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COMPARING HAND TRACKING AND CONTROLLER-BASED INTERACTIONS FOR A VIRTUAL REALITY LEARNING APPLICATION

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ABSTRACT

Pseudo-haptic illusions can simulate haptic sensations using visual stimulus only. Pseudo-haptic feedback methods are valuable methods to simulate haptic feedback for virtual reality users. In this thesis, pseudo-haptic feedback is examined in conjunction with virtual reality training. Virtual reality training in assembly operations is becoming popular and it is important to raise awareness and knowledge on ways to fully gain and use the benefits of virtual reality in industrial use.

Hand tracking can free the user from using controllers in virtual reality, but hand tracking can have other setbacks. The differences between controller and hand tracking based interactions are examined in this thesis. An experiment was conducted, where it was observed whether the weight of the controller had an effect on the pseudo-haptic feeling of weight for the user. Simulation of weight was done with a control-delay technique, in which the movement of the real hand is delayed in relation to the head mounted display's displayed hand. This can create an illusion of weight for a virtual object. Quantitative, as well as coded qualitative data was gathered from the experimental application, and by using questionnaires. The paired data were analyzed using the T-test. A significant difference between the pseudo-haptic weight sensations was not found. However, it was found that the use of hand tracking was seen as more intuitive for the users, and yielded into higher feeling of presence. Controllers however, were seen as more robust, which was the main advantage of them.

Suggestions are provided for future research, and limitations that were observed during the experiment are discussed.

Keywords: pseudo-haptic feedback, virtual reality, presence, training, immersion

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TIIVISTELMÄ

Pseudohaptiset illuusiot simuloivat tuntoaistimuksia pelkän visuaalisen ärsykkeen perusteella. Pseudohaptiset menetelmät ovat hyödyllisiä tuottamaan haptisia tuntemuksia virtuaalitodellisuuden käyttäjille. Virtuaalitodellisuus on tullut yleiseksi opetusmenetelmäksi linjastolla työskentelevien operaattoreiden koulutustarpeeseen. Siksi on tärkeää ymmärtää ja kehittää menetelmiä jotka parantavat virtuaalitodellisuutta näissä olosuhteissa.

Käsiperusteinen interaktio vapauttaa käyttäjän ohjainten käytöstä, mutta sillä on muita haittoja. Käsi- ja ohjainperusteisen interaktion eroja tarkastellaan tässä työssä. Työssä kuvataan koe, jossa seurattiin onko ohjaimen fyysisellä painolla vaikutusta pseudohaptiseen painon tunteeseen. Painon simulointi toteutettiin viivästystekniikalla. Tämä tarkoittaa sitä, että käyttäjän näkemän virtuaalikäden liikehdintää hidastettiin verrattuna käyttäjän omaan käteen. Tämä voi luoda painon tunteen virtuaaliselle esineelle. Koesovelluksen sekä kyselyjen avulla kerättiin sekä kvantitatiivista, että koodattua laadullista dataa. Tulokset analysoitiin T-testillä. Tulosten perusteella ei löydetty merkittävää eroa pseudohaptisen painon tunteen voimakkuuksista. Tulosten perusteella todetaan kuitenkin, että käsiperusteinen interaktio voi olla intuitiivisempi käyttäjälle sekä tuottaa käyttäjälle vahvemman paikkailluusion tunteen. Ohjaimien todetaan tosin olevan vakaampi interaktiomenetelmä; mikä on niiden suurin vahvuus.

Lopuksi työssä annetaan ehdotuksia tulevaa tutkimuksia varten sekä keskustellaan nykyisen työn rajoituksista.

Avainsanat: pseudohaptiikka, virtuaalitodellisuus, paikkailluusio, opetussovellus, immersio

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FOREWORD

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Eetu Laukka

LIST OF ABBREVIATIONS AND SYMBOLS

2D	two-dimensional
3D	three-dimensional
5G	fifth-generation
6DOF	six degrees of freedom
C/D	control-to-display
CPU	central processing unit
FPS	frames per second
GPU	graphics processing unit
HMD	head mounted display
LED	light-emitting diode
OS	operating system
PC	personal computer
SC	sensorimotor contingencies
SDK	software development kit
SUS	Slater, Usoh, and Steed
UV	ultraviolet
VE	virtual environment
VR	virtual reality
XR	extended reality

1. INTRODUCTION

Virtual reality (VR) is a continuously growing market. We are seeing new releases of more and more advanced headsets that are capable of complex technologies. Facebook released Oculus Quest in the summer of 2019. Oculus Quest is a standalone VR device, which means that it does not need to be tethered to an additional computer. In the past, the price of VR headsets was an obstructive factor for adaptation of VR for consumers [1]. Oculus Quest was moderately cheap at $399 from the launch, while being mobile without any need to connect it to a computer. This has a potential for taking over the mass markets. The price is around the same compared to the price of Oculus Rift that Laurell et al. used in their research [1]. However, it should be considered that Oculus Quest does not require a high-end PC to operate. The computers needed to run VR applications can easily cost over thousands of euros.

VR has already crawled its way to many disciplines, with various different tasks. The potential of VR is starting to be realized in different fields. VR is already considered to be in a mature state, but certain challenges remain. These findings were found in an industry survey done by Berg L.P. & Vance J.M in 2016; their goal was to understand the current state of VR applications especially in the engineering-focused businesses [2]. They looked into the challenges of VR that were realised in 1999 in a seminal paper by Fred Brooks [3]. Berg L.P. & Vance J.M wanted to know if these challenges had been overcome and what were the current challenges. A total of 20 companies using VR took part in the study and a total of 62 people were interviewed. Many of the challenges had been overcome but more interesting were the current, still existing, or new challenges that had emerged. Among the current challenges, there can be seen one major component: a wish for high-fidelity haptic devices. [2]

VR has been used to train employees in different assembly tasks or operations. Assembly training with a VR training tool has been proved to be more effective than conventional media [4].

With the expected rise in the use of VR and the need for improvements, it is good to explore ways to find solutions to current problems and find ways to improve the use of VR for businesses.

1.1. Virtual Reality

VR extends to multiple disciplines, varying from military [5, 6], health care [7] and education into multiple different areas, mostly in computer science and engineering, but also into areas such as: Social sciences, medicine, mathematics, material science and much more [8, 9, 6].

VR hovers around illusions of the senses to create an alternative reality for humans. Our perception of the real world comes through our senses. Our eyes capture the visual information, ears the sound, and the central nervous system processes the tactile information. VR attempts to replace these information inputs with computer generated illusions to trick the human senses. Thus, giving humans the possibility to interact in this new reality which is called the virtual reality [10]. VR systems are often thought as immersive, or at least more immersive than the traditional displays [11, 12]. A big factor of VR immersion is that it can produce a sense of presence [13].

Better immersion enhances learning in multiple ways. One being the ability to switch between perspectives, more accurately, between exocentric and the egocentric perspectives [9]. Immersion is defined by Webster as "the state of being absorbed or deeply involved". In common terms this could be thought as of getting absorbed by words of an amazing book [14] or as "the sense of being there" [15, 16, 11]. However, in VR research immersion is not as simple. According to a popular definition, the "sense of being there" is called presence, which is subjective, and immersion is more accurately just what the software and hardware can provide and is more objective [17]. This difference is detailed more in chapter 1.3.

The backbones for enabling this aspiring technology came from the development of the computers, especially the personal computer. VR must be interact-able in real-time and at the same time it has to look as realistic as possible [18] [19 p.53-86]. This immersiviness that the virtual environment (VE) can provide comes from the high-level of sensory fidelity, mimicking real-life sensory inputs such as visual, auditory and others [6]. This requires an immense amount of computing capacity. However, today even some laptops can achieve this, but these laptops are expensive.

1.2. Mobile and Standalone VR

Compared to the more traditional PC tethered VR, mobile VR provides much more flexibility and a better outlook for growth especially with the mass market appeal. The use cases and benefits of mobile VR are obvious. Companies can easily setup their VR product anywhere without the need for a tethered PC. The everyday user could even change the tight space, when traveling long flights, to limitless by just putting on a mobile VR headset. [19 p.1-14]

Oculus Quest is a standalone mobile VR headset aimed towards entertainment use for every household. It requires no additional computer, or any tracking base stations. Oculus quest runs on Android operating system (OS). It can run demanding VR applications moderately. Although some applications have been scaled down slightly to keep up a stable frames per second (FPS) for the application. At the moment, being mobile comes at the cost of lower performance.

But for the future, these problems might go away. Already now, Facebook is pushing out new versions of the Oculus Quest with even better processing capabilities. According to the chip maker Qualcomm, the new Snapdragon XR2 Platform can deliver two times the CPU and GPU performance than the previous generation chips that were used in the first Oculus Quest [20]. On top of this, the new 5G cloud computing has given good indicators that processing in the cloud could be a key enabler for mobile VR. 5G cloud computing could fix the issues of bandwidth that causes low latency [21], with techniques like mobile edge computing [22], thus possibly eventually deprecating tethered VR.

1.3. Immersion and Presence

Earlier it was mentioned that sense of being there is commonly used with the term immersion [11]. But a deeper look at these two terms is necessary in this paper since presence will be measured in the experience. Immersion and presence are not the same, even though they are often used interchangeably [6]. More accurately put, immersion is the objective measure of the capabilities of the technology used to create the VE. For example, the more the system provides from an objective point of view in sensory displays and tracking that preserves the fidelity between the real world sensory modalities and their virtual world counterpart, the more immersive it is. It is worth mentioning that interactivity could possibly also be part of immersion, which was excluded by Bowman & McMacahan [6], this would lead to also including the input interpretation software in the immersion, which is now separated in Figure 1. Keeping this in mind, if immersion is to be measured it is worth looking at the approach that Slater provides in his latest definition of immersion: *"a property of the valid actions that are possible within the system"*. This means evaluating the amount of sensorimotor contingencies (SC) that the system supports [23]. Presence on the other hand is a subjective measure of a feeling that a person experiences while in the VE. The same immersive system does not guarantee the same amount of presence experienced by a subject [17].

Putting aside the definitions of immersion and presence, the difference can still be seen in Figure 1. There, immersion is only dependent on the rendering software and display devices. Presence on the other hand, is purely subjective. Some users can have higher presence in lower immersive systems and other users might have higher presence in higher immersive systems [17]. This is why place illusion is a better term, because then it is clear that both low immersive and high immersive systems can create an illusion of being in a place. However, in higher immersive systems the senses are catered more, which can create different reactions between people [23]. Nevertheless, a greater sense of presence seems to have significant positive effects on the learning outcome on educational applications [24]. Some research on the other hand has reported lower learning [25], so this could be highly application dependent. It is good to keep in mind that even though one might be experiencing high presence, the person might still perform poorly [26]. Also, the benefits are somewhat complex and require further research into what type of performance VR can boost with increased presence and immersion [27].

1.4. Haptic Feedback

In VR, the haptic feedback to the user often comes from the interaction techniques used with the virtual environment. There are numerous different types of controllers developed for virtual reality. Controllers aimed for consumers have more or less the same concept: a handheld controller with tracking capabilities and various sensors and buttons. Researchers have the possibility to try out more novel solutions, and multiple approaches have been tried out to improve the haptic feedback of the controllers, for example, by shaking the controller or giving force feedback to the fingers with claw-like structures [28, 29]. Other novel ways have also been developed by using air drag or distribution of weight in the controller [30]. Zenner & Krüger created a controller that had motor controlled fans that affected the air drag when moving the controller, thus creating force feedback to the hand [30]. This could be used to simulate weight. But there are often many limitations to these designs. Some are obvious and some

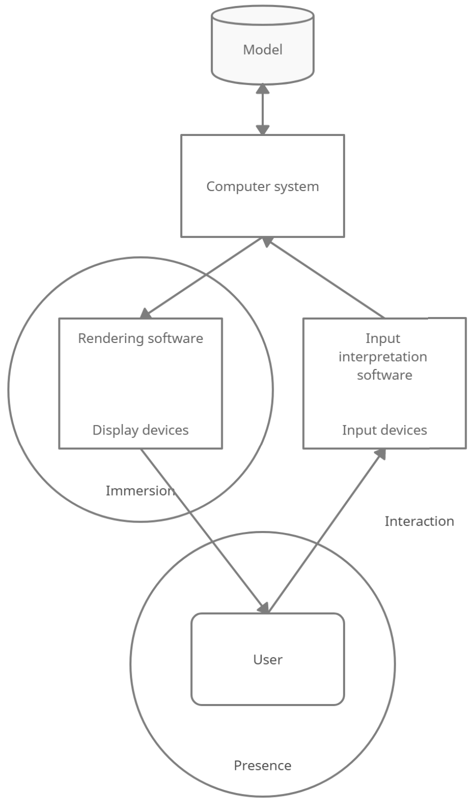

Figure 1. Interaction flow with a virtual environment. Adapted from [6].

of them have been found during research. For example, in the Zenner & Krüger paper, the device caused faulty haptic feedback since it had moving parts which caused additional noise from the transformation between the states of the device, thus reducing the sense of presence [30]. Additionally, the device is much larger than a traditional controller, which limits the movement of the hands. Strong haptic feedback can also be obtained by using actual real-life objects to identify actions to virtual reality, like throwing [31]. Lotnschar et al. used an actual baseball that was conductive to detect a throw, so the throwing of that baseball is very intuitive and natural. But this of course, can have massive limitations of space. These were some examples of creating a haptic feedback for the user. The aim of this study is to achieve a similar novel way to improve immersiveness while maintaining the haptic feedback with pseudo-haptic feedback technique, which is also available for consumer users.

1.5. Pseudo-Haptic Feedback

Pseudo-haptic feedback strives to simulate a haptic feedback without the actual haptic perception. For example, creating a haptic feedback only by using visual cues to create a sensory conflict between the real movement of the hand and virtual hand movement in the VR. This is an effective and cheap solution in certain cases since it can be done at the software level, and there is no need for hardware changes or requirements [32]. This simulated force feedback produced by the pseudo-haptic feedback can be called a haptic illusion [33]. It has been proven that mass can be simulated with pseudo-haptic feedback techniques [34]. This can be achieved by modifying the ratio of which the virtual object moves in comparison to the users hand movement: this ratio is called Control-to-Display ratio (C/D ratio) [35].

Control-delay technique is similar to the C/D ratio. With control-delay, the movement is delayed by a parameter which is explained more in detail in section 3.4. Instead of just multiplying the users input by a certain amount like in the C/D ratio, in control-delay, the movement is delayed. One could think of it as moving in slow motion. This increases the depth for the feeling of the weight [36]. In VR, we can slow down the movement of the virtual hand with the control-delay technique, when it is holding an object that is considered heavy. This can induce a sense of weight [36].

1.6. Motivation

The motivation for this study came from the desire to research ways that would improve the presence and thus the effectiveness of VR applications. Better presence and immersiveness is important in any VR application. Additionally, we want to figure out if the perceived weight is affected by physically holding a controller compared to only using hand tracking without any controllers. We also want to see if hand tracking will give a more realistic feeling of the simulated weight compared to using a physical controller. At the same time, we explore the opinions on hand tracking and the preferences of both methods. We also want to see whether the feeling of presence is higher with the hand tracking compared to using a physical controller. There is a clear need for these research questions, since they have not been researched before.

This research also provides value to designers and users who aim to implement simulation of weight or mass to virtual reality. The possible influence of controllers in the perceived weight might impact applications that aim to accurately simulate the weight of a virtual object. Secondly, if the pseudo-haptic feedback is weaker when using a controller versus hand tracking, this will motivate designers to focus more on the development of hand tracking based interactivity.

1.7. Goal

The goal of the current study was to implement improvements to an existing assembly training VR application that has been tested in ABB Vaasa. The improvements focused on the problems realized in the phase one of the research project which was part of the Reboot IoT project of University of Oulu. While these improvements were made, we conducted an experiment of testing the simulation of weight with control-delay technique and measured the perceived weight of the test subjects, while monitoring the subjects' presence in the VE.

Another goal was to explore previous research findings and conduct experiments to find out if these findings have the same possibilities in VR, to improve the overall VR effectiveness in assembly training tasks.

In section 2 we will present the related work of pseudo-haptics, virtual reality training applications and the feeling of presence. Section 3 includes the research method, details about the experiment and the software used in the experiment. We will also explain the data gathered and how they are analysed. Section 4 includes the results of the analysed data and finally in section 5 we discuss the findings and limitations of the study whereas section 6 concludes the thesis and proposes future work.

2. RELATED WORK

2.1. Pseudo-Haptic Feedback

As early as 2000 Lécuyer proved that an isometric input device can produce a pseudo-haptic force feedback by just creating an illusion through software controlled displacement of a virtual object. In their experiment, they controlled the stiffness of a virtual spring that the user could manipulate with force. This visual cue affected the subject's applied force [37]. Ever since, pseudo-haptic feedback has been researched intensively over the past two decades [33, 32, 36, 38, 39, 40]. Pusch and Lécuyer even provide some general design guidelines and some foundations of pseudo-haptics [40].

The guidelines include 8 steps to take for designing a pseudo-haptic simulation. The steps are generic and practical. It starts by observing users interacting with a haptic property we want to simulate, for example, to see which muscles are used and what phenomena are happening during the interaction. In the second step they suggest looking at the physical laws that are present in the real world, in order to utilize the prior knowledge of the user's physical world while simulating the haptic property in a virtual world. Later in the steps we must consider the technical restrictions of the wanted simulation and for properties or actions that will not be accounted for, we should think of easy workarounds to add a complementary stimuli. [40]

Quite many features can be simulated using visual cues. Some of these include: stiffness, texture and mass [32]. Li et al. showed a novel way of simulating softness of a surface through a pseudo-haptic method. In their method the deformation of the surface and the speed of the avatar would simulate the softness [41]. The more the surface would deform and slow down the avatar, the softer the surface was. If we think back to the guidelines, here is a great example of a complimentary property for the surface. It does not only deform a certain amount, it also slows down the movement of the avatar that is on the surface. This makes the simulation more believable, since softer surfaces often feel harder to move in. You could imagine that walking on concrete is much easier and faster than moving in deep snow. Different approaches and experiments on pseudo-haptic weight have also been conducted. Mostly, C/D ratio technique seems to be in use [42, 43, 32], but Hirao and Kawai [36] proposed a great way to simulate weight over the more used C/D ratio. In their experiment they delayed the movement of the virtual hand compared to the real hand movement. This was confirmed to present more levels of sense of weight compared to just changing the C/D ratio [36].

Hirao et al. have done great research concerning pseudo-haptic weight and virtual environments and also provided guidelines on how to conduct such an experiment [36, 38, 44]. In their experiments control-delay technique is often used. They also guide towards not using physical adjustable weights for experiments but rather make the subject feel the weight that must be remembered, after which they must take that knowledge with them into the VE. This means the subjects should not feel the actual object while in the virtual environment since this gives a real haptic feeling which could negatively affect the pseudo-haptic simulation of weight. Additionally, their research shows that controller based pseudo-haptics work similarly to motion-based. But interestingly, unnaturalness seems to grow in higher weights in the motion-based system. This could be due to the gap between the virtual and real hand [44]. The gap is the length of the displacement between the user's real hand and the virtual hand that is being displayed to the user. But they do mention that it could be different in 3D interaction since their experiment was done through 2D interaction. [38]

The effect of pseudo-haptic feedback on presence has also interested researchers. Here are some examples of these studies: Biocca et al. conducted a research in 2002 on the visual cues and their place in cross-modal haptic illusions [45]. In their study they did not find support that visual cues enhanced the sense of presence. However, they confirmed that visualizing haptic feedback can lead to haptic illusions [45]. On the other hand, Bjørkå's results support the thought that by stimulating more channels of the human sensory system, we can increase the user's sense of presence. They wanted to investigate if the perception of weight by using a pseudo-haptic method is interrelated with the sense of presence. Their results show a possibility that there exists a significant correlation between the occurrence of pseudo-haptic feedback and sense of presence [39].

2.2. Virtual Reality Training

Virtual reality as a training platform is gaining more and more popularity. VR provides a safe environment to train in, without any danger or fear of breaking something. For example, training to handle weapons has no danger in virtual reality compared to the danger when handling actual weapons. Second example could be that assembling of a fragile and expensive piece of equipment could be risky to train in real conditions, if there is possibility to the same training with virtual objects. Virtual reality makes it possible to enable the learning by doing practice when there are constraints to do it in real life. If you need to train to use a machine but it is not available for some reason, it is still possible to train to use that machine in VR if such a simulation has been developed. Along with these benefits, in some circumstances VR based training has been suggested to yield better results than in traditional training [46]. In an experiment conducted by Gavish et al., their VR group performed significantly better in assembly training compared to the control-VR group who were using a filmed demonstration [46].

They also have provided design guidelines for VR training systems for assembly tasks in 2011. Gavish et al. identified four main domains: *"observational learning, cognitive fidelity versus physical fidelity, guidance aids and enriched information"*. They claim that when properly integrated, observational learning will increase the training performance. They suggest combining cognitive fidelity and physical fidelity since their attributes compliment each other, which together enhances the learning of procedural skills. Only focusing on one of them was inferior in their tests. For guidance aids they suggested to use only a certain amount of guidance. Too much help affects negatively on the task learning, since it reduces the user's own exploration and does not encourage thinking of performance strategies. Finally, they suggested using enriched information since it helped create a better mental model of the task. [47]

In 2019, Abidi et al. made an observation that in assembly training operations interaction devices seem to be key as they increase the immersion and they allow natural interaction. This means the learned skills should transfer better into the real world from the virtual world. [48]

Virtual reality training seems to require longer time than a more conventional method. This could be a cause of the new interaction methods that the participants have to learn in order to learn to use VR. However, overall VR training systems are thought of having great potential, but with still some limiting factors [46]. Haptic feedback is seen as an important part of a training task when it comes to virtual training. It can help fill some of the requirements needed for learning a task [49]. Many training simulations have been done for manufacturing processes for research but they seem to focus only on a small number of processes and are often not in a mature state [50]. Interestingly, not much research has been done concerning pseudo-haptics and virtual reality training, if at all. But some positive thoughts have been spread. Crison et al. [42] created a virtual training application, which was used to teach new trainees how to operate a milling machine. The mill produced a pseudo-haptic feedback by modifying the C/D ratio to create a resistance from the machine. The trainees found the force feedback a positive addition, and the trainees were eager to use this training application especially in the beginning of the training [42].

2.3. Presence

Mel Slater has laid a lot of the foundation for presence in immersive virtual environments. In 1994 in a research they described a study where presence among other features was measured. Presence could be measured through questions related to the subjects' feeling of "being there". These questions are rated from 1 to 7 and the score comes from the amount of 6 and 7 score answers. So in their case they had 3 presence questions, which can lead to a presence score of 0 to 3 per subject [51]. In 1997 Slater M. & Wilbur S. proposed a full framework for presence. And at the same time to give some clearance on the difference of immersion and presence [13]. The guide to use the Slater, Usoh, and Steed (SUS) questionnaire was published in 2000 [52]. This questionnaire has become popular because of the ease of use and it being a post-test questionnaire so it does not disturb the experiment while it is going on.

Later Slater has made corrections on the definition of immersion to clarify the confusion between these terms. In 2003, Slater proposed a terminology for immersion and presence among other useful notes on terms and concepts of virtual environments [17]. In the latest terminology update, Slater suggested the sensorimotor contingencies to be used as the evaluation of immersion [23]. For presence, Slater suggested the term *"place illusion"*, and in more detail: *"It is the strong illusion of being in a place in spite of the sure knowledge that you are not there"* [23].

3. RESEARCH METHOD

We aim to answer four research questions by conducting a simple VR experiment where weight is simulated in a VE with a pseudo-haptic feedback technique. The goal of the experiment is for the participants to complete the same task two times, with a controller and without controller by using hand tracking. The task is to estimate the virtual weight of an object in a VE. By first feeling the real-life counterpart of that same object, and transferring that knowledge into the VR.

These are the four main research questions we aim to study:

1. Does the physical controller affect the pseudo-haptic simulated weight of a virtual object inside a VE, compared to using hand tracking?
2. Does the hand tracking give more realistic or natural feeling compared to interacting with a physical controller?
3. What are the differences in opinion why some people prefer hand tracking and some controllers?
4. How does the hand tracking affect the presence of a subject compared to a physical controller?

3.1. Virtual Reality Assembly Task Training

The VR assembly training application used in this experiment has been used to train new assembly operators to assemble a product sold by ABB Group. Shortly and simply put, the item is a voltage switch which has many parts to be connected and assembled by an assembly operator. This item is presented in the virtual environment with very accurately sized and high definition 3D parts which must be assembled the same way as one would assemble the actual real part, by using tools like screwdrivers.

This application was first used with a very traditional VR setup, a head mounted display (HMD) and two controllers. There were reports of some users having trouble with using the controllers intuitively. This can be due to lack of use of such devices before. It was estimated that the previous use of video-game controllers help the use of controllers intuitively. Another note was that the controllers are in the way of transferring the fine tuned haptics of the assembly operations to the real world. Grabbing of small parts is very unnatural with controllers since your real hand is holding a big controller while pressing a button, and it is impossible to pinch grab a screw with such a device.

By leaving out the controllers and switching to only using Ultraleap hand tracking with Leap Motion Controller to track the user's hand position and the gesture of the hand, it was possible to assemble the product in the VE by using real hand gestures and using pinch grabbing like a person would in real-life. Extra actions were added to some specific parts when assembling, since attaching of some parts require the assembly operator to hold a piece in place while attaching a screw. Previously the part would snap into place and stay there even if the screw was not yet in place. Now the assembly operator in the VE would have to hold the part in the correct position while screwdriving the part, like in real-life.

The Leap Motion controller can be used by putting it on the table, or by attaching it to the VR headset to point forward. Our setup had a 3D printed mount glued to the headset where the Leap Motion controller could be mounted. With Oculus Quest, which is a stand-alone headset it only required one USB connection to the Leap Motion controller as seen in Figure 2.

Figure 2. Ultraleap Leap Motion controller attached to Oculus Rift S with 3D printed mount.

3.2. Leap Motion Hand Tracking

Ultraleap Leap Motion can detect hand movement and gestures. It translates these components to spatial coordinates, which can be used in VR development. This enables the user to interact with a software without any need for controllers, rather, the interaction is done by the users own hand gestures [53 p1-22] [54 p13-30]. This type of interacting with the experiment software will be referred to as "hand tracking" in this paper.

Leap Motion uses LEDs to project an infrared pattern to the user's hand, which are then captured by the two cameras on the device with depth information. This data is then post-processed with the attached computer through the Leap Motion Software developer kit (SDK). The Leap Motion SDK outputs the hands that were detected from the frame with rotation, position, velocity and movement compared to the earlier frame along with other useful information [53 p1-22]. An example can be seen in Figure 3.

Possible benefits of changing to hand tracking from using controllers are explored in this paper. Some users for example have to spend more time on learning the hardware of the virtual reality system [55], which is a limiting factor. One hypothesis is that by making the interaction more intuitive, by using the users own hand gestures to grasp, move and handle objects, it is more natural to start using the VR system and to interact with the VE.

While our goal was to provide an accessible solution to all consumers, our experiment still requires additional hardware: Ultraleap Leap Motion controller, to provide hand-tracking capability which allows the development of software based pseudo-haptic feedback functionalities. This approach was chosen because, when the application development started, Oculus did not yet have the support for hand tracking in Unreal Engine development. But as of today, it is possible to create similar functionality, if not exactly the same functionality with the Oculus development tools. This would enable all Oculus Rift or Quest owners to benefit from the hand tracking based pseudo-haptics without buying any extra hardware.

Figure 3. Ultraleap hand tracking with Leap Motion controller. Retrieved from "https://www.ultraleap.com/tracking/" with permission.

3.3. Software

The experiment was constructed with Unreal Engine version 4.23. Unreal Engine is a powerful game engine designed to create real-time 3D creation tool. The mature toolset of Unreal Engine provides easy solutions to challenging problems like animations, visual effects and high-quality visualization. It can do all this and have a high and stable frame rate. All of these are important for VR. Unreal Engine is also scalable in the development. It can be used by a single developer or scaled to a large team. Big benefit is also their blueprint system, their easy-to-learn visual coding style [19 p15-51]. This version supported the Leap Motion plugin version 3.5.0. This was the most up to date leap motion plugin for Unreal Engine at the time of the experiment.

3.4. Experiment

The pseudo-haptic feedback technique used in this experiment is control-delay technique where the virtual hand movement is delayed by a parameter k compared to the real-world hand movement. This technique has been proved to produce more depth in the sense of weight for the users [36]. Hirao & Kawai, expressed as in the equation 1, where in the current frame f, y_f is the position of the controller or the position of the hand in the case of the hand tracking where the position comes from the output of the Ultraleap Leap Motion controller. Then we determine the position of the virtual hand Y_f by multiplying the difference of movement from the previous frame by the parameter k. This way the movement will be slightly delayed depending on the k-value.

$$Y_f = Y_{f-1} + (y_f - Y_{f-1}) * k \tag{1}$$

The participants goal is to match the sense of weight between the real and the virtual object by first feeling the real object, and after that modifying the k-value with a keyboard to fit the simulated sense of weight. The participants would grab the virtual object with their dominant hand and start to move it around while the object is being affected by the k-value. They would do this task with the controllers and without the controllers, by using the Ultraleap hand tracking technology of the Leap Motion controller. The participants would repeat this task three times with each time the starting value of k would be different, after which they would fill a questionnaire on the feeling that they had from that experiment. Additionally, the participants filled a presence questionnaire [52] to measure the experienced presence. Next, the participants would do the same task again three times but with the opposing condition that they started with. For example, if they started without controllers they would do the second task with controllers and vice versa. The order of the start value of k was also switched between participants. Half of the participants started without any weight in the virtual object and half started with the maximum weight.

Hirao et al. have conducted experiments for simulation of weight with the control-delay technique. Their results suggest that there is a certain range of k-values where the sensation of weight is very little or not at all [38], because the movement is delayed by a very negligible amount from k-values close to 1. There is no accurate point where this changes but following their results and confirming it in our pilot experiment, our starting k-value for no weight or very little weight was set to 0,15. After that there was noticeable change in the speed of the object. The maximum weight in our experiment was the smallest k-value possible which was 0,005. The second iteration of the experiment the k-value was always set at 0,05, a relatively average value of the pilot experiment results. The subject could change the k-value higher or lower with intervals of 0,005.

Participants were instructed not to rotate their wrists since this movement was not affected by the control-delay. This is a limitation of the solution which was not foreseen before the experiment. For future research, it would be wise to also add the control-delay for rotation of the objects with the wrist.

Since the formula 1 is based on frames, the frames per second (FPS) was monitored during the experiment. The FPS stayed stable in all of the experiments except in one of the sessions of one participant, but it seemed to not be significant since the results of the participants other two sessions did not differ. This slight imbalance of the FPS could be caused by a lot of things, for example automatic updates and such. It is good to disable these in similar experiments and run the program on a stand-alone setup, if possible. It could also be possible to adjust the k-value with the delta-time (the time in milliseconds between frames) to circumvent this problem.

3.5. Sample

The experiment was done with 20 participants of which nine were female and 11 were male. The test subjects age ranged from 24 to 61, and distributed uniformly, with the age class 20-29 being the most represented. 12 subjects were in their twenties and the rest varied from ages 30 up to 61. The age range distribution can be seen in Fig. 4. The amount of participants was greatly affected by the 2020 global pandemic. The subjects varied a lot by previous VR experience, from people that had never tried VR to daily users. The same goes with video game experience.

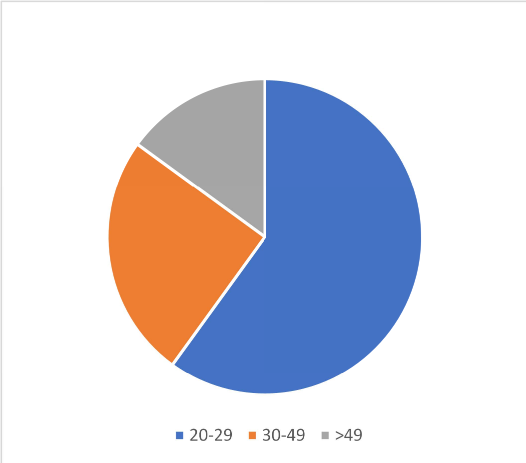

Figure 4. Experiment age ranges. Blue is ages 20-29, orange is ages 30-49 and grey is over 49 year olds.

3.6. Setup

Oculus Quest was first designed to be used in the experiment, but it was later changed to Oculus Rift S, since it seemed to give more stable FPS, while running the experiment application. So while Oculus Quest was the top of the line mobile VR machine, with the full six dimension of freedom (6DOF) with inside-out tracking[19 p.141-167] and the capability to bring high-performance wireless room-scale tracking, it was lacking due to the stable FPS requirement of the experiment.

The setup included Oculus Rift S VR headset and a Oculus Touch controller, with two accessories, a keyboard and the real object that was assessed in the virtual reality. The participants would sit on a chair in front of a similar table than in the virtual environment. The position of the chair was marked to keep the participants in the same position between sessions in case the chair was moved, the setup can be seen in Figure 5 and the VE view of the participant can be seen in Figure 6. In the beginning of the experiment the participants would get to know how to use the controllers and how to put on the HMD. They would then enter the learning phase of the experiment where they would be placed in the same VE but with a different practice object. In this learning phase the participants would practice handling the object with and without the controllers. Once they would feel comfortable with the controls, the learning phase would end.

After the learning phase, they were instructed on the task they were about to do in the VE. Before each session, the participants would feel the actual object in real life so they could assess the weight of the real object before trying to assess it in the virtual environment. Between and after the sessions the participants would fill a questionnaire which had presence measuring questions using the SUS questionnaire [52] and weight sensation questions that can bee seen from section 4.2. After the experiment the participants filled a background information questionnaire, that had questions on their previous VR experiences and whether they usually play video games.

The experiment was conducted at the Perception Engineering Laboratory, at the University of Oulu. The experiment was done in the summer of 2020, during which the world was going through a global pandemic. Thus, the experimenter had to stay two meters away from the participants and was required to instruct them from that distance. This sometimes caused difficulties in the learning phase when the subjects were learning to use the VR headset and where to place the controllers while using hand tracking. None of the participants mentioned it to be an obstacle or that it would have somehow affected their answers for the questionnaires.

Figure 5. Experiment setup.

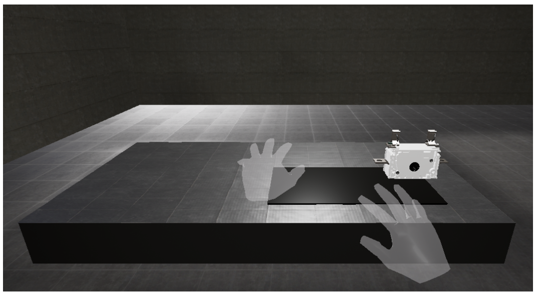

Figure 6. VE view of the subject with hand-tracking.

Also worth mentioning of the setup was the cleaning equipment between the participants due to the virus pandemic. A specialised ultraviolet (UV) light box was used to clean the HMD and alcoholic wipes were used to wipe down all surfaces. These measures ensured that the experiment was possible to conduct under the university guidelines at the time. These measures greatly limited the available time for the study and the amount of participants that we were able to gather.

3.7. Condition

Half of the participants started the experiment with the controller whereas half of the participants started with the hand tracking. In addition the starting mass of the object switched between maximum and no mass at all, between participants. The condition of the experiment is the usage of the controller, and the value measured is the k-value that was being recorded when the participant was satisfied with the gained sensation of weight of the simulated mass. The average of the three results would be recorded as the preferred k-value for a participant, which in their opinion would match the perceived weight from the simulation of mass and the real mass of the object. The two values gained from each participants leaves us with a paired sample, which are dependent on the controller usage (with or without).

3.8. Data Gathering & Analysis

3.8.1. K-Value

The experiment saved the participant chosen k-value of each session. There were a total of six sessions, three with controllers and three without. The average of the three values would be used as the k-value with and without controllers, resulting in a paired sample, where the condition changing is the controller usage. The values were assessed with a paired samples T-test. The questionnaires would be also quantified and assessed by a paired samples T-test.

After analysing the data, four outliers were removed from the sample since the participants reported of not gaining any sensation of weight. This also goes for the weight sensation questionnaire. But the presence was measured from everybody.

3.8.2. Questionnaires

After each session, one session being three attempts with or without a controller. The subject would fill a presence SUS questionnaire [52], a weight sensation questionnaire. After the second session, they answered whether they preferred controller or hand tracking with open ended questions to gain additional information for analysing the data. The weight sensation questionnaires included five questions with questions one and three having adjacent open ended question:

Weight sensation questions

1. How realistic was the feeling that you were actually holding a machine piece in virtual reality?
    (a) Why?
2. How realistic was the feeling that the machine piece that you were holding in virtual reality had weight?
3. How strong was the feeling that the weight of the machine piece that you were interacting with in virtual reality was changing?

   (a) Any comments?
4. How natural did grabbing the machine piece feel?
5. How easy was it to grab the machine piece?

Controller and hand tracking preference was asked after the second session with questions:

Interaction preference questions

1. Which method (using controllers or using hand tracking) did you prefer?
   (a) Why?
2. Which method was easier to use?
   (a) Why?

The presence SUS questionnaire is analysed by counting the amount of 6 or 7 answers of each questions. This gives the presence score for each question. Since we have again two sets of the presence scores of each participant, separated by the condition of using or not using a controller, we end up with paired samples. These were then tested with a paired samples t-test.

The weight sensation questions were analysed on a 1-to-7 Likert scale. As mentioned before, there were four outliers since those subjects did not experience any weight. This means we had 16 paired samples of answers which were then ran through a paired samples t-test.

Interaction preference questions were more open ended answers, with either possibility to prefer hand tracking or controller. Additionally, we asked which one of them they found easier to use. They were accompanied with an open ended question "Why?, which would be then used to look for reasons for their answers. Expert judgement was used to go through all the answers and find common categories from each answers, the answers were then grouped into two groups: people who preferred controllers and people who preferred hand tracking. Then their answers would be analyzed to see which categories come up in their reasoning, thus giving us some quantifiable detail into what is good about controllers and what is good about hand tracking.

Five categories were identified from the subject's answers: immersive, intuitive, easier, robust and haptic. The immersive category includes answers that found one or the other to give a more realistic feeling. Intuitive category included answers that found hand tracking to be more natural to use. Easier category is self explanatory, where the answer was only that one or the other was easier to use. Robustness category was mostly answers that found the hand tracking not to be accurate or that the controllers are quicker and more reliable to use. Haptic category includes an answer that had the experience that the haptic feedback of the controller helped with feeling the object and the weight.

4. RESULTS

4.1. K-Value

As seen from the box plot in Figure 7, the centers of the paired k-value samples are somewhat close together. Because of this, the paired samples T-test was predicted not to give a significant enough result. This was quickly proved when looking at the T-test results. The results of the average k-value paired samples are shown in table 1. The preferred k-values between the controller and hand tracking did not have a statistically significant difference ($p>0.05$). This suggests that for the research question 1, there is no significance on the use of a controller to the perceived weight with a pseudo-haptic feedback method.

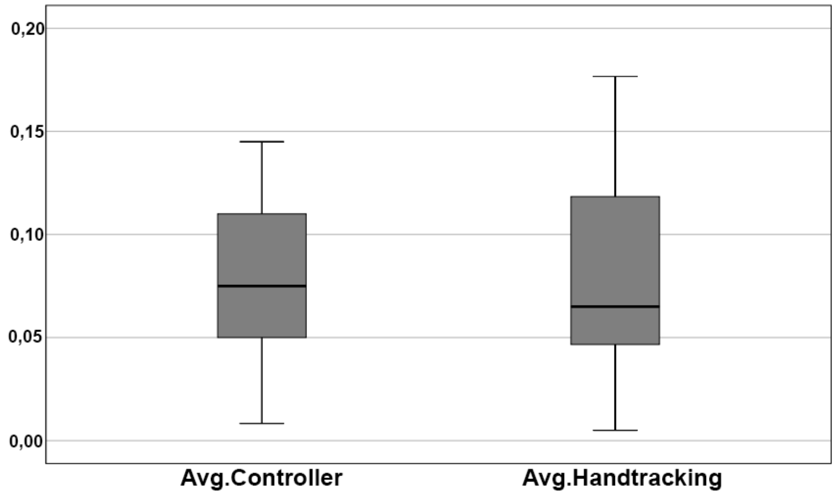

Figure 7. Controller and hand-tracking average k-values. Controller on the left and hand tracking on the right.

Table 1. Paired samples T-test for preferred k-values with and without controller

	Mean±SD	t value	Sig.(two-tailed)
Controller k-value	0,0846±0,0537	-1,062	0,305
Hand tracking k-value	0,1234±0,1822		

With only such a small sample it was unlikely to find statistical differences between the k-value. A bigger sample and more in depth view of the k-value could lead to other conclusions though. What was noticed during the experiment was that the k-value seems to affect the simulated weight more on smaller values. As mentioned before, and what the results show in the experiment made by Hirao et al. k-values close to 1 does not produce much weight sensation [38] or not at all. For example, k-value of 0,9 produces delay but it is so small that it is difficult to notice it. This could also be due to different FPS amounts, if it is not maintained by delta-time between frames. There could be a need for a framework for measuring pseudo-haptics that use frames to simulate haptic feedback. For example, the equation 1 could be modified to include the delta-time to avoid situations where one might run an application at 60 frames per second and one might run it at 120 frames per second.

4.2. Weight Sensation

The weight sensation questions are shown in Table 2. For easier access, the questions are also listed above the Table. Four of the five questions (questions 1-4) did not give a statistically significant difference on the use of controller versus hand tracking. Based on this, controllers did not have any effect on the realistic or natural feeling while interacting with the VE. Question 5 showed significant leaning towards controllers as being easier to use ($p<0.05$). This does not answer our second research question, but it was analysed separately to look into why this particular question gave a very different outcome. Reasons for this are analyzed in the qualitative answers.

1. How realistic was the feeling that you were actually holding a machine piece in virtual reality?
2. How realistic was the feeling that the machine piece that you were holding in virtual reality had weight?
3. How strong was the feeling that the weight of the machine piece that you were interacting with in virtual reality was changing?
4. How natural did grabbing the machine piece feel?
5. How easy was it to grab the machine piece?

Table 2. Weight sensation questions rating T-tests

		Mean±SD	t value	Sig.(two-tailed)
question 1	Controller rating Hand tracking rating	4,5000±1,15470 4,6875±0,87321	-0,481	0,637
question 2	Controller rating Hand tracking rating	4,7500±,93095 4,5000±1,26491	0,565	,580
question 3	Controller rating Hand tracking rating	5,1875±1,10868 4,6875±1,62147	1,168	0,261
question 4	Controller rating Hand tracking rating	4,75±1,552 4,30±1,490	1,229	0,234
question 5	Controller rating Hand tracking rating	6,45±0.759 5,50±1,192	3,866	0,001

4.3. Preferred Interaction Type

The subjects could choose after the second session which of the interaction methods they preferred better. The results showed that different reasons divide the sample group in half. People who preferred the controller liked the reliableness of the controller and the ease of use, since they found that pressing a button to grab is fast and easy. On the other hand, some people found hand tracking to be easier to use. This could be due to not having experience with controllers, maybe through not playing video games. Thus, those people mostly answered that the hand tracking was more intuitive and immersive. This can be seen in Figure 8.

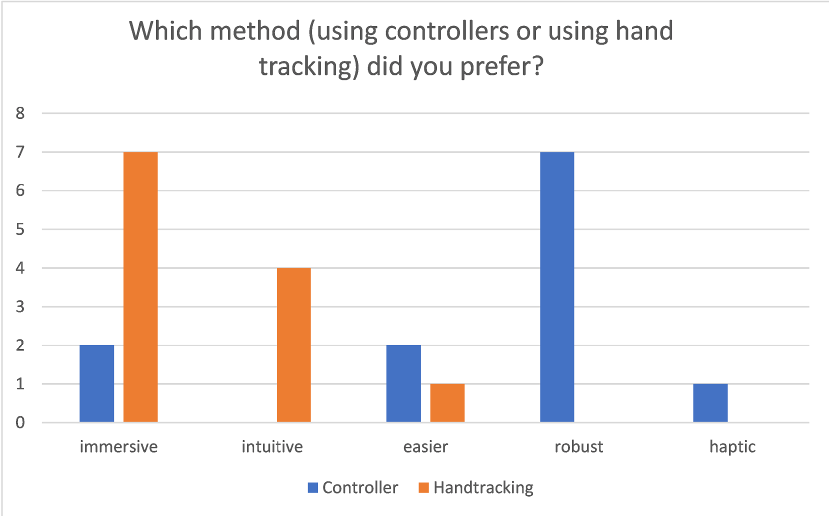

Figure 8. Categories of answers to question: Which method (using controllers or using hand tracking) did you prefer? Orange is hand tracking and blue is controller.

The second question was to find out more on why was either controller or hand tracking easier to use. But the answers followed the previous question answers quite closely as can be seen in Figure 9. This would suggest that the question was not formed correctly, but rather gave more confirmation to the question five results in the open ended answer reasoning.

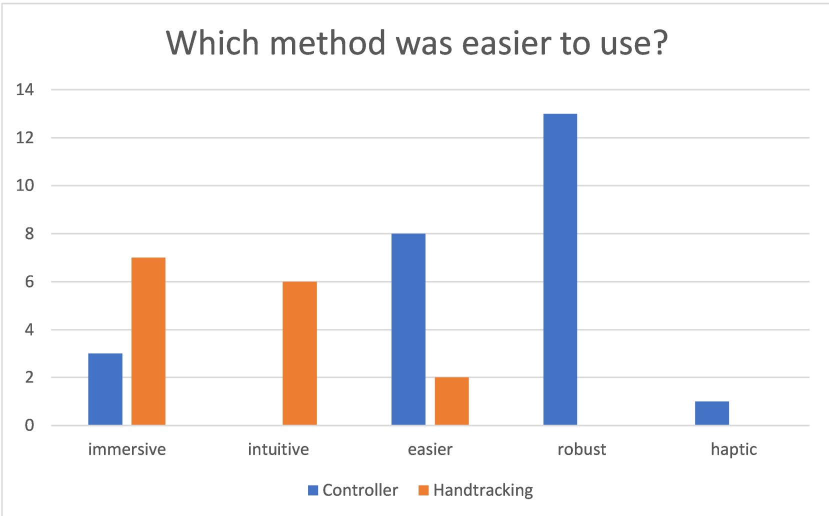

Figure 9. Categories of answers to question: Which method was easier to use? Orange is hand tracking and blue is controller.

4.4. Presence

The way the presence scores are calculated is by calculating the amount of 6 and 7 answers [52]. This gives the presence scores for each questions. These scores were then analysed by the paired samples t-test by putting the question's presence score results together. The result of the t-test is seen in Table 3.

Table 3. Presence T-tests

		Mean±SD	t value	Sig.(two-tailed)
Presence scores per question	Controller k-value Hand tracking k-value	5,83±3,971 8,00±2,966	-3,313	0,021
Presence scores per person	Controller k-value Hand tracking k-value	1,75±1,618 2,40±1,818	-1,782	0,091

The presence scores were analyzed in two different ways, first by combining the presence scores gained from each presence SUS question [52]. There were 6 different questions with the presence score ranging from 0 to 20, since there were 20 subjects. This method is labelled as "Presence scores per question" in Table 3. The other method to measure presence was to combine each persons' given total presence scores from the presence SUS questionnaire [52]. So one subject could have a minimum presence score of 0 and maximum of 6, since there were 6 questions. This second method is labelled as "Presence scores per person" in Table 3. We can see a statistically significant presence score increase when using hand tracking ($p<0,05$) in the presence scores per question T-test. The presence scores per person does not quite give the p value under 0,05. But it could be due to the small size of the sample. This suggests that changing to hand tracking from controllers can increase the felt presence in virtual environments.

The box plots of these scores are shown in Figure 10 and Figure 11 to give additional visual for the results. The presence scores of each question clearly shows an increase in the perceived presence.

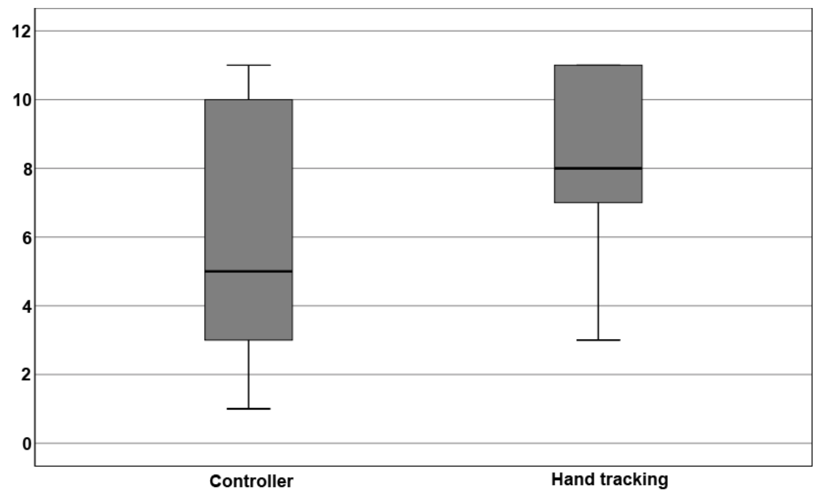

Figure 10. The presence graph per question.

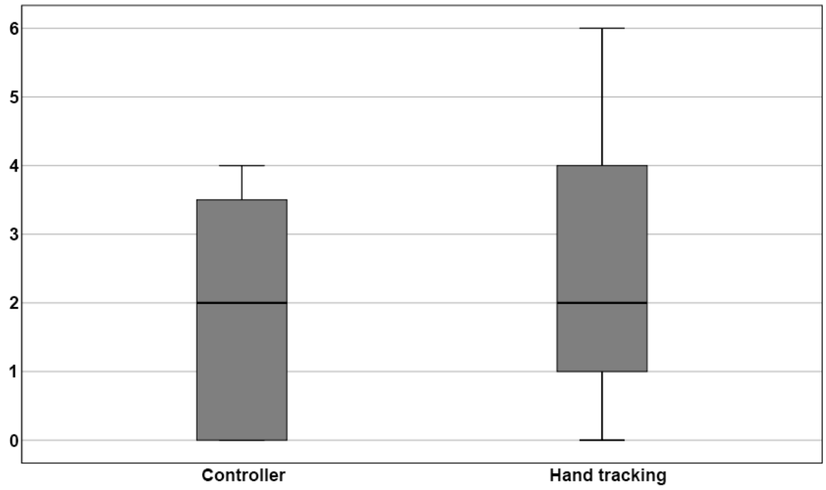

Figure 11. The presence graph per person.

5. DISCUSSION

The main research question was: Does the physical controller affect the pseudo-haptic simulated weight of a virtual object inside a VE, compared to using hand tracking? The result of this question is measured in Table 1. We did not find a conclusive difference on the feeling of the weight between the conditions. The sample size was only 20, which is likely to be too small to find a statistical difference. But the experiment gave some insight for developers and researchers to keep in mind while conducting similar experiments. Firstly, on top of using the control-delay technique to delay the movement of a weighted object, it should also delay the rotational movement of that object. Secondly, a framework for testing pseudo-haptic feedback with techniques related to frames per second (FPS) is needed, for example, to figure out if different FPS amounts have different outcomes and how to deal with the unwanted FPS drop or rise. One way to do this, is by using delta-time to synchronize between FPS changes.

The second research question was: Does the hand tracking give more realistic or natural feeling compared to interacting with a physical controller? For this also, we did not get statistically significant results. Some insight was gained into the differences of the two interacting types and why some people prefer the other. The controller was found to be more easier to use when grabbing an object inside the VE. The reason for this was that the controller was more robust. By pressing a button to grab a virtual object is a very effective interaction method, if the user is familiar with any common controller. With hand tracking the grabbing can be implemented in multiple ways and the experiment showed that some people do not make clear enough gestures for the grabbing. The Ultraleap hand tracking with Leap Motion controller requires the hand to close in order to grab. But this was seen too inconvenient in the pilot experimentation so it was changed to grab from the speed of the gesture changes, either by closing or opening of the hand corresponding to grabbing and releasing. This solved mostly the problem, but it still produced some infrequent error grabs and releases.

The third research question: What are the differences in opinion why some people prefer hand tracking and some controllers? The biggest reason why people preferred the controller was the robustness of the controller. This could be due to the hand tracking not being able to judge the grab and release of various different grabbing styles. Some people like to only close their hands very slightly when intuitively trying to grab something in a VE. Some people on the other hand, close their fist very violently. Thus causing some confusion on the grabbing and releasing when using hand tracking. But interestingly, people preferred hand tracking because it felt more intuitive to use. The participants did not need to think about the controller and which button to press, but they could often just start grabbing and dropping or even throwing objects in the VE quite naturally. Interesting note from the experiment was that with hand tracking some people wanted to try out throwing instinctively, which did not happen with controllers. This could be because it is sometimes difficult to grasp throwing while holding a controller. But this was not part of this research. Additionally, more people found the hand tracking interaction to be a more immersive and realistic way of interacting. This information suggests that it could be worthwhile to find ways to make hand tracking more robust, to overcome the issues mentioned before, such as with AI or machine learning techniques to learn the users' different ways of grabbing. This would create the VE more immersive and more intuitive for people, thus making the experience more effective. This also supports the findings of previous studies where it is suggested that more natural controllers translate to better perceived experience in the VE [56]. This possibly makes the learning tasks more effective, by translating the real-world mental models better to the game's model [56].

The fourth research question: How does the hand tracking affect the presence of a subject compared to a physical controller? The results of this can be seen in Table 3. This is the biggest finding of the study: presence scores were significantly higher when using hand tracking compared to a physical controller. This suggests that changing to hand tracking from controllers can increase the felt place illusion in virtual environments, but further research is needed to confirm this finding. This also supports previous findings where perceived naturalness is positively correlated to the experienced realism [57] and a previous study where hand tracking was observed to increase presence compared to controllers [58]. Keeping this in mind, along with the better immersiveness of the hand tracking, hand tracking is a very promising technology that should be developed further to overcome the current problems. After this, hand tracking as an interaction method could be a better interaction method than controllers. However, haptics should be kept in mind when developing on hand tracking platforms.

An interesting observation was made during the experiment. With hand tracking, the subjects seemed more exploratory. Some of the subjects were trying to create the universal signs with their fingers jokingly, and kind of were wondering their hands. In comparison to controllers where the subjects were found pausing and waiting for instructions. This could confirm further the find that the use of hand tracking increases presence compared to using a controller. This would need to be confirmed by measuring it, possibly with behavioural measures [26].

These findings give value to the developers who are deciding on which interaction type they want to implement in their virtual reality application.

5.1. Limitations

The implementation of the hand tracking was not perfect and this limits our findings slightly. Mostly the missing control-delay on rotational movement. Secondly some false grabs and releases were noticed during the test which negatively affects the VR experience. This could be solved through further development.

The small sample size limits greatly the findings of the perceived pseudo-haptic weight results. Especially, since four measurements had to be discarded as outliers, after the participants reported not feeling any weight.

Our finding of the positive relation between hand tracking and presence is limited by our chosen measurement. We only used a questionnaire to measure the presence or place illusion. This is not enough to fully confirm the positive relation between hand tracking and place illusion, but rather this acts as a complimentary result for possible future research on hand tracking and place illusion.

6. CONCLUSION

This study aimed to compare hand tracking and controller-based interactions in a virtual reality learning application. The study consisted of implementing hand tracking to an existing virtual learning application, that has been used by ABB Vaasa to teach assembly operators to assemble products. The study also included conducting an experiment using a pseudo-haptic feedback method to simulate weight of a virtual object. The experiment results were analysed and presented with discussion on the research questions that were realized in the beginning of the study. Different measures were used and future work is presented as the final suggestions for further research.

6.1. Future Work

For future work, the experiment should be repeated with control-delay added to the rotational movement and with a larger sample size to further confirm the perceived weight when using pseudo-haptic feedback by simulating virtual object weights with control-delay technique.

This experiment should be repeated with the place illusion in mind. This means measuring the presence in multiple ways to complement each others results. Possible methods for this could be some behavioural measures. Behavioural measures solve a major problem of the questionnaires in that they are objective [26]. For our case, these measures should be explored when assessing hand tracking over controllers. For example, what was observed during the experiment was that with hand tracking, the subjects seemed more exploratory. Perhaps this could be measured using behavioural measures. Other ways of measures that have been suggested are psychophysical and physiological measures [26].

It is also suggested that updates are made for the pseudo-haptic method to simulate weight with control-delay technique. For example it would be important to know the k-value where the subjects starts to feel weight and how does the k-value affect the perceived weight on different ranges of k-value. The frame dependency should be removed by adding the delta-time to the equation 1.

Great value would be to find solutions to hand tracking implementations that would minimize the errors and the inaccuracies that exists compared to controllers, in order to increase the robustness of hand tracking.

7. REFERENCES

[1] Laurell C., Sandström C., Berthold A. & Larsson D. (2019) Exploring barriers to adoption of Virtual Reality through Social Media Analytics and Machine Learning – An assessment of technology, network, price and trialability. Journal of Business Research 100, pp. 469–474.

[2] Berg L.P. & Vance J.M. (2017) Industry use of virtual reality in product design and manufacturing: a survey. Virtual Reality 21.

[3] Brooks F.P. (1999) What's Real About Virtual Reality? IEEE Comput. Graph. Appl. 19, pp. 16–27.

[4] Boud A.C., Haniff D.J., Baber C. & Steiner S.J. (1999) Virtual reality and augmented reality as a training tool for assembly tasks. Proceedings of the International Conference on Information Visualisation 1999-Janua, pp. 32–36.

[5] Lele A. (2013) Virtual reality and its military utility. Journal of Ambient Intelligence and Humanized Computing 4, pp. 17–26.

[6] Bowman D. & McMahan R.P. (2007) Virtual Reality: How Much Immersion Is Enough? Computer 40.

[7] Riva G. (2002) Virtual reality for health care: the status of research. Cyberpsychology & Behavior 5, pp. 219–225.

[8] Freina L. & Ott M. (2015) A literature review on immersive virtual reality in education: state of the art and perspectives. In: The international scientific conference elearning and software for education, vol. 1, vol. 1, pp. 10–1007.

[9] Dede C. (2009) Immersive interfaces for engagement and learning. Science 323, pp. 66–69.

[10] Bates-Brkljac N. (2012) Virtual Reality. Computer Science, Technology and Applications, Nova Science Publishers, Inc.

[11] Pausch R., Proffitt D. & Williams G. (1997) Quantifying immersion in virtual reality. In: Proceedings of the 24th annual conference on Computer graphics and interactive techniques, pp. 13–18.

[12] Juliano J.M., Spicer R.P., Vourvopoulos A., Lefebvre S., Jann K., Ard T., Santarnecchi E., Krum D.M. & Liew S.L. (2020) Embodiment Is Related to Better Performance on a Brain–Computer Interface in Immersive Virtual Reality: A Pilot Study. Sensors 20. URL: https://www.mdpi.com/1424-8220/20/4/1204.

[13] Slater M. & Wilbur S. (1997) A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. Presence: Teleoperators and Virtual Environments 6, pp. 603–616.

[14] Boas Y. (2013) Overview of virtual reality technologies. In: Interactive Multimedia Conference, vol. 2013, vol. 2013.

[15] Heeter C. (1992) Being There: The Subjective Experience of Presence. Presence: Teleoperators and Virtual Environments 1, pp. 262–.

[16] Robertson G., Czerwinski M. & Van Dantzich M. (1997) Immersion in desktop virtual reality. In: Proceedings of the 10th annual ACM symposium on User interface software and technology, pp. 11–19.

[17] Slater M. (2003) A Note on Presence Terminology. Presence Connect 3.

[18] Burdea G.C. & Coiffet P. (2017) Virtual Reality Technology. Wiley - IEEE, Wiley. URL: https://books.google.fi/books?id=hMQ8DwAAQBAJ.

[19] author Hillmann C. (2019) Unreal for Mobile and Standalone VR : Create Professional VR Apps Without Coding. Apress, Berkeley, CA, 1st ed. 20 ed., 324 p.

[20] Qualcomm (2020), Qualcomm Snapdragon XR2 Platform Commercially Debuts in Oculus Quest 2 | Qualcomm. URL: https://www.qualcomm.com/news/releases/2020/09/16/qualcomm-snapdragon-xr2-platform-commercially-debuts-oculus-quest-2, accessed 18.1.2021.

[21] Yu H., Lee H. & Jeon H. (2017) What is 5G? Emerging 5G mobile services and network requirements. Sustainability 9, p. 1848.

[22] Sun Y., Chen Z., Tao M. & Liu H. (2019) Communications, Caching, and Computing for Mobile Virtual Reality: Modeling and Tradeoff. IEEE Transactions on Communications 67, pp. 7573–7586.

[23] Slater M. (2009) Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philosophical Transactions of the Royal Society B: Biological Sciences 364, pp. 3549–3557.

[24] Selzer M.N., Gazcon N.F. & Larrea M.L. (2019) Effects of virtual presence and learning outcome using low-end virtual reality systems. Displays 59, pp. 9–15. URL: https://www.sciencedirect.com/science/article/pii/S0141938218300398.

[25] Makransky G., Terkildsen T.S. & Mayer R.E. (2019) Adding immersive virtual reality to a science lab simulation causes more presence but less learning. Learning and Instruction 60, pp. 225–236. URL: https://www.sciencedirect.com/science/article/pii/S0959475217303274.

[26] Skarbez R., Brooks Jr. F.P. & Whitton M.C. (2017) A survey of presence and related concepts. ACM Comput. Surv. 50.

[27] Back T., Tinga A., Tinga@uvt A., Louwerse M. & Louwerse@uvt M. (2018) Presence is key: unlocking performance benefits of immersive virtual reality.

[28] Sinclair M., Ofek E., Holz C., Choi I., Whitmire E., Strasnick E. & Benko H. (2018) Three Haptic Shape-Feedback Controllers for Virtual Reality. In: 25th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018 - Proceedings, pp. 777–778.

[29] Dipietro L., Sabatini A.M. & Dario P. (2008) A Survey of Glove-Based Systems and Their Applications. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 38, pp. 461–482.

[30] Zenner A. & Krüger A. (2019) Drag: On – A virtual reality controller providing haptic feedback based on drag and weight shif. Conference on Human Factors in Computing Systems - Proceedings , pp. 1–12.

[31] Lontschar S., Deegan D., Humer I., Pietroszek K. & Eckhardt C. (2020) Analysis of Haptic Feedback and its Influences in Virtual Reality Learning Environments. Proceedings of 6th International Conference of the Immersive Learning Research Network, iLRN 2020 , pp. 171–177.

[32] Lécuyer A. (2009) Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback. Tech. Rep. 1.

[33] Lécuyer A., Cuquillart S. & Coiffet P. (2001) Simulating haptic information with haptic illusions in virtual environments. Tech. rep., ANATOLE LECUYER SURESNES (FRANCE) AEROSPATIALE MATRA CCR.

[34] Dominjon L., Lécuyer A., Burkhardt J.M., Richard P. & Richir S. (2005) Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. Proceedings - IEEE Virtual Reality 2005, pp. 19–26.

[35] Lécuyer A., Burkhardt J.M. & Etienne L. (2004) Feeling bumps and holes without a haptic interface. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI ’04, Association for Computing Machinery, New York, NY, USA, pp. 239–246.

[36] Hirao Y. & Kawai T. (2019) Augmented cross-modality: Translating the physiological responses, knowledge and impression to audio-visual information in virtual reality. IS and T International Symposium on Electronic Imaging Science and Technology 2019.

[37] Lecuyer A., Coquillart S., Kheddar A., Richard P. & Coiffet P. (2000) Pseudo-haptic feedback: can isometric input devices simulate force feedback? In: Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048), pp. 83–90.

[38] Hirao Y., Takala T.M. & Lecuyer A. (2020) Comparing Motion-based Versus Controller-based Pseudo-haptic Weight Sensations in VR , pp. 305–310.

[39] Bjørkå H., Daniliauskaite K., Hansen L., Magnúsdóttir Á., Paerregaard J., Serafin S. & Bruni L. (2021) Feeling Objects in Virtual Environments: Presence and Pseudo -Haptics in a Bowling Game .

[40] Pusch A. & Lécuyer A. (2011) Pseudo-Haptics: From the Theoretical Foundations to Practical System Design Guidelines. In: Proceedings of the 13th International Conference on Multimodal Interfaces, ICMI '11, Association for Computing Machinery, New York, NY, USA, pp. 57–64.

[41] Li M., Sareh S., Xu G., Ridzuan M., Luo S., Xie J., Wurdemann H. & Althoefer K. (2016) Evaluation of Pseudo-Haptic Interactions with Soft Objects in Virtual Environments. PLoS ONE 11, p. e0157681.

[42] Crison F., Lécuyer A., Savary A., Huart D., Burkhardt J.M. & Dautin J.L. (2004) The use of haptic and pseudo-haptic feedback for the technical training of milling.

[43] Samad M., Gatti E., Hermes A., Benko H. & Parise C. (2019) Pseudo-haptic weight: Changing the perceived weight of virtual objects by manipulating control-display ratio. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI '19, Association for Computing Machinery, New York, NY, USA, p. 1–13.

[44] Hirao Y. & Kawai T. (2019) Can We Create Better Haptic Illusions by Reducing Body Information? In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp. 974–975.

[45] Biocca F., Inoue Y., Lee A. & Polinsky H. (2002) Visual cues and virtual touch: Role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence .

[46] Gavish N., Gutiérrez T., Webel S., Rodríguez J., Peveri M., Bockholt U. & Tecchia F. (2015) Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. Interactive Learning Environments 23, pp. 778–798.

[47] Gavish N., Gutierrez T., Webel S., Rodríguez J. & Tecchia F. (2011) Design guidelines for the development of virtual reality and augmented reality training systems for maintenance and assembly tasks. vol. 1.

[48] Abidi M., Al-Ahmari A., Ahmad A., Ameen W. & Alkhalefah H. (2019) Assessment of virtual reality-based manufacturing assembly training system. The International Journal of Advanced Manufacturing Technology 105.

[49] Hannaford B. (2001) Virtual Training for a Manual Assembly Task .

[50] Knoke B., Gorldt C. & Thoben K.D. (2019) Literature Review on Training Simulators in Manufacturing Processes.

[51] Slater M., Usoh M. & Steed A. (1994) Depth of Presence in Virtual Environments. Presence 3, pp. 130–144.

[52] Usoh M., Catena E., Arman S. & Slater M. (2000) Using Presence Questionnaires in Reality. Presence: Teleoperators and Virtual Environments 9.

[53] Spiegelmock M. (2013) Leap Motion Development Essentials : Leverage the Power of Leap Motion to Develop a Fully Interactive Application. Community Experience Distilled, Packt Publishing.

[54] Nandy A. (2016) Leap Motion for Developers. Springer.

[55] Zhou Y., Ji S., Xu T. & Wang Z. (2018) Promoting Knowledge Construction: A Model for Using Virtual Reality Interaction to Enhance Learning. Procedia Computer Science 130, pp. 239–246. URL: http://www.sciencedirect.com/science/article/pii/S1877050918303867.

[56] McGloin R., Farrar K. & Krcmar M. (2011) The Impact of Controller Naturalness on Spatial Presence, Gamer Enjoyment, and Perceived Realism in a Tennis Simulation Video Game. Presence 20, pp. 309–324.

[57] McGloin R., Farrar K. & Krcmar M. (2013) Video Games, Immersion, and Cognitive Aggression: Does the Controller Matter? Media Psychology 16, p. 65.

[58] Voigt-Antons J.N., Kojic T., Ali D. & Möller S. (2020) Influence of hand tracking as a way of interaction in virtual reality on user experience. In: 2020 Twelfth International Conference on Quality of Multimedia Experience (QoMEX), IEEE, pp. 1–4.