase along with higher frequency levels

[181]. This indicated that glabrous skin was more sensitive with decreasing frequency and less sensitive with increasing frequency.

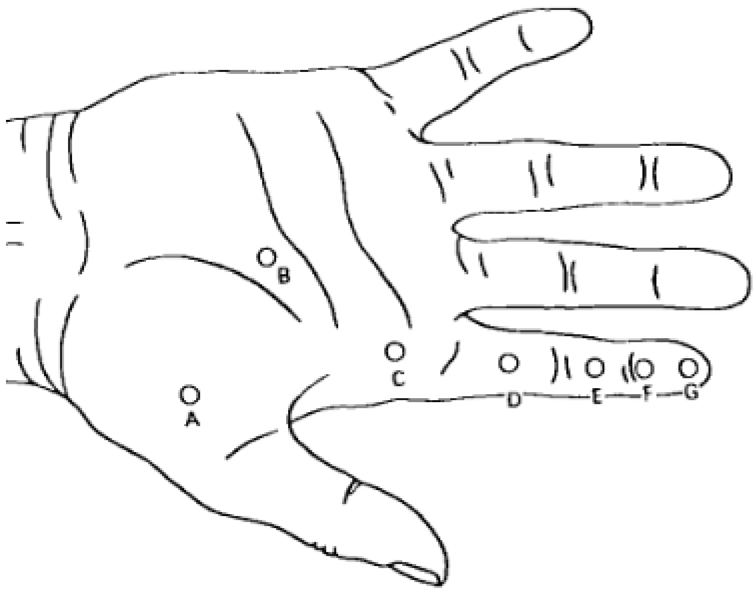

Figure 20. The seven test points on the glabrous skin of the hand [123].

Besides tactile feedback perception on hands, whole-body perception studies were also done by researchers. Miwa and Yonekawa [236] conducted an experiment exploring the relationship in between vibration level and emotional reaction. Participants were seated on vibration cushion and experienced both vertical and horizontal vibration. Within 10 minutes of exposure below 200 Hz frequency, unpleasant level was found at 40 dB for vertical and 50 dB for horizontal [236]. Endurable limit was found at 55 dB for vertical and 65 dB for horizontal. Merchel et al. [237] performed a seat vibration study. Six different frequencies were selected (10, 20, 50, 100, 150, 200) and presented to the participants to judge the intensity. Vibrations varied in acceleration levels from 90 to 130 dB in 5 dB steps [237]. In their study, Steven's exponent in between 0.75 and 0.97 were measured. As a result, no significant variation of Steven's exponent with frequency was found, indicating that tactile suprathreshold intensity perception does not depend on frequency that were less than 250 Hz [237] (Figure 21). Lower sensation levels were found at higher magnitude levels in vertical whole-body vibration.

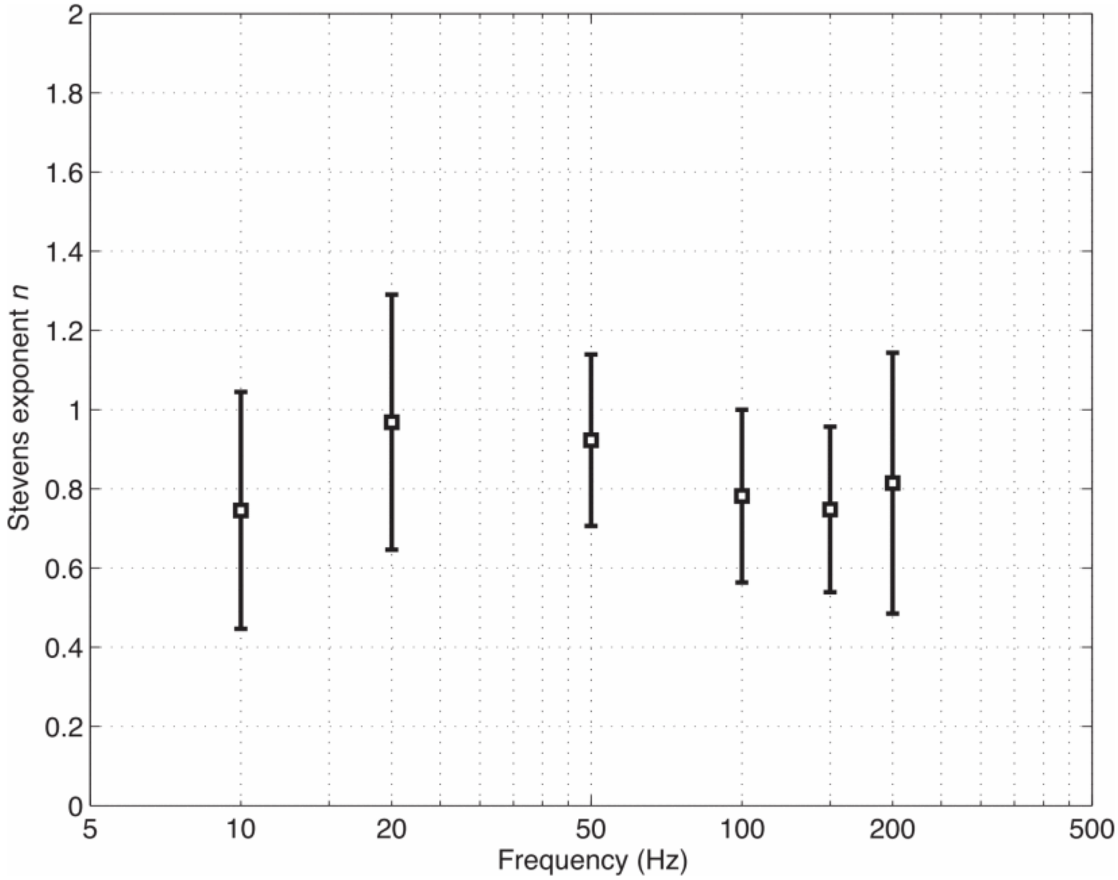

Figure 21. The sensation expressed as Steven's exponent [237].

The sensation of tactile feedback depends on the different part of skin, in terms of density and distribution of mechanoreceptors in that area of the human body. In addition, horizontal and vertical both have different effects of human tactile sensation. In this case, certain frequency and magnitude will need to be set for various part of the body for tactile sensation to work. This area of psychophysics is valuable of further studies to understand unknown skin tactile sensations in unexplored body parts. The past studies provided a standard design principle on the strength, frequency, and variation for tactile feedback. However, limitations on the technology of the older study existed. Therefore, problems such as understanding tactile perception on the full-hand, certain points of the hand and other body parts remained unclear. With the help of modern technology, delivering tactile feedback onto specific parts of the body will be possible. Studies on more detailed sensation area should be conducted.

2.4.2 Energy integration

The ability to integrate energy could also affect tactile feedback perception [124]. This topic was usually discussed with the duration and threshold (or intensity) of a stimulus. Gescheider et al. [238] conducted a study about temporal summation. Temporal summation refers to a phenomenon that the detectability of a stimulus improves as stimulus duration increases. Vibro-tactile feedback with intensity range of -30 dB to 20 dB were provided to the participants in duration of either 10ms or 1000ms. As a result, participants who experienced the 1000ms condition had higher proportion of correct response on the intensity than those participants who experienced 10ms condition [238]. This indicated that temporal energy integration existed in the tactile domain. Besides the duration, Verrillo [152] also tried to explore the effect of contactor area on the vibrotactile threshold. Subjects' hands were put on the one of the three types of contactors (each with different contact area), mounted on top of the vibrator. As a result, in frequencies between 80 to 320 Hz, the threshold decreases with 3 dB per doubling the contact area of the hand [152] (Figure 22). The amount of energy per area was decreased by enlarging the contact area. Thus, energy had a negative correlation with tactile perception. While both studies explored the effect of energy integration from different angles, only single type of stimulus was used.

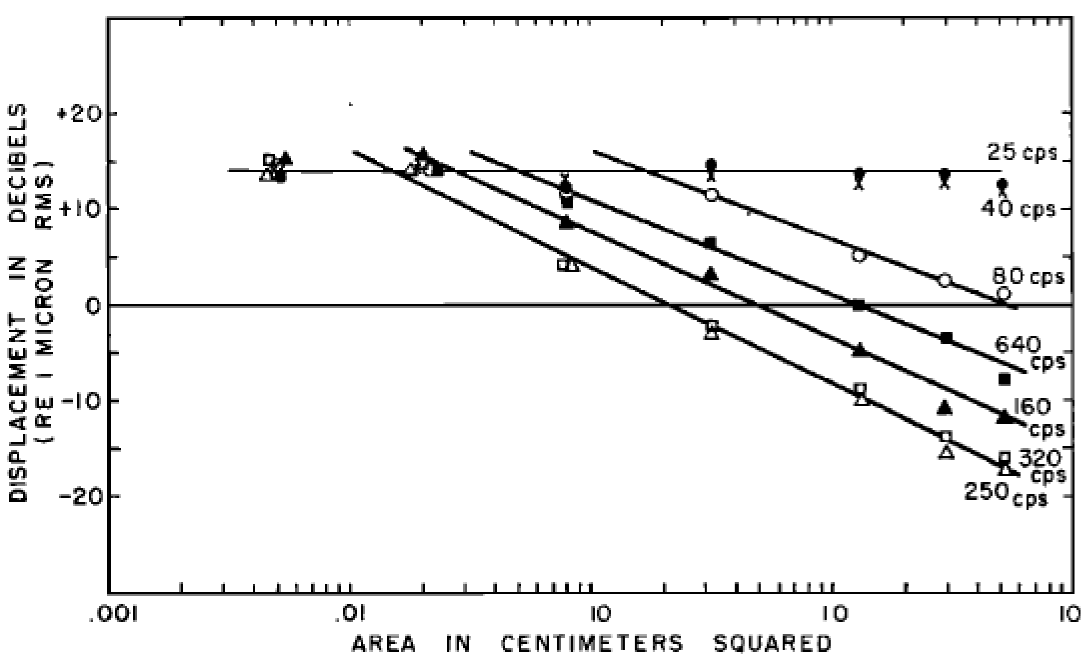

Figure 22. The change of vibrotactile threshold as the contractor area increases. Curves drawn through experiment points have a slope of 3db per doubling the area [152].

Studies related to energy integration have proven that temporal energy exists in the tactile domain. Also, the amount of energy changes the tactile sensation threshold of certain body parts. A longer duration of the feedback such as 1000ms with a frequency range under 320 Hz will generate enough energy for perception. It is worth exploring of the amount of energy needed for all individual body parts. It is also valuable studying the technology of controlling the tactile feedback to generate the right amount of energy in certain areas. The effect regarding multiple stimulus on the same and multiple area remained unknown. It would be important to understand those effects for future studies because interaction in simulation and real life included simultaneous stimulus.

2.4.3 Age and Gender

Two other factors affecting human perception thresholds of tactile feedback were /are gender and age. Verrillo [239] tried to compare vibrotactile threshold and suprathreshold responses in men and women. Similar to the previous study [181], Verrillo used the same setup for the experiment with the same set of sinusoidal frequencies, except the condition was the gender. As a result, no significant differences were found for tactile perception in between different genders. In a later study, Matsumoto et al. [240] also performed a whole-body vibration study in order to understand the differences of tactile perception of gender. The study was done by using a shaker bed. Participants were lying on the bed to feel the vibration. Continuous sinusoidal vibrations at 2, 4, 8, 16, 31.5, and 63 Hz with different lengths (0.5, 1.0, 2.0 and 4.0s) were provided. In the end, Matsumoto et al. [240] found similar results to the past studies, that no significant differences were found in the perception threshold of continuous sinusoidal vibration in between different gender.

Different from gender, age had a considerable effect on tactile thresholds. Verrillo et al. [241] explored the effect of aging on the subjective magnitude of vibration. They recruited subjects in two different age groups (17-31 years old for the younger group and 63-73 years old for the older group). Again, a similar setup as the previous studies was used with a Goodmans 390-A shaker providing vibration in different frequencies to the hand. As a result, the older group had higher thresholds in the Pacinian (P) and NP II channel than the younger group, which indicated that the sensitivity decreases over age (Figure 23). Stuart et al. [242] also performed a study finding the effect of age on vibration thresholds. Four different skin areas were tested (palm, forearm, shoulder and cheek). Two different frequencies of vibration were used (30 Hz and 200 Hz) on two age groups (17-27 years old for younger group and 55-90 years old for older group). In conclusion, aging had a significant deteriorating effect on vibration sensibility, showing that the older group had higher threshold than the younger group.

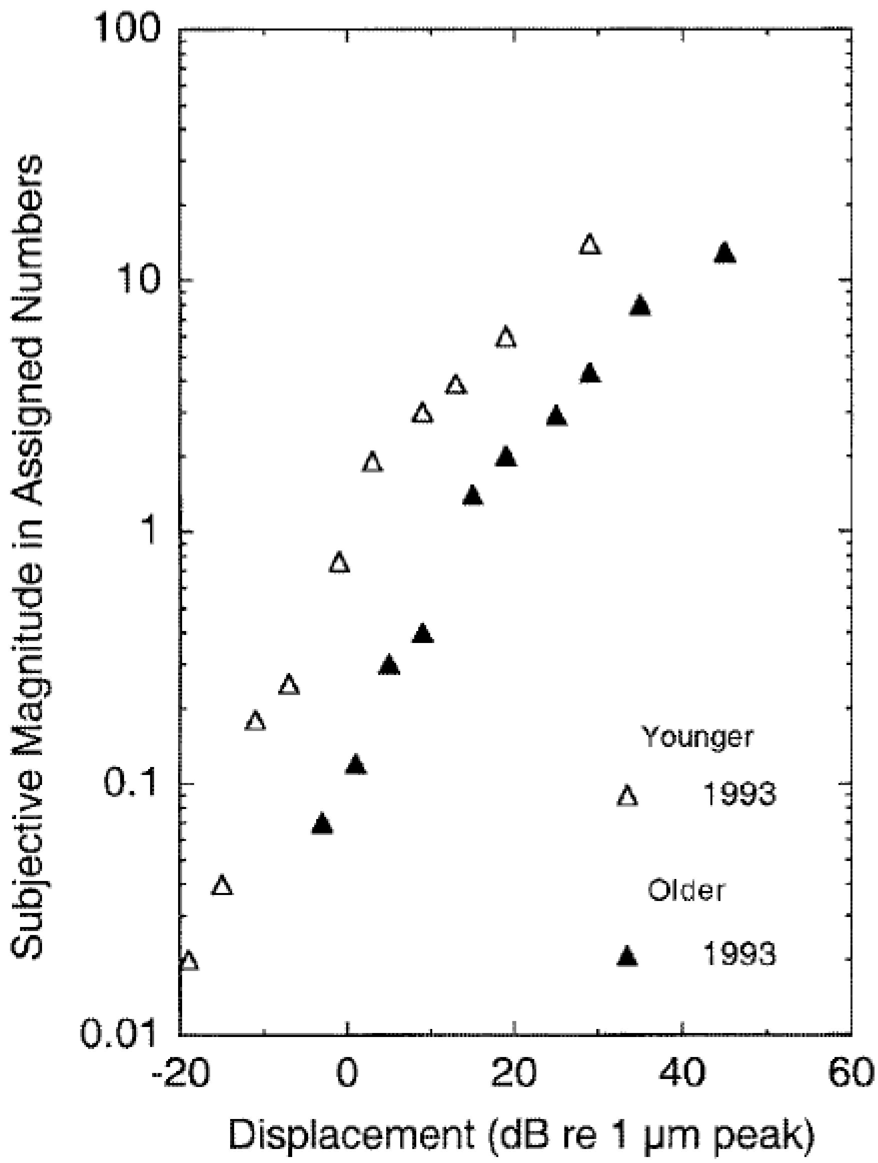

Figure 23. Result comparison of subjective magnitude of the 250-Hz vibration [241].

On the one hand, gender has no effect on tactile sensation. On the other hand, aging can affect tactile sensation threshold. Older people have higher tactile sensation threshold than younger people. Considering the range of age for applications with tactile feedback, it is worth studying on more various age groups such as teenager and younger children.

2.4.4 Frequency discrimination and differential sensitivity

Two sets of words were used to describe the minimum level and frequency that can be perceived by human: Just noticeable differences in level (JNDL) and just noticeable differences in frequencies (JNDF). Goff [153] performed a study about fingertip vibrotactile stimulation in order to understand differential discrimination of frequency. In his experiment, five frequencies (25, 50, 100, 150 and 200 Hz) were used in the same level (20dB above the threshold). In the end, Goff [153] found that participants could relatively discriminate frequencies below 100 Hz. Rothenberg et al. [154] went for a similar approach by applying vibrotactile feedback on the forearm. Sinusoidal signals between 25 to 500 Hz were used. The level was set to be 14 dB above thresholds. As a result, suggested frequencies for detecting differences were from 4 to 75 Hz [154] (Figure 24). Moreover, whole-body tactile sensation discrimination was explored by Merchel and Altinsoy [156]. A vibration chair was used with four different sinusoidal frequencies (20Hz, 40Hz, 80Hz, 160Hz). Vibration acceleration level peak was set to 100 dB. In conclusion, measured JNDF was approximately 7-66 Hz [156].

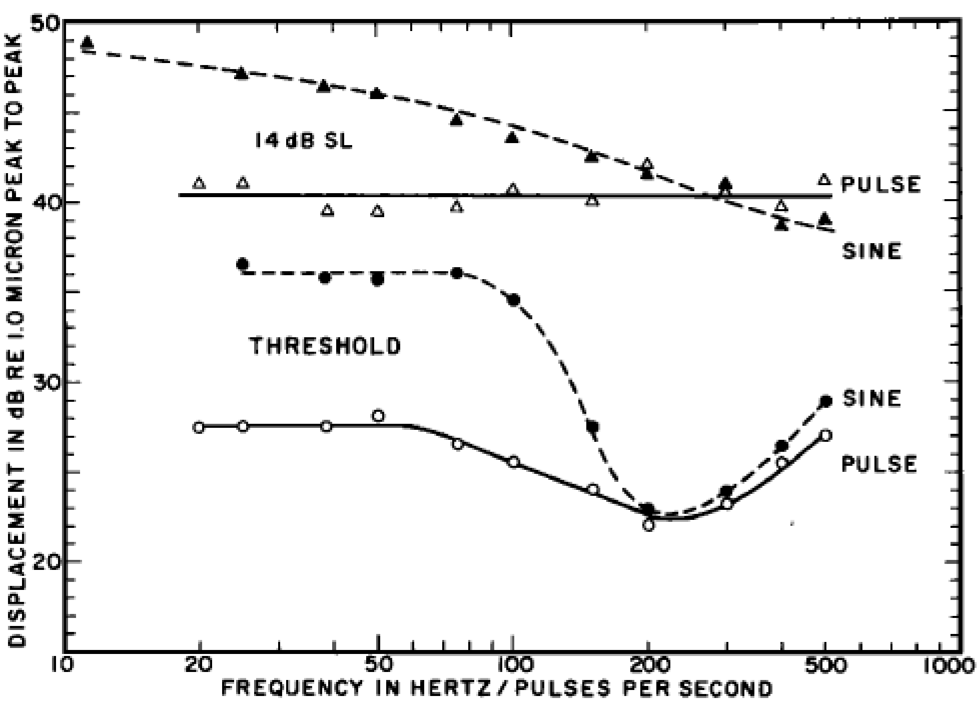

Figure 24. The sensitivity of the volar forearm to sinusoids and 1-msec Gaussian pulses. The top horizontal line indicates the threshold at 14db SL [154].

Different JNDL values were also found in many studies. Matsumoto et al. [157] tried to discover differences in vibration magnitude in a whole-body experiment. Participants were seated on the shaker, experiencing frequencies in 4, 8, 16, 31.5, 63, and 80 Hz. Magnitude variation was modified by 0.25 dB in between trials. In the end, 0.5dB was the JNDL for seat vibrations [157]. Griffin and Whitham [158] took a similar approach to finding the effect of impulsive whole-body vibration using vibration seat. They used frequencies of 4, 8, 16 and 32 Hz with a duration of 1 second to 4 seconds. Griffin and Whitham [158] reported a median range of less than 1 dB for the JNDL. Furthermore, Morioka and Griffin [159] explored more on the threshold for intensity perception of vertical whole-body vibration. Two frequencies (5 and 20 Hz) and two different magnitudes (0.1 and 0.5 ms-2 r.m.s.) were used. After each a trial an increase of 0.25 dB was applied to the magnitude. As a result, a range of 0.92 to 0.75 dB was found for JNDL [159]. None of the studies reported relationship in between JNDL and frequency, and thus JNDL was hypothesized as dependent of frequency.

Based on the previous studies, there are several standards for JNDL and JNDF. Seat vibration JNDL is in between 0.5dB to 1.0dB for whole body vibration; forearm JNDF is in between 4 to 75 Hz; whole body JNDF is in between 7-66 Hz. There is no significant relationship in between JNDL and frequency. In tactile feedback setup, strength and frequency need to be considered separately for the feedback to work. From the previous findings, understanding the JNDL and JNDF range can provide better design considerations when exploring the effect of tactile feedback, and therefore it is worth studying towards the direction because there are more things to be understood in the future. If the magnitude and frequency value were not set in range, participants would not sense the difference in different conditions. While the studies were mostly done on upper limbs and whole-body, there should be more exploration on other body parts and skin types as well. Moreover, factors that can potentially affect JNDL and JNDF, such as the applied area of tactile feedback, are also yet to be identified and explained.

2.4.5 Adaptation and Fatigue

A common phenomenon found in these studies was, given an extension of stimulus, that the sense of tactile feedback tends to become weaker over time. This phenomenon was referred to either adaptation or fatigue. Nevertheless, this phenomenon could result in decline of perception and leading into incorrect judgement of feedback properties or misbehaving of experiments. In

Hahn [151]'s study, two different tactile feedbacks (10 and 200 Hz with 14 db sensation level) were applied on the finger pad to two different participant groups. Experiments were done in 2, 4 and 8 minutes and recovery timed for 4 minutes. In the result, both 10-Hz and 200-Hz threshold recovery were the same with a rate of dropping 0.45 db per 100 seconds [151]. In another study, Hollins et al. [150] tried to study this phenomenon's relationship with vibrotactile channels. Three experiments were done using finger vibrotactile feedback exploring threshold, adaptation time and action spectrum for elevation of threshold. Hollins et al. [150] reported that adaption decreased between 10 to 30 Hz but stayed flat in between 30 to 90 Hz (Figure 25). Because Pacinian corpuscles were more sensitive in different frequency ranges than the non-Pacinian channels, it could be concluded that adaption/fatigue could not occur between different vibrotactile channels.

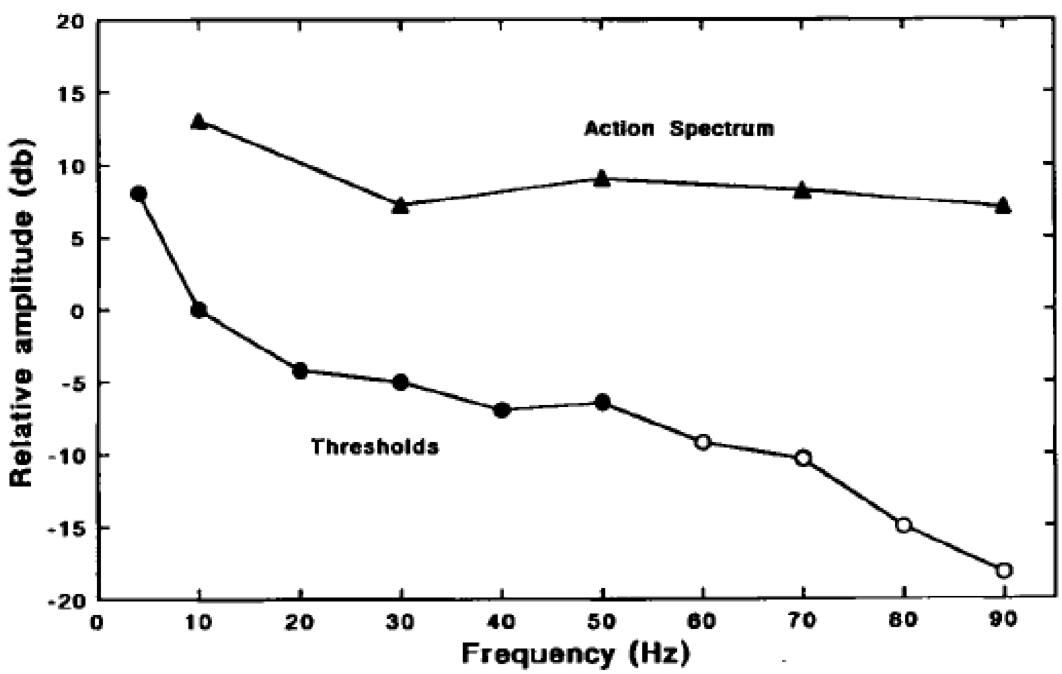

Figure 25. Top line: the threshold of vibration with adaption. Botton line: the threshold of vibration without adaption [150].

2.4.6 Location Discrimination

Spatial sensitivity was studied on different body parts. Studies have shown that spatial acuity varies significantly in different body surface [124]. A general measurement of spatial sensitivity was the two-point discrimination tasks: two separated stimuli were either simultaneously presented or one happened after the other. Cholewiak and Collins [248] did a study of vibrotactile localization on the arm. In the experiment, they explored the ability to localize vibrotactile stimuli on a linear array of seven tactors on the forearm (Figure 26). As a result, stimulus frequency and age showed much less effect than that of the position of stimulus sites relative to body landmarks, in this case, joints of the elbow and wrist [248]. In addition, Cholewiak et al. [249] performed an extended study of the same concept on abdomen. The experiment included identification of six stimuli location on abdomen using vibrotactile feedback. Neither the structure of skin nor the types of tactile feedback affected localization; instead, anatomically defined anchors (e.g., body landmarks), in this case near the spine or the navel, had significant effect on estimating localization [249]. In addition, Cholewiak [250] also proposed that spatial acuity be related to receptor density. Several vibrotactile experiments were conducted on different body parts. It was found that regions with high receptor density (e.g., fingers) had low spatial discrimination threshold than regions with low receptor density (back).

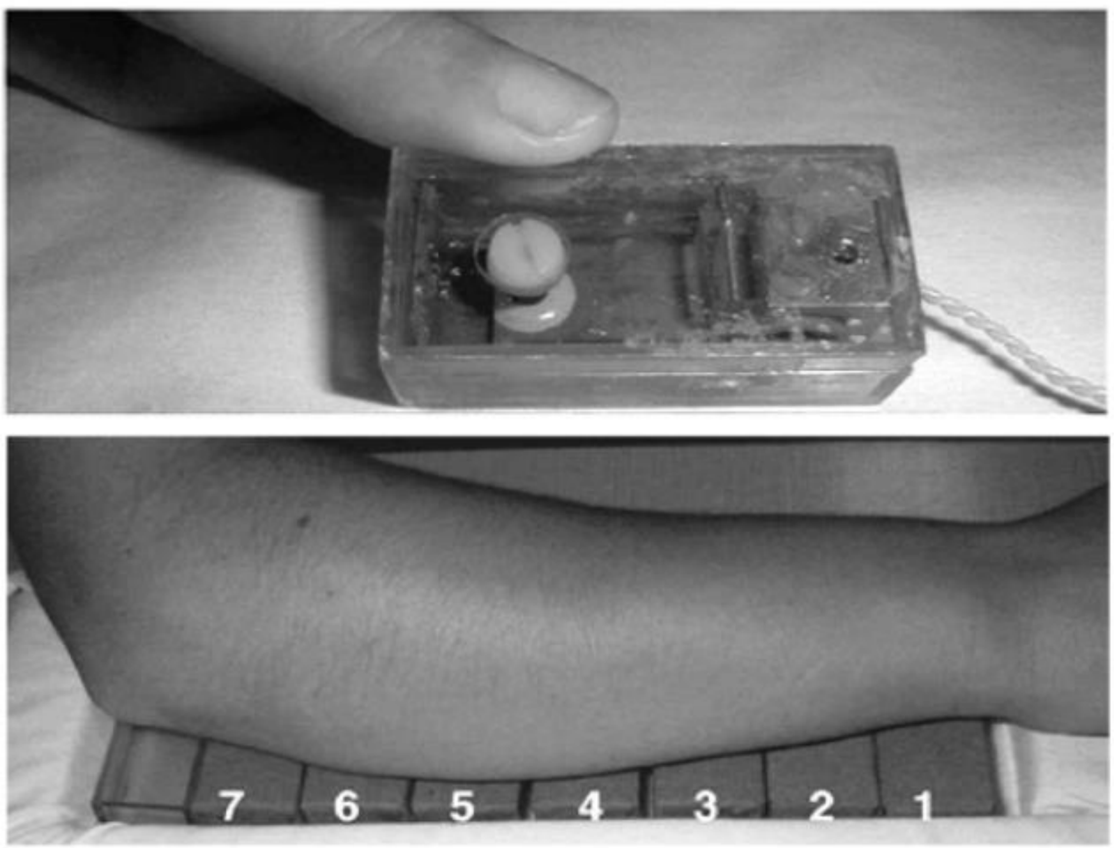

Figure 26. The experiment setup for spatial sensitivity of arm [248].

2.4.7 Further Modern Approaches

With the conclusion from the previous studies, researchers either extended the studies or found new directions to study related to psychophysics. Wu et al. [251] studied the bio-response of osteocyte under vibration. In their study, they were trying to understand how low magnitude and high frequency (LHMF) was perceived by osteocytes. A cell vibration culture system was used to generate vibration and perceive data. Four different frequency, acceleration and practical vibration amplitude were used. Wu et al. [251] found that bio-response of osteocytes was frequency dependent. Jamalzadeh et al. [252] explored effect of remote asking on tactile perception using electro vibration of touch screens. Three different experiments were done to explore participants' detection threshold, masking propagation on four locations of index fingers and intensity threshold. In their results, psychophysical masking effect existed due to central neural process [252]. Vibrotactile channels were in control of discriminating the different amplitude levels, not the tactile feedback itself.

Gaudeni et al. [125] focused on a new direction by studying relocation of tactile feedback using a haptic ring. In their experiment, they presented a wearable haptic device that could represent different textures to three locations of the hand and forearm (finger, phalanx, and wrist) (Figure 27). In conclusion, vibrotactile frequency threshold was the highest on the wrist. Participants were able to perceive fingertip information regarding virtual textured surface on a different location of the hand [125]. Ravikanth and Hariharan [253] performed a study related to textural perception under the effect of temperature. They prepared different materials for the participants to feel while controlling the surrounding environment by changing temperature (20-24 Celsius for controlled room, 35-40 Celsius for open environment, 28-30 Celsius for closed room). As a result, close room participants spent least time on perceiving different material textures [253]. It was also proposed that higher temperature was helpful with slow adaptive receptors.

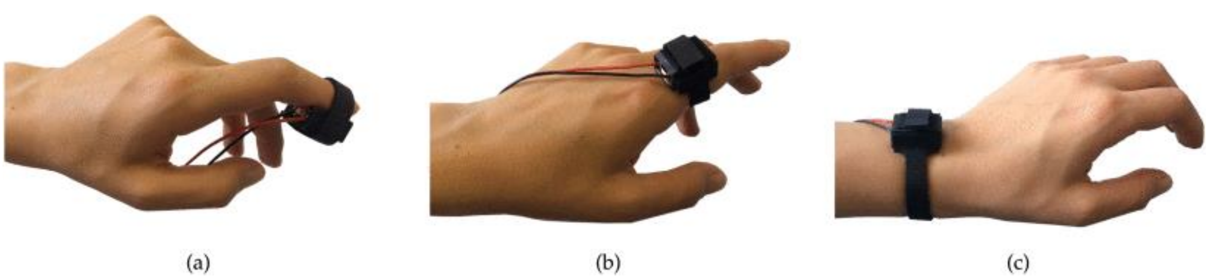

Figure 27. The haptic ring on (a) fingertip, (b) proximal phalanx and (c) wrist [125].

CHAPTER 3. PRELIMINARY REMARKS AND IMPLEMENTATION DETAILS

3.1 Introduction

In the past, researchers had evidence in supporting that Virtual Reality was associated with embodiment in VHI and tactile feedback studies. Based on previous studies, one important factor when studying these effects was interaction task within the virtual environment [76][77]. In order to explore the effect of hand appearance and find out the JND of tactile feedback, we developed an application that included strong hand interaction. Fortunately, game engines such as Unreal Engine and Unity 3D can provide realistic immersive environment and experience for participants. In this chapter, we will discuss our basic design decisions on application development.

3.2 Assembly Application

Hand interaction is key to generating VHI. Therefore, it is necessary to consider hands-on tasks in our VR application design. One frequently used category of hand interaction tasks is engineering and medical training. Among VR applications, training application is widely used in different areas. For example, Toyota, one of the largest automobile makers, uses VR for assembly line training [256] (Figure 28). Ford Motor Company uses VR prototypes to inspect and operate vehicles to optimize their design process [254] (Figure 28). In addition, Gabler Engineering gains benefit by training their operators on the machining process for their product [255] (Figure 30). We can foresee a trend that the use of virtual reality is coming to substitute training sessions that take place in the real-world setting.

Figure 28. Toyota Assembly line training presentation [256].

Figure 29. A Ford designer interacts with their CAD design in VR [254].

Figure 30. Gabler operators are training on the machine process in VR [255].

For our study, we needed to create an application that did not contain complicated tasks for participants. Moreover, the interaction process needed to implement tactile feedback to the hand and provide realistic experience. The idea of using virtual assembly applications started in 1990s. Gupta et al. [257] at MIT developed a desktop virtual environment for design assembly (VEDA) with haptic force feedback to provide a realistic assembly experience. Jayaram et al. [258] developed a full-scale VR Assembly Design Environment (VADE) using position tracking and CAD model data to provide visual and simulation realism. Wan et al. [259] and Zhu et al. [260] created a Multi-Modal Immersive Virtual Reality System (MIVAS) using CyberGrasp haptic device (Figure 31). MIVAS was able to provide additional fidelity by allowing the user to feel the size and shape of a part with force feedback [259][260]. Many research groups developed virtual assembly applications for their studies, and they found that it was affective in simulating a realistic situation and improving sense of presence [261]. In order to complete our study, we developed a VR assembly application prototype. We will discuss our development process and application design in the following sections.

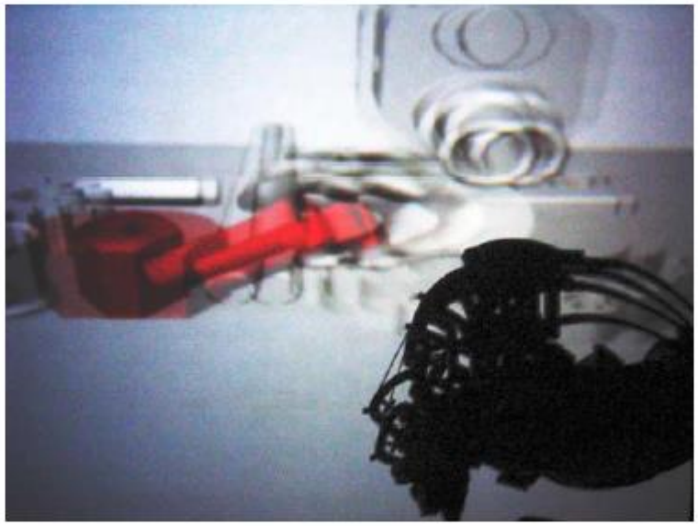

Figure 31. A participant is performing a virtual assembly task using CyberGrasp [260].

3.3 Application Design

3.3.1 Virtual Environment

For our virtual assembly application, we used Unreal Engine 4 since it was capable of importing various 3D model files (e.g., obj, fbx.) into the virtual world. For each individual study, we decided to keep the environment simple so that we didn't distract the participants. The virtual world was designed as a white room with gray floor (Figure 32). Participants could only see the objects in the room but nothing outside of the room. We will discuss more in detail in the following chapters for each individual study.

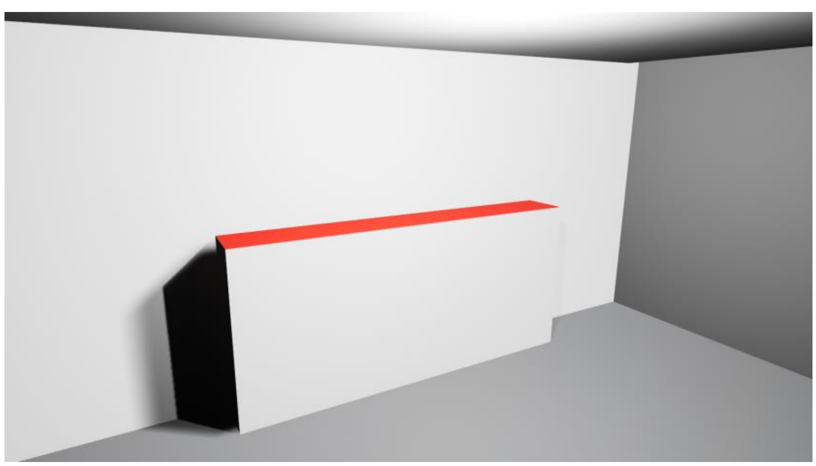

Figure 32. The simple room setup for VR assembly application.

3.3.2 VR Hardware

We used the Oculus Quest 2 HMD and the Oculus Touch controllers (Figure 33). This set of HMD's is easy for connection and does not require complicated setups. The controllers can also provide vibrations during interaction. Unreal Engine 4 has full support for Oculus hardware and provides sufficient adjustability for vibrotactile feedback. Developers can manually create vibration patterns including intensity, frequency, and duration. Figure 34 shows a sample blueprint node for vibration settings.

Figure 33. The Oculus Quest 2 device with Oculus Touch controllers.

Figure 34. Sample blueprint node for controller vibration effect.

3.3.3 Interaction Mechanics

We used the VR Interactive Assembling project[2] from UE Marketplace to help with our development. The project offers various functions on virtual object interaction. The major function we utilized was the "insert" function: by placing an object into a corresponding holo slot, the object would snap on. We manually developed our experiment virtual world based on this function. We also added tactile feedback during object pickup. When participants pick up an object, the hand-held controller delivers a short duration of vibrotactile feedback that was preset in the application. An example of the assembly process is shown in Figure 35. More figures regarding the blueprint are also shown afterwards.

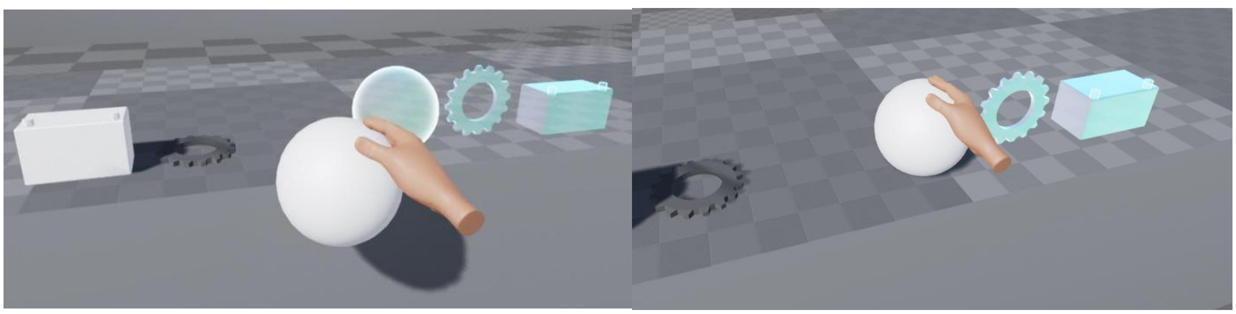

Figure 35. Left: in the virtual environment, participant can grab the virtual object using the virtual hand. Right: When the object is placed on the holo slot, the slot disappears and the object snaps on.

[2] https://www.unrealengine.com/marketplace/en-US/product/vr-interactive-assembling

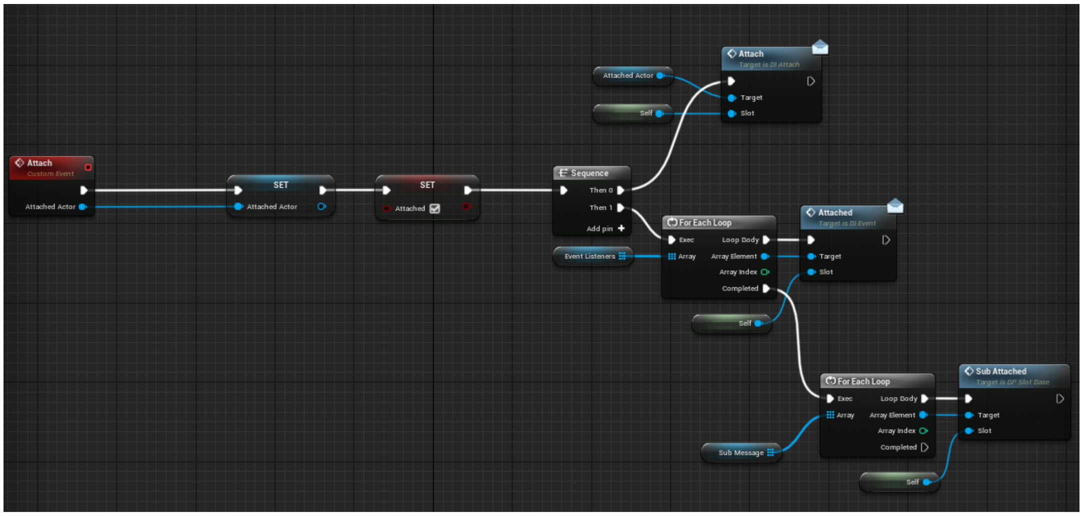

Figure 36. Visual script (Blueprint) for attaching objects to the holo slot. When the slot matches the object type, the slot will disappear and set the object to the position of the slot. The blueprint then updates the status of the slot.

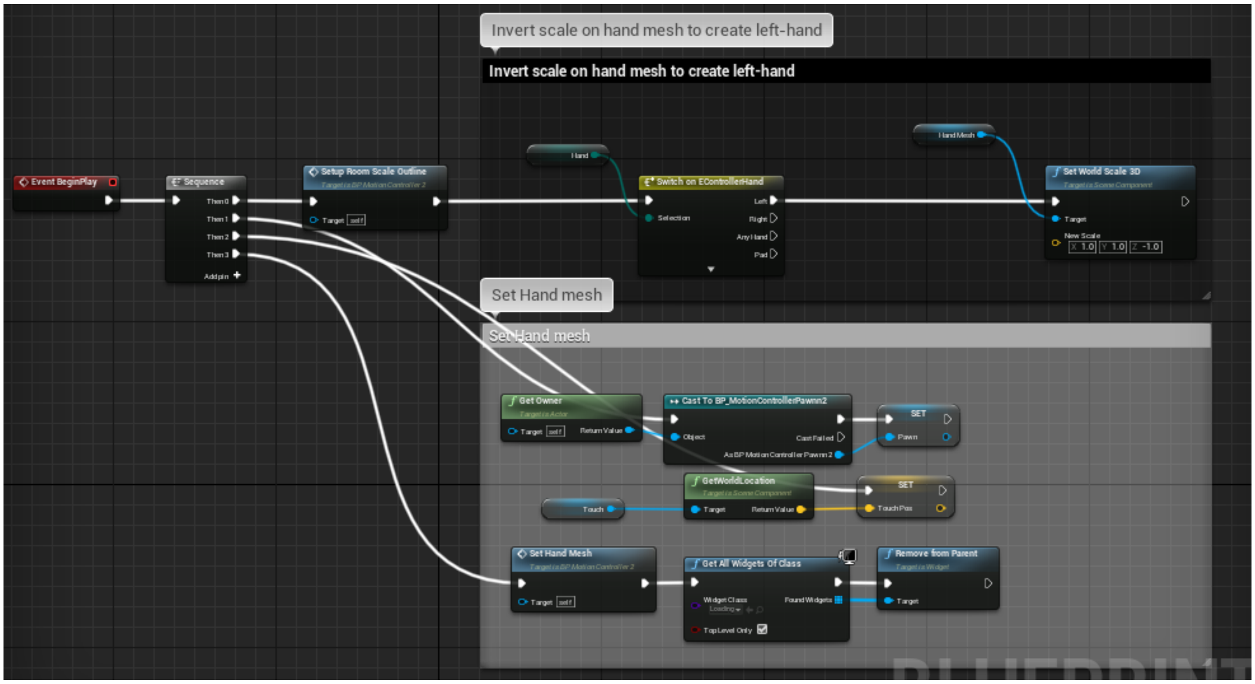

Figure 37. Visual script (Blueprint) for the virtual hand creation at the beginning of the application. This code creates an inverted hand for the left hand, then it sets the hand mesh based on the conditions set before the application started.

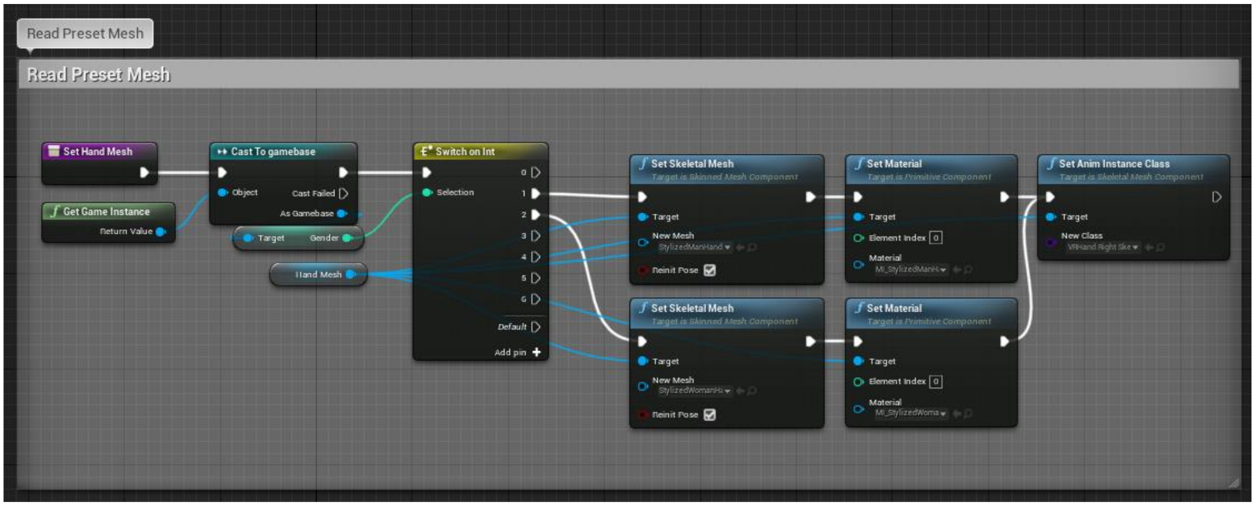

Figure 38. The function that reads the preset mesh for the hand. In this example we are setting hand meshes depending on the gender. We set the integer "gender" value to 1 for male and 2 for female.

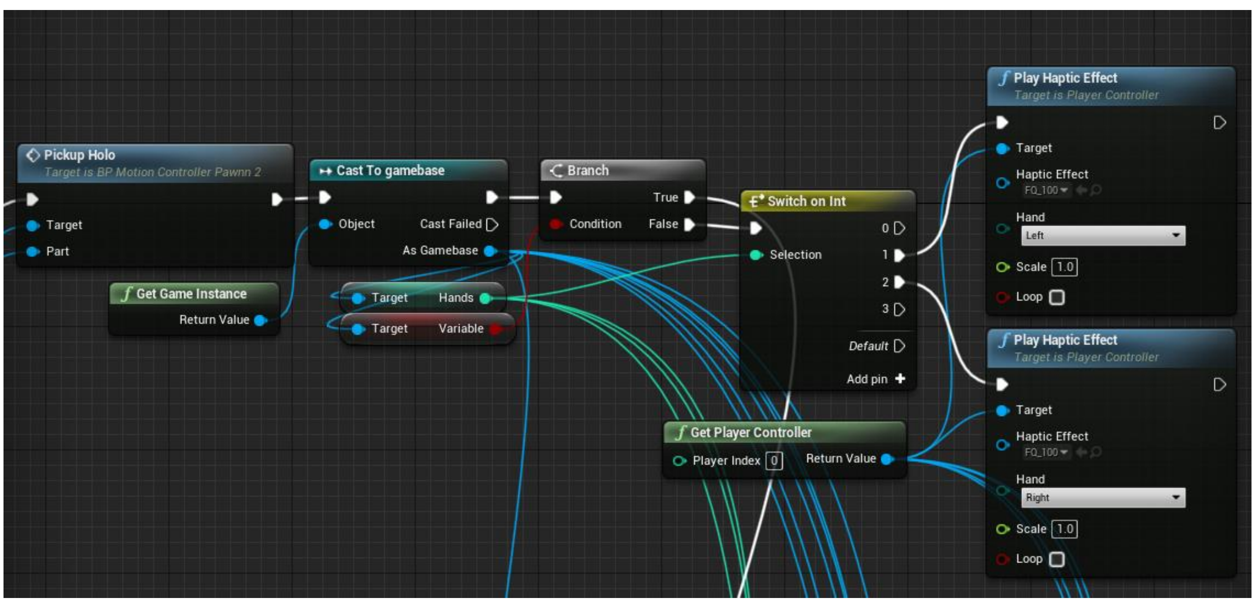

Figure 39. Part of the pick-up function node. When the virtual hand picks up the object, the controller generates tactile feedback by playing a preset haptic effect.

Besides the major assembly function, we also imported an unlock function. For every single application we used in all three studies, participants needed to unlock the next holo slot or hidden interaction object by placing existing objects into the required slot (Figure 40). This was required for the participants to complete the experiment. Doing this not only provided participants a sense of accomplishment but also prevented them from seeing the final interaction task. We will discuss more on how we utilize this mechanic for individual studies in the following chapters.

Figure 40. Under the same perspective: starting with only the center slot and the gear (left). When the gear is assembled to the center slot, the right slot gets unlocked and appears (right).

CHAPTER 4. AN ON-SITE AND REMOTE STUDY DURING THE COVID-19 PANDEMIC ON VIRTUAL HAND APPEARANCE AND TACTILE FEEDBACK

4.1 Introduction

In our first study, a virtual reality assembly application was developed, and participants were asked to interact with the examined conditions so that we could explore the aforementioned embodiment dimensions. From our point of view, considering that there are various applications using hand models and tactile feedback to help users assemble objects [59][60][61], it was deemed essential to explore how the appearance of hand models and tactile feedback could affect the examined embodiment dimensions in a virtual environment.

Participants in our study were recruited both from on-campus and remotely during the COVID-19 pandemic. Based on our study design, we aimed to answer the following research questions:

- RQ1: How do the three different hand models affect participants' perceptions of ownership, external appearance, and tactile sensation?
- RQ2: Is tactile feedback associated with stronger ownership, external appearance, and tactile sensation?
- RQ3: How do remote participants rate ownership, external appearance, and tactile sensation compared to lab participants?
- RQ4: Does the prior virtual reality experience of the participants affect their ratings of ownership, external appearance, and tactile sensation?
- RQ5: Does the age of the participants affect their ratings of ownership, external appearance, and tactile sensation?

4.2 Methodology

This section presents all the details related to the methodology that was followed in our study.

4.2.1 Participants

We conducted an a priori power analysis to determine the sample size using G*Power 3.10 software [46]. The calculation was based on 95% power, a medium-to large-effect size of .30 [47], six (3 x 2) groups with six repeated measures, a non-sphericity correction of ε=.60, and an a=.05. The analysis resulted in a recommended sample size of 48 participants. We recruited 48 participants (18 to 48 years-old) for the experiment. Specifically, 12 participants were recruited from the XR Distributed Research Network (XRDRN) , which is a platform for researchers in the Cross-Reality (XR/VR/AR) discipline created in response to the Covid-19 emergency lockdown, and 36 participants were from our department. There were 16 female (age; M=23.12, SD=3.30) and 32 male (age; M=24.75, SD=5.95) participants. All participants had prior experiences with VR. No compensation was provided for participation.

4.2.2 Virtual Reality Application

For this study, we developed our VR application using Unreal Engine 4. The application runs on all Oculus devices. In this application, there were two sections: the tutorial level and the main level. The tutorial level (Figure 41) was a simple one with four assembly parts (two gears, one small ball, and one big ball). A table was placed in front of the participants, upon which the assembly parts (gears and balls) were placed. Instructions regarding the application's operations were rendered on the wall of the virtual environment. There were no specific tasks the participants needed to complete. Participants were able to move around freely in the virtual environment and pick and assemble parts in the tutorial level to familiarize themselves with the operations of the application. For the tutorial level a 3D cube was used to represent the position of the controller in the virtual environment. In this level no tactile feedback was implemented. For the assembly process, participants needed to grab the parts using the side button on the controller and move them near to the corresponding semi-transparent slots of a similar shape. When the selected part was close enough to the corresponding semi-transparent slot, it automatically "snapped" onto it. The instructions then directed the user to push the red button on the table to transition from the tutorial level to the main level.

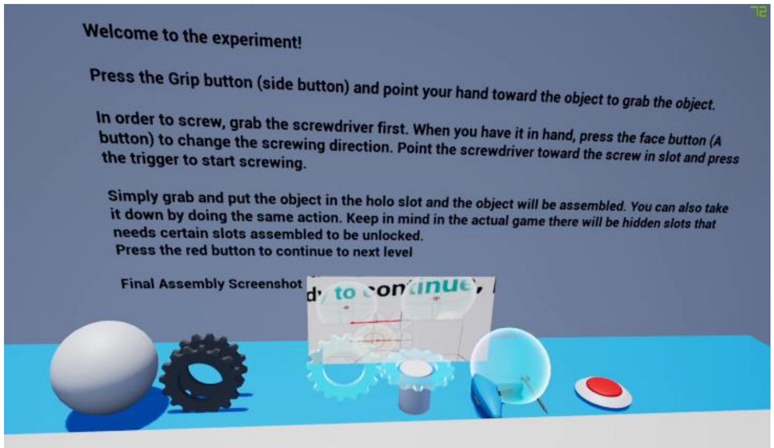

Figure 41. Screenshot of the tutorial level used in our study.

We created six variations of the main level (Figure 42), where each variation assigned one of the three hand models, with controller tactile feedback or not. For the hand models, an animation of a grabbing movement was included for each hand. Specifically, the mannequin and realistic hand models performed a grab animation with the fingers, while the abstract hand performed a simple bending motion. There were two big balls, four small balls, and five gears to assemble as the main task. A table was placed in front of the participants in the virtual environment. All the parts were placed on the table in front of the user. The task for the participants was to assemble a 3D structure by placing all the individual parts into their slots. The task required the participants to successfully assemble the following parts: two big balls on the top of the structure, four small balls in the center, four gears at the bottom, and one gear on a small cylinder. The cylinder was located at the center of the large cube. Participants needed to push the gear from the outside slot of the cylinder into the inside. The parts did not need to be placed in any particular order, but there were two hidden slots (one small ball and one gear) that necessitated other slots be completed first. When all the parts were assembled, a red button would appear. Participants would have to press the button in order to continue to the next variation of the application. A hint regarding the final assembly was rendered on the wall.

Figure 42. The assembly task the participants need to complete. The left image shows the unassembled structure with the parts; the middle image shows the assembly structure partially finished; and the right image shows the fully assembled structure.

4.2.3 Experimental Conditions

Six experimental conditions were developed (abstract hand and tactile, abstract hand and no tactile, mannequin hand and tactile, mannequin hand and no tactile, realistic hand and tactile, and realistic hand and no tactile) by following a 3 (abstract, mannequin, and realistic hand models) x 2 (tactile and no tactile feedback) within-group design; meaning all participants experienced all conditions of the study. If the condition contained tactile feedback, the controller would vibrate when the participants grabbed the object. The conditions were randomized by following Graeco-Latin square so that each participant would experience the sequence of the conditions differently.

4.2.4 Measurements

We used the body ownership, tactile sensations, and external appearance dimensions of the embodiment questionnaire provided by Gonzalez-Franco and Peck [1]. The questionnaire was distributed to our participants using Qualtrics, an online survey tool. The questions were adjusted to fit the scope of this study. All questions were answered on a scale from 1 (strongly disagree) to 7 (strongly agree). Table 1 shows the questionnaire that we have used in this study.

Table 1. The statement and questions used in this study.

No.	Variable	Questions
1	Hand Ownership	I felt as if the virtual hand was my real hand. 1 indicates strongly disagree, and 7 indicates strongly agree.
2		It felt as if the virtual hand I saw was someone else's. 1 indicates strongly disagree, and 7 indicates strongly agree.
3		It seemed as if I might have more than one hand. 1 indicates strongly disagree, and 7 indicates strongly agree.
4	Tactile Sensation	It seemed as if I felt the vibration of the equipment in the location where I saw the virtual hand touch the object. 1 indicates strongly disagree, and 7 indicates strongly agree.
5		It seemed as if the vibration I felt was located somewhere between my physical hand and the virtual hand. 1 indicates strongly disagree, and 7 indicates strongly agree.
6		It seemed as if the touch I felt was caused by the hand touching the object. 1 indicates strongly disagree and 7 indicates strongly agree.
7		It seemed as if my hand was touching the object. 1 indicates strongly disagree and 7 indicates strongly agree.
8	External Appearance	It felt as if my (real) hand were turning into an "avatar" hand. 1 indicates strongly disagree and 7 indicates strongly agree.
9		At some point, it felt as if my real hand was starting to take on the posture or shape of the virtual hand that I saw. 1 indicates strongly disagree and 7 indicates strongly agree.

4.2.5 Testing Procedure

To recruit remote participants, our study was posted on the XRDNR website. The remote participants were asked to visit the study's Qualtrics webpage and read the consent form that was approved by the Institutional Review Board (IRB) of our university. Upon agreement, the remote participants filled out a demographics questionnaire. Then, a link to download the developed application was provided. Remote participants began the application at the tutorial level. At this stage, a text with detailed information on how to control the virtual hand by using the controller to grab an object, how to assemble the parts, how to move around, and the goal of the tasks, were all rendered on the wall behind the assembly parts. After the participants were confident enough with the set-up, they pressed the red button on the table to proceed to the main levels. We kept the text instructions on the wall of the main level in case the participants needed instructions for the tasks they were asked to perform. In addition, instructions regarding taking off the headset to complete the questionnaire on the Qualtrics webpage using their own personal computer were also provided at the rendered text. After completing all the variations of the experiment, the remote participants would need to record and input a passcode that was rendered on the wall. They needed to take a photo of their own equipment and upload it to the Qualtrics survey website. The last two steps were requested so that we could ensure that all remote participants had access to a head-mounted display and completed the entire study.

For the on-site part of the study, upon arrival at the lab of our department in which the study was conducted, the participants were informed about the study and asked to read the consent form, which was approved by the IRB of our university. Upon participation agreement, the participants were asked to fill out a demographics questionnaire. Then, they were asked to put on the Oculus Quest head-mounted display and adjust it to their head accordingly. After the adjustments, the participants started the study at the tutorial level. When the participants became familiarized with the operations, they pressed the red button on the table and continued to the main level, in which they experienced the experimental conditions (Figure 43). As mentioned in the application section, participants were required to finish the assembly tasks for each variation of the main level. In between each level variation, they took off their head-mounted displays and were asked to answer the provided questionnaire distributed to them in a computer-based format (in Qualtrics). After finishing the sixth variation of the main level, the researcher answered participant's questions, and then the participants were thanked and dismissed. Both the remote and on-site participants spent no more than 60 minutes for the study.

Figure 43. A participant assembling a gear part in the virtual environment with all three hand models (from the left: realistic, abstract, mannequin).

For the on-site part of the study, in considering the current COVID-19 pandemic situation and following our institution's instructions, we secured a 60-minute gap in between each participant to ensure the risk of infection was minimized. All on-site participants were tested negative for COVID-19 before coming to the lab. Moreover, before and after each participant's arrival at the lab, all equipment and furniture were carefully sanitized by the research team. Once participants arrived at the lab, we asked them to sanitize their hands, and during the study, all participants were asked to wear face masks and VR sanitary masks (HYPERKIN Universal VR Sanitary Mask V2.0).

4.3 Results

All results obtained from the study are summarized in this section. All analyses were performed using the IBM SPSS v.26.0 statistical analysis software. The normality assumption of the objective measurements and subjective ratings were evaluated with Shapiro-Wilk tests at the 5% level and graphically using Q-Q plots of the residuals. The measured items of the ownership, external appearance, and tactile sensation scales were tested for reliability (Cronbach's alpha: .79< \alpha <.86), and due to sufficient correlation, we used the cumulative score of all items for each scale as the final result and treated them as continuous scales, a practice which is typically used. For all statistical tests, $p<.05$ was deemed as statistically significant.

4.3.1 Ownership

A two-way repeated measures analysis of variance (ANOVA), with the hand and tactile feedback types being the independent variables and the ownership being the dependent variables, was used to analyze the obtained data. We found a statistically significant main effect for hand appearance [Λ=.714, $F(2,46)$=9.195, p=.000, $\eta p2$=.286]. Post hoc comparison using Bonferroni corrected estimates showed that the participants' ownership when exposed to a mannequin hand (M=4.79, SD=.14) was significantly higher than when exposed to the realistic hand model (M=4.27, SD=.13). However, neither a statistically significant effect for tactile feedback [Λ=.983, $F(1,47)$=.798, p=.376, $\eta p2$=.017] nor an interaction (hand appearance x tactile feedback) were found on ownership [Λ=.900, $F(2,46)$=.027, p=.973, $\eta p2$=.001].

4.3.2 Tactile Sensation

The two-way repeated measures ANOVA with the hand and tactile feedback types being the independent variables and the tactile sensation being the dependent variables revealed a significant main effect for hand appearance [Λ=.740, $F(2,46)$=8.071, p=.001, $\eta p2$=.260]. Post hoc comparison using Bonferroni corrected estimates showed that the abstract hand model was rated lower (M=3.87, SD=.14) than the mannequin hand (M=4.39, SD=.10) and realistic hand (M=4.46, SD=.11) models. We did not find a statistically significant effect for tactile sensation on the tactile feedback conditions [Λ=.963, F(1,47)=1.000, p=.187, ηp2=.037]. However, a significant interaction effect (hand appearance x tactile feedback) for tactile sensation was found [Λ=.874, F(2,46)=3.308, p=.045, ηp2=.126]. The estimated marginal means showed that, in the presence of tactile feedback, participants rated the tactile sensation higher when exposed to either the mannequin or realistic hand models compared to when exposed to the abstract hand model.

4.3.3 External Appearance

For the external appearance dimension of embodiment, the two-way repeated measures ANOVA showed a significant effect for hand appearance [Λ=.692, F(2,46)=10.247, p=.00, ηp2=.308]. The post hoc comparison using Bonferroni corrected estimates showed that participants rated the abstract hand model (M=3.35, SD=.22) lower than the mannequin hand (M=4.42, SD=.17) and realistic hand (M=4.56, SD=.21) models. Moreover, a significant effect for external appearance on tactile feedback was also found [Λ=.909, F(1,47)=1.187, p=.035, ηp2=.091]. Post hoc comparison using Bonferroni corrected estimates showed that the participants rated the tactile feedback conditions (M=4.21, SD=.15) higher than the no tactile feedback conditions (M=4.01, SD=.14). Finally, no significant interaction effect (hand appearance x tactile feedback) was found [Λ=.951, F(2,46)=1.187, p=.314, ηp2=.049].

4.3.4 Experimental Site

A three-way mixed ANOVA (hand appearance x tactile feedback x experimental site) with the experimental site setting (remote vs. on-site) as a between-subject factor was conducted to investigate the effects of the experimental site on the participants' responses. A statistically significant interaction effect (hand appearance x experimental site) was found for the external appearance dimension of embodiment [Λ=.779, F(2,45)=6.398, p=.004, ηp2=.221]. The estimated marginal means showed that the in-person participants' rated the external appearance of the realistic hand model higher (M=4.89, SD=.23) than that of the remote (M=3.60, SD=.41) participants.

4.3.5 Virtual Reality Experience

We conducted three-way mixed ANOVA (hand appearance x tactile feedback x VR experience) on the participants' prior VR experience (less than an hour per week vs. more than an hour per week) as a between-subject factor to investigate the effects of VR experience on the participant responses. Note that 33 participants experienced VR less than one hour per week, and 15 participants experienced VR more than one hour per week. A statistically significant interaction effect (tactile feedback x VR experience) was found for the perception of ownership [Λ=.841, $F(1,46)=8.718$, $p=.005$, $\eta p2=.159$]. The estimated marginal means showed that in the presence of tactile feedback, participants who were exposed for less than one hour per week with VR rated the tactile sensation higher (M=4.74, SD=.14) compared to the participants who were exposed for more than one hour with VR per week (M=4.01, SD=.21). Additionally, a statistically significant interaction effect (hand appearance x VR experience) was found for the external appearance dimension of embodiment [Λ=.796, $F(2,45)=8.718$, $p=.006$, $\eta p2=.204$]. The estimated marginal means showed that in the presence of a realistic hand model, participants who were exposed for less than one hour per week with VR rated the external appearance of the virtual hand model higher (M=4.57, SD=.13) when compared to the participants who were exposed for more than one hour with VR per week (M=3.14, SD=.22).

4.3.6 Age Groups

We explored whether age could affect the way the participants experienced the six experimental conditions. We conducted three-way mixed ANOVA (hand appearance x tactile feedback x age group) tests with age groups (younger; 29 participants aged between 18 and 24 vs. older; 19 participants aged between 25 and 48) set as a between-subject factor to investigate the effects of VR experience on the participants responses. A statistically significant interaction effect (hand appearance x age) was found for the tactile sensation dimension of embodiment [Λ=.851, $F(2,43)=3.758$, $p=.031$, $\eta p2=.149$]. The estimated marginal means showed that in the presence of a realistic hand model, the younger participants rated the tactile sensation higher (M=4.56, SD=.14) than the older participants (M=4.03, SD=.18).

4.4 Discussion and Limitation

In this study, we explored how the appearance of a virtual hand model and tactile sensation affected three embodiment dimensions: ownership, external appearance, and tactile sensation. The subsections below discuss our findings.

4.4.1 Hand Appearance

We found statistically significant results for the effect of hand appearance on all examined variables (RQ1). The mannequin hands were associated with a higher sense of ownership. On the other side, the realistic hand enhanced the participants' perception of the tactile feedback as it felt more realistic. The abstract hand, being the least realistic, was scored lower by participants throughout the entire three embodiment dimensions (ownership, external appearance, and tactile sensation) compared to the other two styles.

The participants rated their sense of ownership for the mannequin hand as higher than for the realistic hand. This result deviates from previously studies, which have indicated that the realistic hand generates higher levels of ownership in VR [3][4][5]. Argelaguet et al. [2] mentions that ownership is dependent on the appearance of the virtual hand and that morphological resemblance is needed to increase ownership. Hoyet et al. [11] also found participants experiencing higher ownership when using more realistic hands and fingers. In this task, when considering the design of the environment, the mannequin hand appearance had the best resemblance to the virtual environment, since both the virtual environment and the mannequin hand model were low-poly with a semi-realistic appearance. Regenbrencht et al. [65] has mentioned the importance of mimicking the real world in terms of realism in order to get close to visual coherence in an immersive environment. A coherent visual quality can maximize virtual visualization and enhance embodiment. Participants in the present study reported that both abstract hands and realistic hands brought a sense of "style clash" with the environment, which also supports our statement. A contradictory style of appearance (e.g., environment style vs. hand appearance) can reduce feelings of ownership [2], which we think was the reason the participants' ownership ratings were higher under the mannequin hand condition than the realistic hand condition. In addition, the realistic hand uses a white male hand as the model. Peck et al. [40]'s study mentioned about the ethnicity-related changes of virtual body ownership, which supports our assumption regarding the mannequin hand model. In another study done by Schwind et al. [70], female reacted negatively when interacting with male hands. Different gender avatar may evoke uncomfortable feelings. Therefore, ethnicity and gender can be a possible factor for the effect.

In terms of tactile sensation, both the mannequin hand and realistic hand received higher ratings than the abstract hand. This means that the abstract hand was associated with the lowest tactile sensation effect. Lougiakis et al. [6] supports this claim in their study by indicating that in their task, controller and hand appearance were more effective than the abstract representation in terms of user performance and ownership. In our study, the mannequin and realistic hand animations looked more familiar to the participants, while the abstract hand did not really meet participants' expectations. Longo et al. [9] has mentioned that realistic hand appearance underlies tactile sensations because it allows better matching of tactile location and hand position. This statement also supports the reason why the participants' ratings of the abstract hand were not impacted by the presence of tactile feedback in the present study. However, the tactile feedback was responsible for enhancing the tactile sensation of the participants when they were assigned a realistic hand model.

As for external appearance, the abstract hand was rated lower than the other two hand types. This result is reasonable because the abstract hand only featured the basic shape of a rectangular block. In addition, both the mannequin and realistic hands included finger animations of a grabbing movement, while the abstract hand's shape simply bent and behaved like a 3D model with less detail and less precise movement compared to the other two hand models. Kokkinara and McDonnell [62][63] found similar results when experimenting with the animation of virtual faces. Virtual faces were perceived as more appealing when higher levels of animation realism were provided. We think this was the main reason behind the participants perceiving the external appearance of the mannequin hand to be close to that of the realistic hand.

4.4.2 Tactile Feedback

We found a significant effect of tactile feedback on the external appearance ratings of our participants (RQ2). Specifically, our finding proves that tactile feedback made our participants rate the external appearance of virtual hands higher. According to Hoffman et al. [66][67] tactile augmentation enhances the realism of virtual environments and according to Haddadin et al. [8], touching a virtual object has an impact on participants' perception of realism. The mentioned findings support our results.

Although Hills et al. [55] mentioned in their earlier article that haptic and visual signals could be independently accessed in perceptual judgments, our study indicates that tactile feedback enhanced the tactile sensations when accompanied by the realistic hand compared to the other two hands. The significant interaction effect between hand appearance and tactile feedback on perceived tactile sensation suggests that when we apply both factors, the rating of tactile sensation increases. Our finding goes along with Schwind et al. [54], who found that tactile sensitivity was dependent on hand appearance and texture type, as also shown in our findings, indicating that hand appearance affected participants' visual-haptic experience.

4.4.3 Study Site

Our results also revealed a significant interaction effect between hand appearance and study site (RQ3). The in-lab participants rated the external appearance of the realistic hand significantly higher than the remote participants. Although we do not have such evidence, presuming that attention is considered as an important factor in experimental studies [56], we posit that a possible reason for this could be that the in-person participants were more focused than the remote participants, leading to taking the study more seriously and paying more attention to the hand appearances. Thus, we think that future remotely conducted studies need to consider screening participant's attention.

Another possible reason for the effect of the study site on participants' responses is that the in-person study was conducted in a more controlled environment. All the in-person participants completed the study at the lab where most external factors were controlled (e.g., similar environment, noise and temperature). Tiggemann and Boundy [57] suggested that subtle factors can affect experimental studies. However, we were not able to control the experimental environment of the remote participants. We think that additional studies of exploring environment-related factors should be conducted to understand such issues more accurately.

4.4.4 Virtual Reality Experience

Our results indicated that the prior VR experience of the participants could be considered as a factor that affected the participants' ratings in terms of how they perceived the tactile feedback and appearance of the virtual hand models (RQ4). In the presence of tactile feedback, the participants who were exposed for less than one hour per week with VR rated the perceived tactile sensation higher than the participants who were exposed for more than one hour in VR per week. Moreover, in the presence of a realistic hand model, participants who were exposed for less than one hour per week in VR rated the external appearance of the virtual hand model higher than the participants who spent more than one hour in VR per week. In a previous study by Mousas et al. [53], it was found that prior VR experience could affect the emotional reactivity of participants when interacting with virtual characters of different appearance, indicating that the VR experience of participants could potentially also contribute to understanding how participants perceive the appearance of a virtual hand model. We consider this a novel finding, since to the best of our knowledge, none of the previously conducted studies concerning the effects of virtual hand appearance [2][5][6][10][48][54] have reported such findings. However, we argue that further experiments should be conducted to validate such findings.

4.4.5 Age Groups

Another interesting finding revealed in our statistical analysis was that the age of participants could be a factor when affecting their perception of the tactile feedback (RQ5). In splitting our participants into two age groups (18 to 24 and 25 to 48 years old), the statistical analysis revealed that the younger participants rated the tactile sensation higher than the older participants in the presence of the realistic hand. Serino et al. [29] found that older participants (aged 26 to 55 years-old) were more resistant to body changes induced by bodily illusions, while younger participants (ages 19 to 25 years-old) were more affected by such changes. Trauutman et al. [36], who investigated the tactile sensation of participants by using cream products with small and large particles, found that the younger participants were more sensitive to the larger particles than the older participants, who did not sense any differences. Our results are in line with the aforementioned findings and revalidate that younger participants are more sensitive to tactile feedback than their older counterparts.

4.4.6 Limitations

There were a few study limitations applied to both the in-person and remote experiment portions. We decided not to adjust the hand size for any of the hand models because we wanted to standardize the experiment, allowing all participants to experience the exact same hand sizes. Many in-person participants reported that the realistic and abstract hands were bigger than their own hands. Previously conducted research has found that different sizes of different virtual body parts can alter the participants' perception of realism and appearance [48][49][68]. In this study the realistic hand appearance that we used is much closer to that of a male adult hand. We think that this could have affected our participants. In addition, we did not collect background information regarding the ethnicity of participants. We think that this information can help us further understand our findings about hand appearance.

Another study limitation was the potential learning effects. While the conditions in this study varied, the assembly task was the same. By observing our in-lab participants, we realized that almost all participants spent more time in the first experimental condition to which they were exposed compared to the rest five conditions. Although we did not capture the time that each participant spent in each condition, we think that this could have also impacted participants' rating. In future studies, revisions regarding the assembly tasks could be made to avoid learning effects and ensure that all participants spend a similar amount of time in all experimental conditions. Furthermore, the design of the developed application could be improved. Some in-person participants provided feedback such as "I spent a lot of time figuring out where to put the objects" or "I had some issues learning how to perform the assembly." Based on these responses, it looks like the design of the levels needs to be more user-friendly so that the participants can be more focused on the virtual hand model.

There were also some limitations in the remote study. It was our oversight not to collect information on the study sites (e.g., office or home, size, external noise) in which the different participants were located. We neglected to provide specific instructions to the participants as how to engage in the experiment at their individual sites (e.g., controlling noise). Another limitation was related to the sample size. According to Casler et al. [58], when conducting remote studies, a higher sample size is needed. However, in a three-month period during our study posted on the XRDRN, only 12 people decided to participate in this study, which was either due to the lack of compensation provided or because the XRDRN platform is not yet known across the research community.

Moreover, considering the limitations of Oculus controllers, they cannot provide rich contact and shape information when conducting assembly tasks. Pacchierotti et al. [71] found that contact feedback is paramount toward body ownership and sensation of presence. With the development of wearable haptic technologies, it can effectively increase the range of stimuli received. Comparing with fingertip and glove-based devices, hand-held controllers cannot provide as detailed tactile feedback to users.

4.4.7 Design Considerations

We think that the knowledge obtained from this project should be documented by the authors to help the research community develop more efficient VR assembly applications that involve virtual hands and tactile feedback. For those who have not experienced CAD assembly process in the past, this type of assembly application provides an easy head-start for the basic concepts of positioning and constraining the object in a pre-defined setup. Thus, we present in this section our reflections about designing virtual assembly tasks using virtual hands and tactile feedback.

Because hand appearances do affect ownership, external appearance, and tactile sensation, more appropriate to use either a mannequin or realistic style hand model. Hand and finger animation is also important. It is essential to have a realistic animation of finger and hand movement when grabbing different objects. Providing tactile feedback (e.g., vibration feedback when grabbing objects) to users can also be an effective solution to enhancing the three dimensions of embodiment.

In terms of assembly applications, it is essential to provide indicators for the assembly tasks. In this study a few participants complained about the process being “frustrating,” “unclear,” or “time-consuming,” because the only guiding element was the semi-transparent target spots. Designs like an arrow indicator showing the corresponding slot for the part the participant is currently holding could be useful to decrease the amount of effort exerted toward finding the correct target. Other designs, like numbering the order of the parts and slots (e.g., part #1 needs to be assembled in slot #1) could also be effective for users.

CHAPTER 5. EVALUATING VIRTUAL HAND ILLUSION THROUGH REALISTIC APPEARANCE AND TACTILE FEEDBACK

5.1 Introduction

As mentioned, studies in the past focused on different 3D models (3D geometries) of virtual hands [76][77], as well as on different sizes of virtual hands [78][92]. However, to the best of our knowledge, no study has been conducted to explore manipulation based only on hand appearance (render style). For this reason, we conducted a 3 (Appearance: realistic vs. pixelated vs. toon) x 2 (Tactile: tactile vs. no tactile feedback) study to explore further the realistic appearance of virtual hands and tactile feedback in virtual reality. We know previous studies [76][77][79] compared the difference in between hand models with a larger scale, and therefore we decided to use smaller manipulation in terms of shaders to study in more detail about whether such appearance difference can affect embodiment. Moreover, studies in the past already applied similar shaders and have found significant results in human perception [140][141]. In fact, less detailed shaders like pixelation and toon were found to be more likeable [142]. Having more detail on virtual agents would cause the perceived eeriness to decrease [141]. We developed a VR assembly application and instructed the participants to interact with it. We decided to use three shaders to alter the appearance of the virtual hands (Figure 2). Our contribution from this study was regarding the effect of shaders on smaller and specific body parts, in this case, the hands.

Note that shaders are widely used in games to provide not only detailed rendering (e.g., shadows, lighting, and landscape) [93], but also to generate more realistic visual effects (e.g., sprites, particles, and texture gradients) in virtual environments [94][95]. We think that understanding the impact of the realistic appearance of virtual hands will improve our understanding regarding VHI and thus provide more insights to researchers and VR developers. To do so, and based on our study design, we aim to answer the following research questions:

- RQ1: Do different hand appearances affect our participants' sense of presence and VHI?
- RQ2: Does tactile feedback affect our participants' sense of presence and VHI?
- RQ3: Does prior VR experience affect our participants' sense of presence and VHI?

5.2 Methodology

The subsections below present the methodology we followed in this study.

5.2.1 Participants

We conducted an a priori power analysis to determine the sample size of this study. For our calculations, we used a 95% power, a medium to large effect size of f = .32, six (3x2) groups, and an \alpha = .05. The analysis resulted in a recommended sample size of 120 participants (20 participants per group).

We recruited 120 participants (18-48 years old; M=19.49, SD=3.10) for our study through emails and class announcements made to undergraduate and graduate students in our department. Among our participants, 84 were male and 36 were female, equally distributed across participant groups. From the sample, 41 participants had no prior experience with VR, and 79 participants had previously experienced VR. All students volunteered for our study.

5.2.2 Virtual Reality Application

We developed our VR application for the study in Unreal Engine 4 and deployed it on an Oculus Quest 2 head-mounted display. We implemented two sections: the first is the training (tutorial) section and the second is the testing section (Figure 44). We implemented the tutorial section to provide our participants with instructions and familiarize them with the use of virtual reality controllers. Doing so has been shown to improve virtual reality users' performance [106] significantly. Specifically, the tutorial section was reasonably straightforward, including only a gear part, a transparent gear slot, and a red button that starts the testing section. The participants had the freedom to move around in the environment and pick and assemble the gear onto the transparent slot. Participants would only need to use the grip button to "grab" the gear 3D model and "assemble" it by moving the gear toward the transparent slot. When the gear 3D model was close enough to the target slot, the gear would automatically "snap" onto the slot to stay in place. Participants could press the red button to proceed into the testing section whenever they were ready for the experiment.

The testing section included a long counter in the front, a large white cube in the center with four transparent slots on the front side and four gears on the cube's left side. We created six variations of the testing section, where each variation assigned one of the hand appearances, with or without tactile feedback activated. We set the frequency and the intensity of the tactile feedback of Oculus Touch controllers to maximum (frequency = 1.00 and intensity = 1.00). The grasping motion of the hand was the same for all conditions. The task for the participants was to assemble all four gears onto the cube. After that, a transparent sphere would appear in the center of the cube's front side. Participants would put their right hand inside the 3D sphere model for two seconds. Then, a white spike would come out to "pierce" the virtual hand. Depending on the participant group, the tactile feedback of the controller was either activated or not. The spike was added as a metaphor to replicate the rubber hand illusion study. The oculus controller performed a weak to strong vibrotactile feedback as the spike goes out further piercing through the virtual hand. In the initial RHI study, a knife hit the fake limb at the end to explore the effect of synchronous stokes on hand ownership [18].

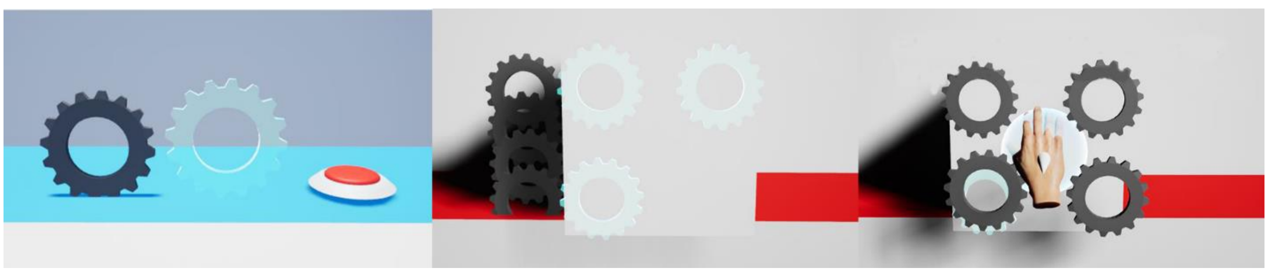

Figure 44. The training (tutorial) and testing sections of our application. From left to right: the tutorial level was provided to participants to familiarize them with the operations and mechanics (left); the testing section in which participants were asked to assemble the gears (middle); and the spike "piercing" the virtual hand (right).

5.2.3 Experimental Conditions

By following a 3 (Appearance dimension: realistic vs. pixelated vs. toon hand appearances) x 2 (Tactile dimension: no tactile vs. tactile) between-group study design, we developed six experimental conditions: realistic tactile, pixelated tactile, toon tactile, realistic no tactile, pixelated no tactile, and toon no tactile. For the hands, we decided to use disembodied body ("floating" hand). There were previous studies [6][79][97] that used the same methodology and there are commercial applications such as BOXVR[3] and Job Simulator[4] that also applied disembodied hand. Each group consisted of 20 participants (14 male and 6 female). Note that, in the conditions in which we activated the tactile feedback, the controller would vibrate when grabbing the objects and getting "pierced" by the spike.

5.2.4 Measurements

In our study, we collected self-reported data using the Slater-Usoh-Steed (SUS) scale [72] on presence, as well as though the avatar embodiment scales (virtual hand ownership, touch sensations, agency and motor control, external appearance, and response to external stimuli) by Gonzalez-Franco and Peck [1]. We used a 7-point Likert scale for all questions/statements (see Table 2). We disseminated the scales to our participants using the Qualtrics online survey tool offered by our university. Note that we made the necessary adjustments to the questions/statements to fit the scope of the study.

Table 2. The statements/questions used in our study.

No.	Variable	Questions
1	Presence	Please rate your sense of being in the virtual environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place.
2		To what extent were there times during the experience when the virtual environment was the reality for you? 1 indicates not at all, and 7 indicates totally.
3		During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment or of being elsewhere? 1 indicates being in the virtual environment, and 7 being elsewhere.
4		During the time of your experience, did you often think to yourself that you were actually in the virtual environment? 1 indicates strongly disagree, and 7 indicates strongly agree.

[3] https://www.oculus.com/experiences/rift/1696375800396854
[4] https://jobsimulatorgame.com

Table 2 continued

5	Hand Ownership	I felt as if the virtual hand was my real hand. 1 indicates strongly disagree, and 7 indicates strongly agree.
6		It felt as if the virtual hand I saw was someone else's. 1 indicates strongly disagree, and 7 indicates strongly agree.
7		It seemed as if I might have more than one hand. 1 indicates strongly disagree, and 7 indicates strongly agree.
8	Tactile Sensation	It seemed as if I felt the vibration of the equipment in the location where I saw the virtual hand touch the object. 1 indicates strongly disagree, and 7 indicates strongly agree.
9		It seemed as if the touch I felt was located somewhere between my physical hand and the virtual hand. 1 indicates strongly disagree, and 7 indicates strongly agree.
10		It seemed as if the touch I felt was caused by the hand touching the object. 1 indicates strongly disagree and 7 indicates strongly agree.
11		It seemed as if my hand was touching the gears. 1 indicates strongly disagree and 7 indicates strongly agree.
12	Agency and Motor Control	It felt like I could control the virtual hand as if it was my own hand. 1 indicates strongly disagree and 7 indicates strongly agree.
13		The movements of the virtual hands were caused by my movements. 1 indicates strongly disagree and 7 indicates strongly agree.
14		I felt as if the movements of the virtual hands were influencing my own movements. 1 indicates strongly disagree and 7 indicates strongly agree.
15		I felt as if the virtual hand was moving by itself. 1 indicates strongly disagree and 7 indicates strongly agree.
16	External Appearance	It felt as if my (real) hand were turning into an "avatar" hand. 1 indicates strongly disagree and 7 indicates strongly agree.
17		At some point, it felt as if my real hand was starting to take on the posture or shape of the virtual hand that I saw. 1 indicates strongly disagree and 7 indicates strongly agree.
18		At some point, it felt that the virtual hand resembled my own (real) hand in terms of shape, skin tone, or other visual features. 1 indicates strongly disagree and 7 indicates strongly agree.
19	Response to External Stimuli	I felt a tactile sensation in my hand when I saw the spike coming out. 1 indicates strongly disagree and 7 indicates strongly agree.
20		When the spike came out, I felt the instinct to draw my hands out. 1 indicates strongly disagree and 7 indicates strongly agree.
21		I felt as if my hand had hurt. 1 indicates strongly disagree and 7 indicates strongly agree.
22		I had the feeling that I might be harmed by the spike. 1 indicates strongly disagree and 7 indicates strongly agree.

5.2.5 Procedure

Upon arrival at our research lab, where the study took place, we asked the participants to read the consent form and sign it upon their agreement. The Institutional Review Board (IRB) of the university approved our study. After agreeing to participate in our research and signing the consent form, we asked the participants to provide demographic data in Qualtrics. Then, we asked them to put on the Oculus Quest 2 HMD and adjust it to their heads accordingly. After the adjustments and after indicating that they were ready for the study, the experimenter started the application from the tutorial section. After becoming familiar with the operations, the participants pressed the red button on the table to continue to the testing section, where they experienced one of the experimental conditions. As mentioned in the testing section, we asked the participants to finish the four-gear assembly first and then to experience the "piercing" of the spike. We used the four-gear assembly task to induce the participants into the virtual environment and to start thinking about their virtual hand as their hand. Then, the spike "pierce" was used as a metaphor for the RHI experiment. After the participants pressed the red button again, they would end the application and take off the headset. We then instructed the participants to fill out the post-survey. After that, the researcher answered the participants' questions, and finally, the participants were thanked and dismissed. Each participant spent less than 30 minutes in our study. Figure 45 illustrates the experimental setting of our research and a participant using our application.

Figure 45. A participant during the study in our lab setup.

Considering the current COVID-19 pandemic and following our institution's instructions, we allowed a 30-minute gap between participants to minimize infection risk. Participants were either vaccinated or followed the instructions of our university regarding regular testing (at least once per week) for COVID-19. Once the participants arrived at the lab, we asked them to sanitize their hands, and during the study, all participants wore face masks and VR sanitary masks. Additionally, the research team carefully sanitized all equipment and furniture before the participants' arrival and after each study session.

5.3 Results

In this section, we report all the results of this study. We performed all analyses using the IBM SPSS v.26.0 statistical analysis software. The normality assumption of all self-reported ratings was screened with Shapiro-Wilk tests at the 5% level and graphically using the Q-Q plots of the residuals. We tested the measured items of the scales for reliability (Cronbach's alpha: .72 < \alpha < .90), and due to sufficient correlation, we used the cumulative score of all items for each scale as the final result and treated them as continuous scales, which is a typically used practice. No removal of items would have enhanced the internal reliability of the scales. For all statistical tests, p<.05 was deemed as statistically significant. In addition to the results presented below, we would like to note that we also screened our data for gender and age differences. We did not find significant results; therefore, we did not report such analyses below. Figure 46 illustrates the boxplots of our results.

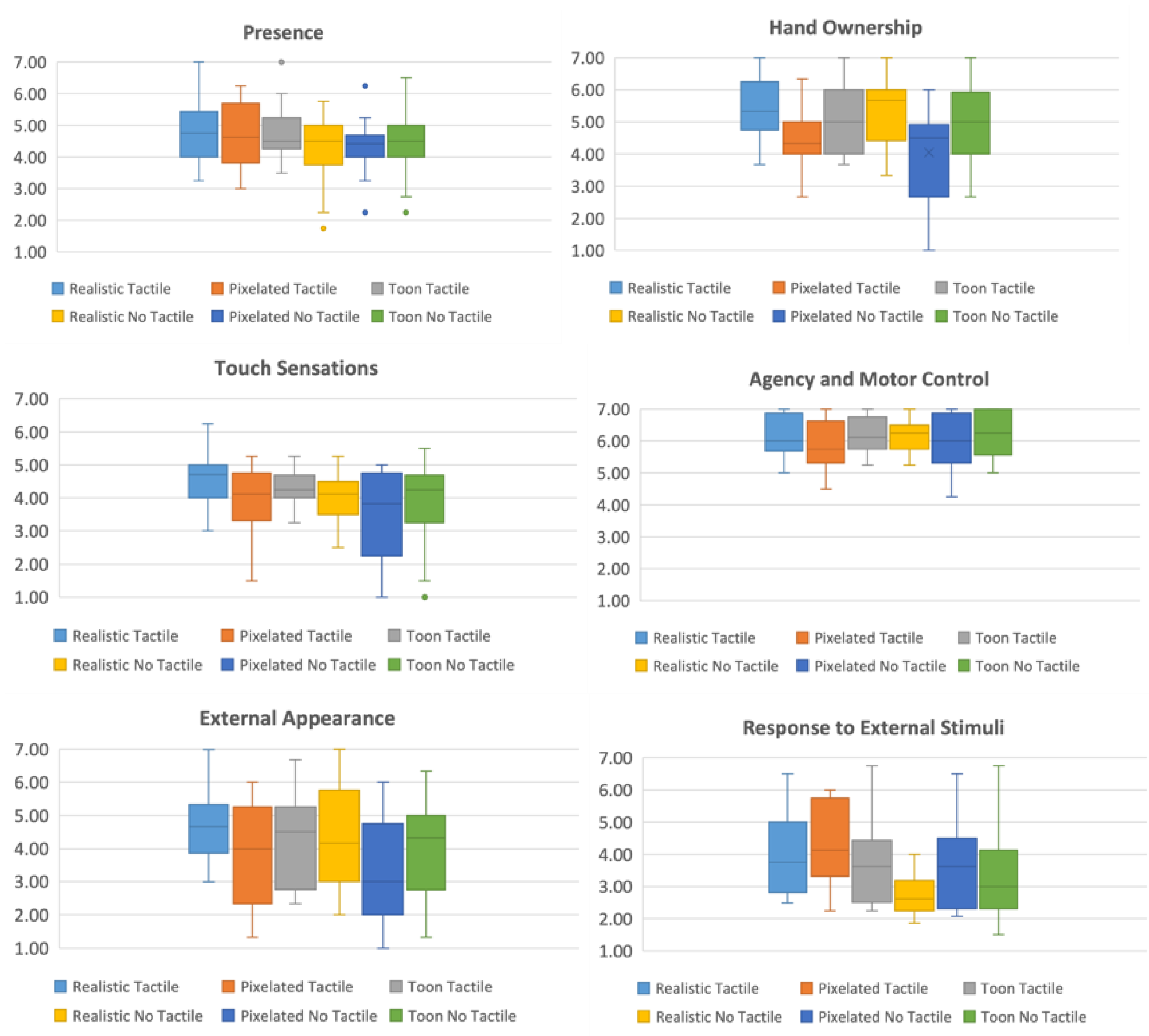

Figure 46. Boxplots of all results for each examined condition. The vertical axis refers to the 7-point scale. Boxes enclose the middle 50% of the data. A thick horizontal line denotes the median.

5.3.1 Presence

In terms of presence, according to the two-way analysis of variance (ANOVA), we did not find an (Appearance x Tactile) interaction effect [F(2,118) = .245, p = .783, ηp2 = .004]. However, we found a significant main effect for the Tactile dimension [F(1,119) = 9.532, p = .003, ηp2 = .077].

5.3.2 Hand Ownership

The two-way ANOVA did not reveal an (Appearance x Tactile) interaction effect [F(2,118) = .045, p = .956, ηp2 = .001] on hand ownership. However, we found a significant main effect for Appearance [F(1,119) = 11.226, p=.000, ηp2=.165]. Post hoc comparison using Bonferroni corrected estimates showed that participants with pixelated hand appearance (M = 4.18) rated significantly lower the hand ownership than those on the toon-hand appearance (M = 4.95) and realistic hand appearance (M = 5.35) conditions. Finally, we did not find a significant main effect for the Tactile dimension [F(1,119) = .933, p =. 336, ηp2 = .008].

5.3.3 Touch Sensation

The two-way ANOVA showed no (Appearance x Tactile) interaction effect [F(2,118) = .045, p = .956, ηp2=.001] in touch sensation. However, we found a significant main effect for the Tactile dimension [F(1,119) = 4.924, p = .028, ηp2 = .041]. Post hoc comparison showed that participants exposed to the no-tactile level (M = 3.84) rated their touch sensation significantly lower than those exposed to the tactile level (M = 4.25). Finally, we did not find any statistically significant main effect for the Appearance dimension [F(1,119) = 2.380, p = .097, ηp2 = .040].

5.3.4 Agency and Motor Control

In terms of agency and motor control, the two-way ANOVA did not reveal an (Appearance x Tactile) interaction effect [F(1,119) = .094, p = .910, ηp2 = .002]. We also did not find any statistically significant main effect on either the Appearance dimension [F(1,119) = 1.597, p = .207, ηp2 = .027] or Tactile dimension [F(1,119) = .132, p = .717, ηp2 = .001].

5.3.5 External Appearance

In terms of external appearance, the analysis did not reveal an (Appearance x Tactile) interaction effect [F(2,118) = .005, p = .995, ηp2 = .000]. However, we found a significant main effect for the Appearance dimension [F(1,119) = 6.402, p = .002, ηp2 = .101]. Participants assigned to the realistic hand appearance (M = 4.57) rated higher the external appearance of the virtual hand model than those exposed to the pixelated hand appearance (M = 3.47). Finally, we did not find a statistically significant main effect for the Tactile dimension [$F(1,119) = 1.886$, $p = .172$, $\eta p2 = .016$].

5.3.6 Response to External Stimuli

No (Appearance x Tactile) interaction effect was found [$F(2,118) = 1.073$, p =. 346, $\eta p2 = .018$] on the response to external stimuli. However, we found a significant main effect for the Tactile dimension [$F(1,119) = 9.740$, $p = .002$, $\eta p2 = .079$]. Post hoc comparison showed that participants exposed to the no-tactile level (M = 3.34) rated their response to external stimuli significantly lower than those exposed to tactile level (M = 4.04). Finally, the analysis did not provide a statistically significant main effect for the Appearance dimension [$F(1,119) = 1.997$, $p = .140$, $\eta p2 = .034$].

5.3.7 Prior VR Experience

We conducted a three-way ANOVA (Appearance x Tactile x Prior VR Experience) to explore whether prior VR experience could potentially impact participant ratings (see Figure 5 for the interaction plots). For the agency and motor control, our analysis did not reveal either a three-way (Appearance x Tactile x Prior VR Experience) interaction effect [$F(2,118) = .393$, $p = .676$, $\eta p2 = .007$] or a two-way (Tactile x Prior VR Experience) interaction effect [$F(1,119) = .103$, $p = .749$, $\eta p2 = .001$]. However, it revealed a two-way (Appearance x Prior VR Experience) interaction effect [$F(1,119) = 3.594$, $p = .031$, $\eta p2 = .062$]. In the presence of a pixelated hand appearance, we found that participants with no prior VR experience provided a higher rating on agency and motor control than those with prior VR experience. We also found a significant main effect for Prior VR Experience [$F(1,119) = 6.831$, $p = .010$, $\eta p2 = .059$]. Pairwise comparison showed that participants with no prior VR experience provided lower ratings on the agency and motor control than those with prior VR experience.

We also explored the response to external stimuli variable. According to our results, the ANOVA did not reveal a three-way (Appearance x Tactile x Prior VR Experience) interaction effect [$F(2,118) = .208$, $p = .813$, $\eta p2 = .004$]. Moreover, we did not find a two-way (Tactile x Prior VR Experience) interaction effect [$F(1,119) = 2.544$, $p = .114$, $\eta p2 = .023$]. However, we did find a statistically significant two-way (Appearance x Prior VR Experience) interaction effect

[F(2,118) = 3.559, p = .032, ηp2 = .062] (Figure 47). Specifically, we found that in the presence of the pixelated hand appearance, participants with no prior VR experience provided lower ratings on their responses to external stimuli compared to those with prior VR experience. Finally, we did not find a main effect of Prior VR Experience on response to external stimuli [F(1,119) = .436, p = .510, ηp2 = .004].

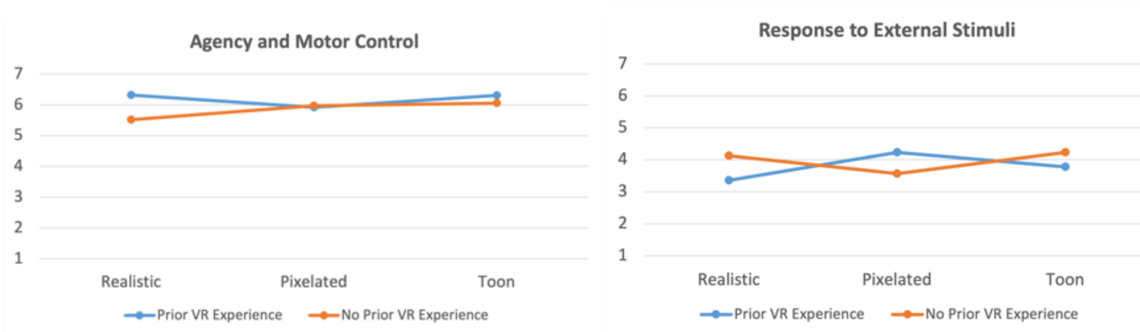

Figure 47. Interaction plots (Appearance x Prior VR Experience) for the agency and motor control, and the response to external stimuli. The vertical axis refers to the 7-point scale.

5.4 Discussion and Limitation

In this study, we aimed to explore how the appearance of virtual hands (Appearance dimension) and the tactile feedback (Tactile dimension) impacted our participants in terms of presence and body ownership dimensions (hand ownership, touch sensation, agency and motor control, external appearance, and response to external stimuli). In addition, we reported significant findings regarding the effect of participants' prior VR experience. The subsections below discuss our findings and our study's limitations and design considerations.

5.4.1 RQ1: Realistic Appearance

To answer RQ1, according to our results, we first found significant Appearance effects on hand ownership. Participants who had the pixelated hand reported significantly lower hand ownership than those who had experienced the toon and realistic hands. Previous studies have already proved the effect of avatar realism in immersive environments, indicating that a realistic avatar tends to generate stronger virtual body ownership [73][74][75]. Moreover, studies regarding virtual hands specifically mentioned that a more realistic/human-like hand style would provide stronger hand illusion and perceived limb ownership when compared to hand models of different geometries and abstractions [76][77][78]. In addition, Pyasik [42] found that detailed hand appearance could be a contributing factor for VHI, and later studies [96][42] confirmed the conclusion. In our research, the pixelated hand appearance obscured the details of the virtual hand. Our study results extend the previously reported findings indicating that even appearance changes (we kept the geometry of the virtual hand as is) could also impact the hand ownership illusion of participants. We think that the pixelated hand provided a sense of style clash in contrast with the virtual environment to the participants, which made them rate as lower the hand ownership compared to those exposed to the toon or realistic hand appearance. Therefore, we think a more detailed appearance (realistic and toon-hand appearance) was logically likelier to generate a stronger sense of hand ownership than a less detailed one (pixelated hand appearance). Furthermore, in the experiment, no participants reported any negative comments of using a real hand model. In our case, we had more male participants in the study. We would consider the effect of male hand model as minor and therefore we do not think this is a limitation. In addition, we see also from other research [76][77] that only one type of realistic hand/arm was used regardless of gender, and it is reasonable for us to follow the same methodology.

Our statistical analysis also revealed statistically significant results of Appearance on external appearance. Participants exposed to the pixelated hand rated the appearance lower than those exposed to the realistic hand appearance. Previously conducted studies revealed that avatar body style was related to appearance realism [80][81], as well as that the realistic hand model had a stronger effect on the ratings of external appearance compared to other less realistic hands [79]. In addition, based on the comments from the participants, the pixelated hand was referred to as "blurry," "mosaic," and "not clear enough to recognize." In the previous studies, researchers mentioned the visual perception of virtual hands in implicit and explicit methods [116[117][118]. Referring to the comments of our participants (e.g., "I felt my hand was a bit blurry," "I could not connect my pixelated hand to the real hand"), we think the pixelated hand appearance did not help participants perceive the appearance of the virtual hands in both explicit (size and shape) [116[117] and implicit (location of landmarks—in this case, finger joints and wrist) [118] directions—the pixelated hand appearance made the virtual hand unclear and provided less information. The aforementioned is especially true when considering that the realistic hand model contributed a distinct visual appearance.

5.4.2 RQ2: Tactile Feedback

There were several statistically significant results on tactile feedback (RQ2). We first found a significant effect on presence. Participants exposed to no tactile feedback conditions rated their presence levels lower than those exposed to tactile feedback. Previously conducted studies have found that tactile feedback in different avatar body parts can generate a stronger sense of presence [7][28], as well as that those participants exposed to no tactile feedback conditions reported lower presence levels than those exposed to tactile feedback [82]. Khamis et al. [112] also explored the effect of tactile feedback on presence. Their study proved that activating tactile feedback resulted in a higher reported sense of presence when compared to no tactile feedback conditions [112]. In our experiment, tactile feedback was activated when touching the gears and being pierced by the spike. We think that tactile feedback made participants feel that their hands were in the virtual world along with other objects. In contrast, the participants who were not exposed to tactile feedback indicated a lack of relationship between the existence of the virtual world and object interaction, which is a result that confirmed previously published works [82][7][28][112].

Participants who were exposed to tactile feedback reported stronger tactile sensations when interacting with virtual objects than those not exposed to tactile feedback. Fossataro et al. [85] found that tactile feedback could reduce the delusional body ownership for brain-damaged patients. This result revealed that tactile sensation could regenerate and enhance touch sensation for hands. Other studies proved that tactile feedback provided a stronger sense of touch to VR users [86][87]. In this experiment, we instructed the participants to grasp and manipulate gears. The tactile feedback was activated when grabbing the gear, providing participants with a sense of touch location and object interaction.

Finally, we found that tactile feedback significantly affected response to external stimuli. For our experiment, the RHI idea was borrowed and altered. We used a spike to pierce the participants' right hand. Participants in the tactile conditions group rated their response to external stimuli higher than those exposed to tactile feedback. In the original rubber hand illusion study, Botvinick and Cohen [88] found that synchronous stroke generated the sense of "phantom limbs" and noted the reactions of participants after the "stab." In a more advanced setup, D'Alonzo et al. [34] also found that vibrotactile feedback impacted the phantom limb sensation on a prosthetic limb, while also causing a stronger reaction to stimulation. Vargas et al. [117] mentioned that vibrotactile feedback could increase the proprioceptive recognition over a fake limb and could be the reason for a more significant reaction to external stimuli. As for our experiment, the assembly process made participants feel that the virtual hand became their hand since they controlled it. Therefore, the activated tactile feedback made participants have a more realistic reaction when the spike came out and pierced their virtual hands. On the flip side, participants who were not exposed to tactile feedback did not react to the spike, even though they saw the spike piercing their virtual hand.

5.4.3 RQ3: Prior VR Experience

We found interesting results induced to our participants by their Prior VR Experience. Our first finding was the interaction effect between Appearance and Prior VR Experience on agency and motor control. We found that participants with no prior VR experience reported higher ratings on agency and motor control in the presence of the pixelated hand appearance. As for the interaction effect, perhaps participants with no prior VR experience did not have in mind other virtual hand appearances to compare. Therefore, they decided to rate their agency higher than the participants with prior VR experience that most likely had in mind a reference hand used in the past. We also found a significant main effect on agency and motor control. Participants with prior VR experience rated higher than those with no prior VR experience. According to Haggard [89], past VR experience could be a reason for impacting agency on specific actions. Bregman-Hai et al. [90] also revealed the relationship between memories and agency. In our study, most participants had previously experienced VR. They were familiar with VR controls and could finish the tasks smoothly. On the flip side, we think that participants with no prior VR experience had to make extra effort to get used to VR devices, and perhaps this was why they decided to rate their agency and motor control lower.

We found another significant interaction effect between Prior VR Experience and Appearance on response to external stimuli. Specifically, we found that in the presence of the pixelated hand appearance, participants with no prior VR experience provided lower ratings on the response to external stimuli compared to those with prior VR experience. Based on the comments from our participants, those who did not have prior VR experienced considered this VR application to be interesting and presented high rating on the immersive experience with the pixelated virtual hands. The VR-naïve participants did not mention any contradiction in between the virtual hand style and the tactile feedback. On the other hand, the VR experienced participants reported unnaturalness with the virtual hand. They expected a higher fidelity realistic hand for the interaction. We think that the pixelated hand, which had a “mosaic” appearance, made participants feel that such a hand model could not provide a realistic response to external stimuli. For this reason, this participant group decided to give lower ratings. Moreover, the participant group with prior VR experience might have found a match between the low-quality hand appearance and tactile feedback. We think that this “quality matching” would positively impact such a group of participants. However, we could not find any previously conducted studies to support such findings. Therefore, we argue that future research exploring this interaction effect is necessary to understand such results further.

5.4.4 Limitations

Our study has several limitations that should be reported and considered in future studies. Unfortunately, most of our participants were undergraduate students from our department. Thus, we could not divide them into near-equal-size age groups due to the close age range. Furthermore, although we tried to recruit female participants, there was still a difference between male and female participants in each group. We think that such a balance (14 males and 6 females) might have impacted our findings.

The hardware (tactile feedback device) used in this study is another limitation. The controllers of Oculus Quest cannot provide rich contact and shape information when interacting with virtual objects. In our case, compared to haptic gloves and fingertip devices, the controller could not generate detailed feedback for the gear and the spike. Pacchierotti et al. [71] asserted the importance of tactile feedback quality. Thus, we think that using a high-quality tactile feedback device would provide us with more accurate study results.

Furthermore, participants were exposed to a relatively short tutorial section. Based on our discussion, we assume that participants without prior VR experience did not have enough time to get used to the application and the VR system. Therefore, a longer and more complex tutorial section might be necessary for better adaptation.

We consider the design of the spike as an additional limitation. Some participants were able to sense the tactile feedback of the spike but did not instantly notice the spike. Other studies, such as Lin and Jörg [76], used a falling knife from midair, which was more visually appealing. Future studies should provide a more exaggerated visualization as a VR metaphor for RHI.

Finally, we would like to mention a limitation on handedness. We noticed that some participants used their left hand as their dominant hand during the study. We asked our participants to use their right hands to experience the spike in the spike part of the study. It would be interesting to explore the effect of the dominant hand in this scenario.

5.4.5 Design Considerations

We think the knowledge obtained from this study should be documented to help the research community develop more efficient VR assembly applications that involve virtual hand appearance and tactile feedback. Our study was unique comparing to the previous studies as we included more interactive tasks and imported tactile feedback as an additional stimulus. Therefore, this section presents our reflections on choosing an appropriate hand representation and the usage of tactile feedback.

Because hand appearance does affect hand ownership and external appearance, we argue that it is more appropriate to use toon- or realistic-style shaders for the virtual hands. Unless a future study confirms the positive findings on the matching between low-quality hand appearance and tactile feedback, we support the avoidance of using pixelated hand appearances as such representation induces lower VHI, and people regard it as "unable to perceive" and "not visually clear." For development guidelines, either a toon-style hand or a realistic hand can generate a stronger sense of hand ownership. The realistic hand can help with perceiving the appearance of the virtual hand.

On the flip side, in terms of tactile feedback, we recommend the activation of vibrotactile feedback to provide a realistic VR experience when interacting with objects, since tactile feedback impacts presence, touch sensation, and response to external stimuli. Enabling tactile feedback will help with generating a stronger presence and providing better touch sensation to the hand. Tactile feedback also improves the response to external stimuli when receiving an out-of-body stimulus. We think all the above would be effective tools for enhancing virtual hand illusion.

Regarding agency and motor control, developers will need to consider easier operations and tasks for users that does not have prior VR experience so that it will reduce the task load and effort to getting used to VR applications. In addition, developers can add a tutorial section for using the application to help the users with the usage process.

CHAPTER 6. ESTIMATING THE JUST NOTICEABLE DIFFERENCE OF TACTILE FEEDBACK IN OCULUS QUEST 2 CONTROLLERS

For our study, we developed a VR assembly application and instructed participants to interact with the provided stimuli and report any potential differences between the properties of tactile feedback. We explored positive and negative variations of intensity, duration, and frequency [265] of tactile feedback from a commercially available vibrotactile motion controller, the Oculus Touch. We aimed to answer the following research questions:

- RQ1: What is the positive and negative intensity JND for the Oculus Touch controller?
- RQ2: What is the positive and negative duration JND for the Oculus Touch controller?
- RQ3: What is the positive and negative frequency JND for the Oculus Touch controller?

6.1 Methodology

We present the methodology we followed in this study in the subsections below.

6.1.1 Experiment Participants

We recruited 60 participants from our department for our study. Forty-two of them were male (M = 18.65, SD = 1.74), and 15 were female (M = 19.02, SD = 4.42). Three participants identified themselves as non-binary/other gender (M = 18.33, SD = .47). Twenty participants did not have any prior VR experience. All the other participants had a little (less than an hour) or some experience (more than an hour) with VR. All participants volunteered for this study and completed the entire experiment by providing responses in the application.

6.1.2 VR Application

We developed a VR assembly application for the JND study in Unreal Engine 4 and deployed it on an Oculus Quest 2 head-mounted display (HMD). The application included two sections: the tutorial (Figure 48) and the testing (Figure 49). We implemented the tutorial to provide our participants with instructions regarding the operation and to familiarize them with the VR controllers. Researchers in a previous study demonstrated the improved performance of VR users when they were provided with tutorial-based instructions for controllers [106]. The tutorial was straightforward as it only contained a gear part, a transparent target gear slot, and a red button that began the testing. Participants were free to move around and try out the assembly process by grabbing the gear using the grip button on the controller and placing it onto the transparent target slot. When the gear part was close to the transparent target slot, it automatically snapped onto the slot to stay in place. The participants could manipulate the gears by grasping them with virtual hands that they controlled using the VR controllers. We used realistic hand models. We assigned male or female hands to our participants based on their demographic responses. If they indicated that they preferred not to say what gender they were, we assigned them hand models randomly. After the participants were ready for the testing section, they could press the red button to continue.

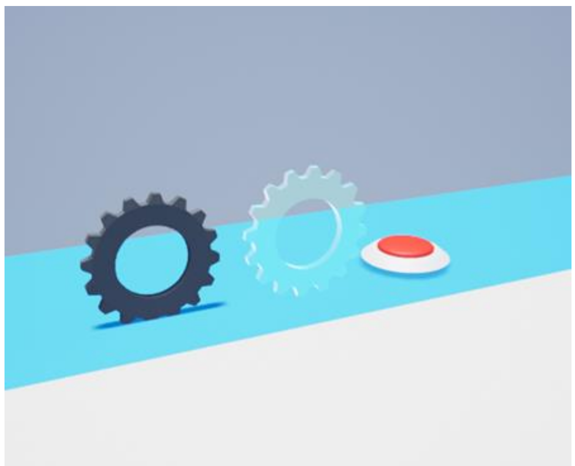

Figure 48. The tutorial of the VR application we developed. A counter was placed in front of the participants. On top of the counter, there was a black gear that we instructed the participant to grab and place in the position of the transparent gear using the Oculus Touch controller. The latter denoted the target spot. We asked the participants to press the red button once they finished the task and felt ready for testing.

The testing section included a long counter with two gears and two transparent slots (Figure 49). To estimate the JND for the three properties (intensity, duration, and frequency) of the VR controllers, we adjusted the corresponding values of one of the gears. Specifically, one of the two gears was the reference, which constantly provided the reference stimuli, and the other was the comparing, which provided the altered stimuli. We used the Oculus Touch controllers to provide tactile feedback to our participants. These controllers were able to generate vibrotactile feedback with a maximum frequency of 320 Hz[5] using linear resonance actuators (LRA). Moreover, Oculus developer documentation suggested that the Oculus Touch controller has less than 10ms latency[6].

For the intensity property, we assigned to the reference gear an intensity of .50 m/s, and the comparing gear provided a value between .10-1.00 m/s, excluding .50 m/s, (i.e., .10, .20, .30, .40, .60, .70, .80, .90, and 1.00 m/s). We would like to mention that 1.00 m/s intensity corresponds to a normalized value which is also the maximum value we can assign to the Oculus Touch controller using Unreal Engine 4. We used values between .10-.40 m/s to estimate the negative intensity JND and values between .60-1.00 m/s to estimate the positive intensity JND. We set the duration at 1.00 s and frequency at 100 Hz during this part of the experiment.

From previous research, we know providing continuous tactile feedback over a specific amount of time can cause a distraction to the participants [193]. Furthermore, human perception of tactile feedback will reach a minimum threshold when the stimulus duration is at 1000 ms (1 s) [181]. Thus, for the duration property, we decided that the reference gear would provide a constant duration of .50 s, and the comparing gear provided a duration value between .10-1.00 s, excluding .50 s, (i.e., .10, .20, .30, .40, .60, .70, .80, .90, and 1.00 s). We used values between .10-.40 s to estimate the negative duration JND and values between .60-1.00 s to estimate the positive duration JND. We set the intensity at 1.00 m/s and frequency at 100 Hz for this part of the experiment.

Human mechanoreceptors have a frequency perception range of 10-1000 Hz [194] and we decide to follow the previous JNDF studies [153][154][156] and set up a lower frequency range for this study as the Oculus Touch controllers are only capable of providing vibrotactile feedback within this range. Thus, for the frequency property, we assigned to the reference gear a frequency of 100 Hz, and the comparing gear provided a frequency value between 50-150 Hz, excluding 100 Hz, (i.e., 50, 60, 70, 80, 90, 110, 120, 130, 140, 150). We used values between 50-90 Hz to estimate the negative frequency JND and values between 110-150 Hz to estimate the positive frequency JND. We set the intensity at 1.00 m/s and the duration at 1.00 s for all trials. To recapitulate, besides the examined values that we changed across trials for each property of the tactile feedback, the rest of the tactile feedback properties remained the same in each examined property. There were nine trials for each tactile feedback property in this experiment for a total of 27 trials.

[5] https://developer.oculus.com/documentation/native/pc/dg-input-touch-haptic/
[6] https://developer.oculus.com/documentation/unity/unity-utilities-overview/

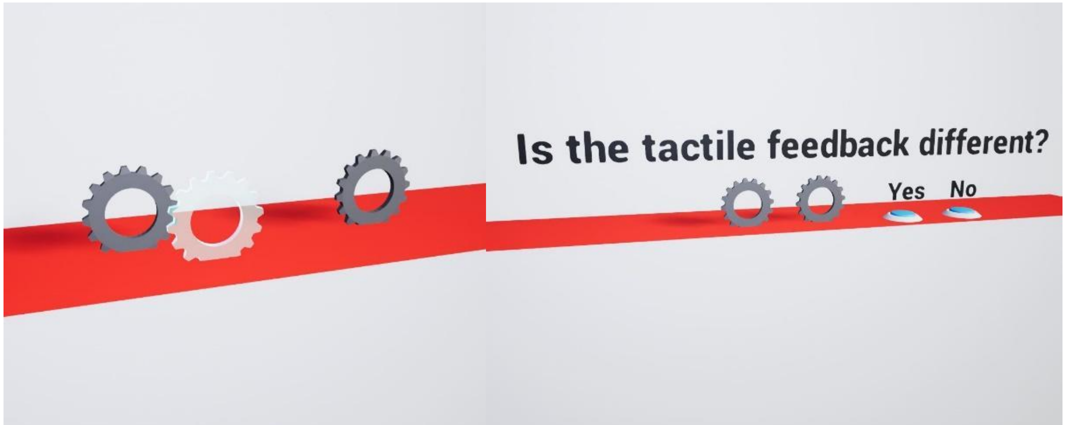

Figure 49. The testing section of the VR application we developed. We instructed the participants to assemble both gears on the two transparent slots (the second slot appeared on the right side after the participant placed the first gear into the transparent slot). After the participant assembled both gears, a question and two answer buttons asked the participant whether they perceived any difference in the two examined variations of tactile feedback. The participants answered the question by tapping on the button of their choice.

6.1.3 Procedure

We conducted our study at our research lab (Figure 50). Upon participants' arrival, we handed them the consent form approved by the institutional review board of our university. Then, we asked the participants to read and sign the forms upon their agreement. After the participants agreed to participate in our research and signed the consent forms, we asked them to provide demographic information in Qualtrics, an online survey tool. Then we assisted the participants in setting up the HMD and helped them adjust the size to their heads accordingly. After the necessary adjustments and indications that they were ready for the study, we started the application for the participants from the tutorial. We asked the participants to experience the tutorial first to familiarize themselves with the operation and controllers. Then, we instructed them to enter the testing once they were ready.

The participants could perceive the tactile feedback only when grabbing the gears. We instructed the participants to place both gears in the two transparent slots in the testing section. The participants were able to decide the grabbing order and the slot destination. After they finished assembling both gears, our application rendered a question in black text on the back wall (Figure 49), asking the participants, "Is the tactile feedback different?". Then, two buttons appeared on the counter with "Yes" and "No" as answers. If the participants agreed that they had sensed different tactile feedback, they pressed the “Yes” button and vice versa. When the participants pressed any answer button, our application loaded the next trial. At the beginning of every trial, although the two gears appeared at the exact same location, the reference gear and the comparing gear were randomly assigned to either the left or right location, which was randomly chosen by our system, so that participants were not able to differentiate based on the gears’ positions. The application ended once the participants experienced all examined tactile feedback properties and their testing variables.

As mentioned earlier, we asked participants first to try to sense the vibration from both gears and then answer the provided question. The responses from the participants were recorded in a CSV file under the application folder, indicating the comparing gear’s intensity/duration/frequency and the answer. When the application had ended, participants took off the headsets. Across the three parts (tactile feedback properties) of our experiment, we provided our participants the chance to take a five-minute break. We first randomized the three properties (intensity, duration, and frequency) and then the examined variables for each property based on the Latin square balancing method [179] to eliminate first-order carry-over effects. After participants completed all three examined tactile feedback properties, the researchers answered the participants’ questions, and finally, the participants were thanked and dismissed. Each participant spent no more than 30 minutes completing the study.

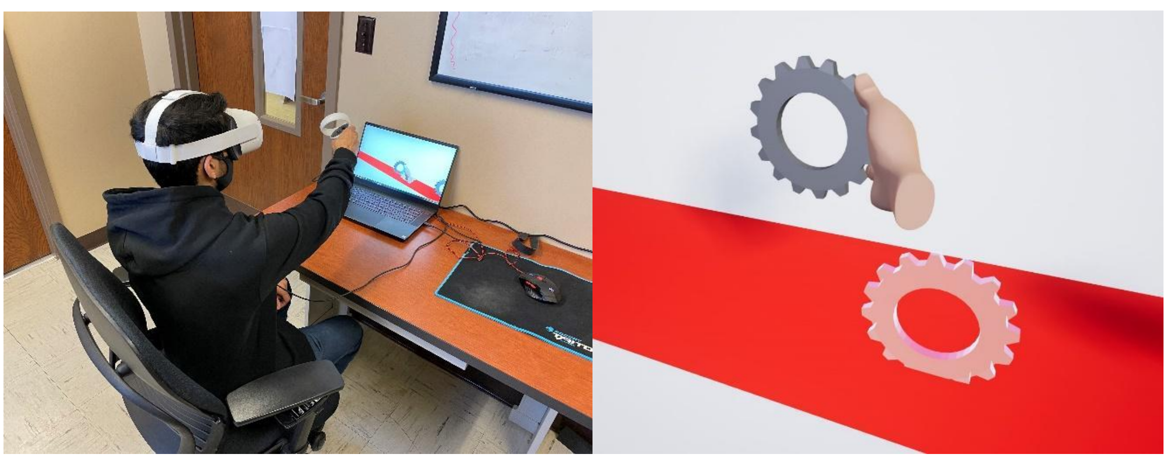

Figure 50. Left: A participant in our lab space experiencing the developed application. Right: A first-person view during the experiment testing.

In light of the COVID-19 pandemic and to follow our institution's instructions, we set a 30-minute gap between participants to minimize infection risk. Participants were either vaccinated or followed the instructions of our university regarding regular testing for COVID-19. We let the participants sanitize their hands upon arrival and asked them to wear face masks. Moreover, we provided them with VR sanitary masks to protect them from the spread of COVID-19. In addition, the research team carefully sanitized all equipment and furniture before and after each participant's turn.

6.2 Results

To analyze the collected data, we used a 75% correct discrimination threshold, which is a standard threshold used in JND studies [143][185][186]. We estimated the JND of the three different properties of tactile feedback as the point where 75% correct discrimination occurs. We used linear interpolation similar to Lee et al. [144] to fit the data set. Lastly, we would like to note that no participants reported any effect of mass or noise on the controller vibration.

6.2.1 Intensity

We analyzed the responses for a noticeable difference between the examined variable from the participants within the application. We provide in Table 3 the intensity JND results. Most participants reported noticeable differences at the .10 m/s offset for both negative and positive values. We used a line graph to visualize the total number of responses regarding intensity differences (Figure 51). For positive intensity JND, we found the cumulative 75% JND value to be .128 m/s, and for negative intensity JND, we found the cumulative 75% JND value to be .092 m/s. Moreover, based on the cumulative data, it is clear that all participants were able to sense the difference when the intensity offset became greater than .30 m/s in both positive and negative. Lastly, to further understand our findings we conducted a Pearson bivariate correlation analysis between the negative and positive cumulative scores. We found a positive correlation [$r(5) = 1.000$, $p=.000$].

Table 3. Percentages of JND intensity results of the collected data.

Offset	Negative (%)	Negative Cumulative (%)	Positive (%)	Positive Cumulative (%)
.10 m/s	81.67	81.67	66.67	66.67
.20 m/s	16.67	98.33	30.00	96.67
.30 m/s	1.67	100.00	3.33	100.00
.40 m/s	0.00	100.00	0.00	100.00
.50 m/s	0.00	100.00	0.00	100.00

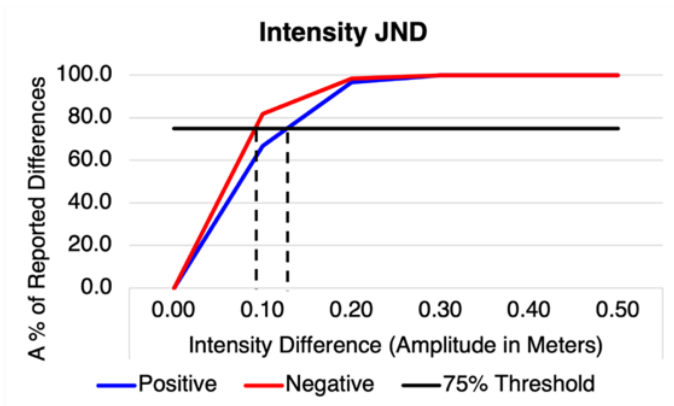

Figure 51. Intensity JND graph. The blue line indicates the responses regarding positive differences, and the red line shows the responses regarding negative differences. We illustrate the 75% threshold for the JND with a black horizontal line.

6.2.2 Duration

For the duration JND, most participants reported a noticeable negative difference at .10 s offset (73.33%), while a smaller number (43.33%) reported a noticeable positive difference at .10 s offset. We also found that 15% of the participants noticed a difference at a positive .50 s offset. As for negative differences, all participants could perceive the difference within a .30 s offset. Table 4 and Figure 52 illustrate the duration JND results. According to our calculations, we found that the positive duration JND at 75% is .240 s, and the negative duration JND at 75% is .108 s. Lastly, the correlation analysis between the negative and positive cumulative scores of duration showed a positive correlation [r(5) =.921, p=.026].

Table 4. Percentages of JND duration results of the collected data.

Offset	Negative (%)	Negative Cumulative (%)	Positive (%)	Positive Cumulative (%)
.10 s	73.33	73.33	43.33	43.33
.20 s	21.67	95.00	25.00	68.33
.30 s	5.00	100.00	16.67	85.00
.40 s	0.00	100.00	0.00	85.00
.50 s	0.00	100.00	15.00	100.00

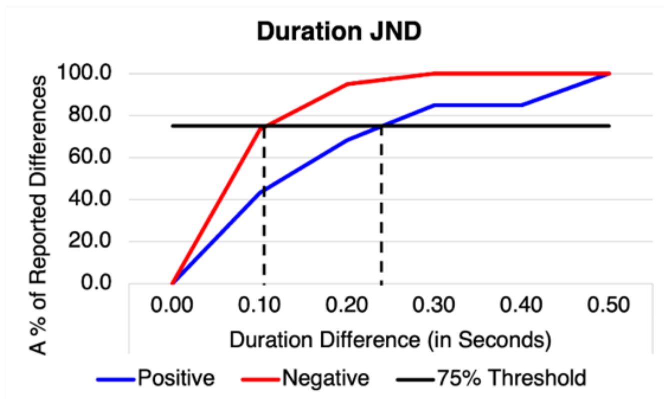

Figure 52. Duration JND graph. The blue line indicates the responses regarding positive differences, and the red line shows the responses regarding negative differences. We illustrate the 75% threshold for the JND with a black horizontal line.

6.2.3 Frequency

Regarding the frequency JND, we found that 75% of participants could sense the difference within 30 Hz offset for positive and 20 Hz offset for negative. We also found that 18.3% (3.3% for 40 Hz and 15% for 50 Hz) to 25% (5% for 40 Hz and 20% for 50 Hz) of participants were only able to sense the difference at 40 Hz offset or higher for both positive and negative directions. Moreover, we found that the 75% positive frequency JND is 23.30 Hz, and the 75% negative frequency JND is 30 Hz. Moreover, the correlation analysis between the negative and positive cumulative scores of duration showed a positive correlation [r(5) =.985, p=.002]. We illustrate our results in Table 5 and Figure 53.

Table 5. Percentages of JND frequency results of the collected data.

Offset	Negative (%)	Negative Cumulative (%)	Positive (%)	Positive cumulative (%)
10 Hz	41.70	41.70	51.30	51.30
20 Hz	15.00	56.70	10.40	71.70
30 Hz	18.30	75.00	10.00	81.70
40 Hz	5.00	80.00	3.30	85.00
50 Hz	20.00	100.00	150	100.00

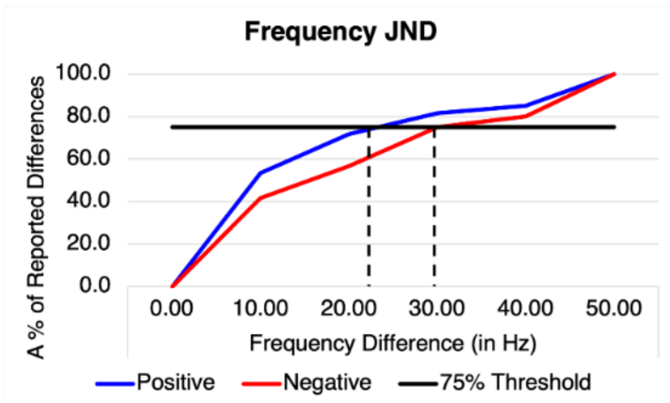

Figure 53. Frequency JND graph. The blue line indicates the responses regarding positive differences, and the red line shows the responses regarding negative differences. We illustrate the 75% threshold for the JND with a black horizontal line.

6.3 Discussion

We aimed to explore the JND for VR vibrotactile motion controllers (the Oculus Touch) for three tactile feedback properties (intensity, duration, and frequency). We also attempted to analyze correlations between age, VR experience, and handedness (right- or left-handed or ambidextrous) with the JND values. However, none of the correlations were significant. We discuss our findings and our study's limitations in the following subsections.

6.3.1 JND for Intensity

We found the positive JND value for intensity was between .10-.20 m/s, and the negative JND value for intensity was slightly less than .10 m/s. For positive difference, we had a JND percentage at between 20-40%, and for the negative difference, we had a JND percentage at around

20%. Previous tactile feedback JND studies had found JND percentages in a minimum of 10% [143] and a maximum of 18-20% [146][147]. Therefore, the intensity JND we found is in accordance with previous studies. This JND range could be due to the mechanoreceptors humans have in glabrous skin. According to psychophysics studies, the center of the hand is quite sensitive [148][149]; therefore, participants could sense the difference of the controller feedback with a minimal unit variation.

6.3.2 JND for Duration

We found the positive JND value for the duration was between .20-.30 s, and the negative JND value for the duration was slightly more than .10 s. We observed that participants were more sensitive toward negative variations instead of positive variations based on the illustrated graph (shown in Figure 5). Several participants did not sense any difference until a positive .50 s offset occurred. This finding could be due to the adaptation of tactile feedback. Hollins et al. [150] and Hahn [151] confirmed that having longer duration of tactile feedback would decrease the sensation threshold over time. We consider that the sensation threshold was not affected by vibration with a duration less than .50 s but gradually decreased with vibrations of more than .50 s. In addition, longer vibrations generated more energy integration with the hand. Temporal energy exceeding a certain amount would also decrease tactile perception [152].

6.3.3 JND for Frequency

Regarding the frequency JND, we found the positive JND for the frequency at 23.30 Hz and the negative JND at 30 Hz. Unlike the other two tactile feedback properties (intensity and duration), the sense of frequency with handheld controllers varied between participants. This is especially true when considering that participants reported differences in every individual value. Very few data existed for JNDF, which was due to difficulty eliminating potential properties (e.g., intensity and duration differences) for tactile perception in past studies [153][154] since researchers were using older devices and had less control over those properties. Goff [153] asserted JNDF for fingertip stimulation is between 8-100 Hz. Since fingertips are more sensitive to tactile feedback than the palm [123], we think the 75% accumulative JNDF of our study (20-30 Hz) is appropriate.

6.3.4 Correlation Between Negative and Positive

For all three properties of tactile feedback, we found strong positive correlation. For intensity we have a positive correlation r(5)=1.000; for duration we have a positive correlation r(5)=.921; for frequency we have a positive correlation r(5)=.985. In the past studies researchers reported that positive and negative JNDs were symmetrical [196][83]. Our results aligned with the past findings, which indicated that the positive and negative JNDs for the three tactile feedback properties were strongly associated and therefore symmetrical. Participants were able to sense the difference of tactile feedback with both increasing and decreasing properties.

6.3.5 Limitations

In this section, we would like to report some of the limitations of our study. First, most of our participants were students from our department. Although we think that such age groups use VR devices more commonly, our results do not represent the general population. Therefore, our results are not generalizable. Second, although we aimed to collect data from all genders, there was still a dominating number of males compared to females. This might have been why we could not observe potential gender differences in the JND data. Third, we consider as a limitation the small range of values we used to explore the JND for different tactile feedback properties. Moreover, we only explored one set of frequency ranges (50-150hz). We assume that there could be different JND values for a different set of ranges. Thus, we think that in future studies researchers should explore additional reference stimulus values to better understand the JND of the tactile feedback in commercially available vibrotactile motion controllers.

CHAPTER 7. CONCLUSION AND FUTURE WORK

7.1 Conclusion

We developed a VR assembly application with different hand appearances and tactile feedback conditions to examine three embodiment dimensions (ownership, tactile sensation, and external appearance). As a result, the mannequin hand had a greater effect on ownership, and the realistic hand had a greater effect on tactile sensation and external appearance. We also found that the tactile feedback condition had a greater effect on external appearance than the no-tactile feedback condition, and the realistic hand appearance in conjunction with the tactile feedback had a significant effect on the perceived tactile sensation. Participants in the lab setting rated the external appearance of the realistic hand model higher than the remote participants. These results can be used as an essential design consideration for future virtual reality assembly-related virtual reality applications. Finally, participants with less VR experience rated higher the tactile sensation and the external appearance when exposed to the realistic hand model conditions. As a contribution, VR developers will need to consider hand model styles based on the background environment. The general guideline is to use hand models that is as realistic as possible. In addition, hand and finger animation should be implemented as an option for VR application.

Secondly, we conducted a VR study to explore the effects of hand appearance and tactile feedback in terms of presence and body ownership dimensions. We developed a VR application in which participants were asked to assemble different parts into a 3D model, with an imitation of the RHI study at the end of the tasks. As a result, pixelated hand appearance induced lower hand ownership and external appearance. On the other hand, tactile feedback generated a stronger sense of presence, touch sensation, and response to external stimuli. As for prior VR experience, we did find that it enhances agency and motor control while also reducing the response to external stimuli ratings. VR developers should avoid unclear hand representations. Moreover, developers should enable the option for activation of vibrotactile feedback for interaction.

Finally, we conducted a JND study for tactile feedback for commercially available VR vibrotactile motion controllers (the Oculus Touch VR controller) to explore their intensity, duration, and frequency properties. We asked the participants to sense two stimuli at a time by grabbing the two gears in the virtual environment and answering whether the two gears provided similar or different tactile feedback. By analyzing our collected data, we found two (positive and negative) intensity JND values (positive: .128 m/s; negative: .092 m/s), duration JND values (positive: .240 s; negative: .108 s), and frequency JND values (positive: 23.30 Hz; negative: 30 Hz). We think that such JND values should be considered by VR developers when implementing tactile feedback variations to their applications. The application of these JND values can be used for user calibration regarding how strong do they want to set the tactile feedback. Furthermore, developers can apply these values to set up variations of notifications for reminders and warning.

7.2 Future Work

In addition to the mentioned limitations in the three studies, there are a few more directions that could be studied in the future. In modern VR, we already have applications that can make good use of legs, feet, and even the upper body. Thus, in future research, we would like to explore the effect of the realistic appearance of the whole body of self-avatars using different character models and realistic body sizes, styles, genders, colors, and age. Such studies can help us better understand how we can evaluate the realistic appearance and tactile feedback in self-avatars and user-controlled body parts in VR applications.

In addition, we can also deepen the research in hand ownership using the Oculus Quest built-in hand interaction model for more approaches comparing with real-world controllers. Oculus Quest has a function that allows users to control their virtual hands without using the Oculus Touch controllers. The motion tracking of the palm and fingers are precise enough to control VR applications. We consider this a convenient function that can eliminate potential factors that can affect VHI since participants do not need to feel the weight and touch sensation of the actual controllers. In addition, we can provide more detailed tactile feedback to our participants such as haptic gloves and fingertip haptic device. Comparing non-controller operation with controller operation would be a valuable future direction.

We would also like to study other factors that can potentially affect JND, such as the applied area of tactile feedback and other vibrotactile motion controllers (e.g., the HTC VIVE controller). Especially for vibrotactile motion controllers, we would like to explore whether the different shapes of such controllers could potentially affect the noticeable differences reported by participants. In addition, we also want to explore more precise control on various aspects of tactile feedback in terms of intensity, duration, and frequency by manipulating patterns and intensity levels so that we can further explore JNDL and JNDF.

Furthermore, we consider a future study using the proposed JND value to discover the effect of tactile feedback on VHI. Instead of the simple on and off conditions, we can apply different levels of tactile feedback in terms of the three properties (intensity, duration, frequency). For example, by providing a gap in between different tactile feedback intensity with our determined JND, we can create several conditions such as no-tactile feedback, weak-tactile feedback, medium-tactile feedback, strong-tactile feedback, and intense-tactile feedback. We would then assign tasks to participants and ask for reports on the sense of embodiment. In addition, having pattern variations of tactile feedback can also be an interesting topic to study in the future.

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2. Cui, D., & Mousas, C. (2022). Evaluating Virtual Hand Illusion through Realistic Appearance and Tactile Feedback. Multimodal Technologies and Interaction, 6(9), 76.

3. Cui, D., & Mousas, C. Estimating the Just Noticeable Difference of Tactile Feedback in Oculus Touch Controllers. Accepted by ISMAR in October 2022.