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A study on wrist-based haptic weight conveyance in immersive virtual environments

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“Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.”

— MARIE SKŁODOWSKA CURIE

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ABSTRACT

Physical properties of objects are some of the features that are lost when users are immersed in today's virtual environments that usually only provide visual and auditory stimuli. In a quest to recover the physical perception of touch, in this work, we present two different studies to assess how force feedback applied solely on the wrist can convey weight. This localized approach is implemented with a wearable device, which is an advantage regarding mobility. Part of our motivation comes from balance tasks that involve interaction with objects, where there is a need to perceive their weight.

We first propose an experiment to assess how we can use the force feedback on the wrist to alter the weight perception when manipulating physical props in VR. Then, we implement and evaluate two experiments in several days setting with a single participant, using only virtual representations of the objects. In the first experiment, we propose a task involving ordering objects, from the lightest to the heaviest. The second experiment also assesses weight perception, but at this time, asking the participants to compare only two objects grabbed at distinct points. In both procedures, the tasks are repeated hundreds of times to remove any bias that can come from memorizing the orders and combinations presented. From these studies, we found that the force stimuli localized on the wrist are sufficient to convey weight information. We also found that grabbing the objects at different points affects the perceived weight to a certain extent due to how the two motion axes of the wrist are placed. The behavior we observed in weight discrimination, and its limitations are equivalent to the ones found in previous studies performed using real weights.

Besides these studies, an additional contribution of this work is an effective experimental design relying on a single participant in a long term setting.

Keywords: Haptics. Virtual Reality. Weight Perception. User Studies.

Compreensão de peso através de feedback de força baseado no punho em ambientes imersivos

RESUMO

As propriedades físicas dos objetos são algumas das características perdidas quando os usuários são imersos em ambientes virtuais, e só recebem feedback visual e auditivo, que normalmente é o que dispositivos modernos de realidade virtual apresentam. Em busca de recuperar a percepção física do tato, neste trabalho, apresentamos dois estudos diferentes para avaliar como o feedback de força exercida exclusivamente no punho pode transmitir a sensação de peso. Esta abordagem localizada é implementada com um dispositivo portátil, o que é uma vantagem em relação à mobilidade. Parte de nossa motivação vem de tarefas de equilíbrio que envolvem interação com objetos, onde há a necessidade de perceber seu peso.

Primeiramente propomos um experimento para avaliar como podemos usar o feedback da força no punho para alterar a percepção de peso ao manipular objetos físicos em VR. Em seguida, implementamos e avaliamos dois experimentos, aplicados entre vários dias, com um único participante, utilizando apenas representações virtuais dos objetos. No primeiro experimento, propomos uma tarefa envolvendo a ordenação de objetos, do mais leve para o mais pesado. O segundo experimento também avalia a percepção do peso, mas dessa vez, pedindo aos participantes que comparem apenas dois objetos segurados em posições diferentes. Em ambos os procedimentos, as tarefas são repetidas centenas de vezes para remover qualquer influência vinda da memorização das ordens e combinações apresentadas. A partir destes estudos, concluímos que os estímulos de força localizados no punho são suficientes para transmitir informações de peso. Também observamos que segurar os objetos em diferentes posições afeta o peso percebido até certo ponto, devido à forma como os dois eixos de movimento do punho são posicionados. O comportamento que observamos na discriminação de peso e suas limitações são equivalentes aos encontrados em estudos anteriores realizados com objetos de pesos reais. Além desses estudos, uma outra contribuição desse trabalho é um design de experimento eficaz, contando com um único participante em um cenário de longo prazo.

Palavras-chave: Háptica, Realidade Virtual, Percepção de Peso, Estudo Experimetal.

LIST OF ABBREVIATIONS AND ACRONYMS

DE	Distance Error
JND	Just noticeable difference
MSE	Mean squared error
VR	Virtual Reality
VE	Virtual Environment
MCC	Matthews correlation coefficient

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1 INTRODUCTION

Virtual Reality devices are capable to render an entire new environment, replacing the vision and auditory senses. While this allows us to partially immerse users, the other senses are still connected to the real environment, where the user is physically located. In order to transpose the touch feeling to the virtual world, haptic devices can help to complement immersive experiences. As in the real world, there are situations where we need the information that comes from the contact with physical objects in order to complete tasks or even to improve the immersion feeling. While visual and auditory displays for virtual reality are widespread, haptics is still marginally used in VR systems. One of the reasons is that effective synthetic haptic stimuli are challenging to produce in VR (SRINIVASAN; BASDOGAN, 1997; WANG et al., 2019). They depend on computing the geometric interactions between human avatar bodies and the virtual environment, which is computationally demanding. They also depend on an often cumbersome device to deliver the appropriate stimulus onto the user's body.

The skin is our largest organ, and together with muscles and joints, they produce two distinct types of information: tactile (the sense of touch) and force (the sense of proprioception) (LIN; OTADUY, 2008; LEDERMAN; KLATZKY, 2009). Not surprisingly, most haptic devices designed for VR focus on the tactile type of haptic feedback (de Jesus Oliveira et al., 2017; OLIVEIRA; NEDEL; MACIEL, 2018). Moreover, they frequently narrow their action to the range of a few vibrotactile notification patterns produced by tiny motors that can be worn. On the other hand, force feedback systems usually rely on a ground anchored device to constrain the user's motion and create the illusion of being in contact with a physical object with weight, stiffness, and other properties (Dominjon et al., 2005; Hara et al., 2008). While these solutions are effective in labs and specific industrial setups, they have limitations in terms of how they scale to the common user, as a grounded device limits the use of force feedback in any VR application where the user is not staying on a pre-determined location. In this context, smaller wearable props seem to be an acceptable alternative (MAISTO et al., 2017), despite their limitations. Some of these devices provide only pseudo-haptic stimuli, stretching the skin at joint or muscle locations (NAKAMURA et al., 2014; Provancher; Sylvester, 2009; PACCHIEROTTI et al., 2016). However, another class of wearable or handheld haptic devices renders force on specific joints, e.g., Grabity (CHOI et al., 2017), iTorqU (WINFREE et al., 2009), Exii

Exos DK2 [1]. An open question then is how the stimuli produced by these wearable props are perceived and understood by users and how the human brain integrates them. This issue is important in the design of more effective VR interfaces, i.e., interfaces that are more immersive, more natural, more capable of generating presence. Given how wearable devices evolved over the years and how popular they became in daily activities, we want to explore them as a more effective tool for other types of applications, where the feedback could be used as a cue, and not just as stimuli resulting from a collision or simple touching interaction.

1.1 Motivation and goals

An important element of realism in VR is the possibility to feel the weight of virtual objects (ELLIS; LEDERMAN, 1999; Lederman; Jones, 2011; Amemiya; Maeda, 2008). From assembly tasks to rehabilitation, many applications can benefit from a meaningful rendering of the objects' weight. However, weight information is composed in the human brain as the combination of forces and pressures along a chain of several joints, muscles, and patches of skin. Is it possible that a device stimulating a single joint or limb conveys weight in a comprehensive manner? As most of the controllers in current virtual reality devices involve the arm – particularly the wrist – movement, it is arguably a hot-spot for haptic feedback. Besides, the wrist provides two degrees of freedom and is at close proximity with the hands, which concentrate most of the somatosensory cortex processing power (DUBIN, 2013).

For these reasons, we suggest that force stimuli on the wrist, coupled with visual and auditory feedback, might convey information that surpasses the local joint constraints, e.g., information regarding a person's balance or about the weight of an object being handled. Fig. 1.1 is an illustration of the general problem we approach in this work. Considering that scenario, we investigate the following questions:

- Can we use force feedback on the wrist as a cue to completing tasks?
- Can the force feedback on the wrist influence the weight perception of real objects?
- Can the body interpret the force feedback, when coupled with the visual stimulus, as the weight attributed to a virtual object?
- Does the grabbing position of the virtual object have any influence on the used

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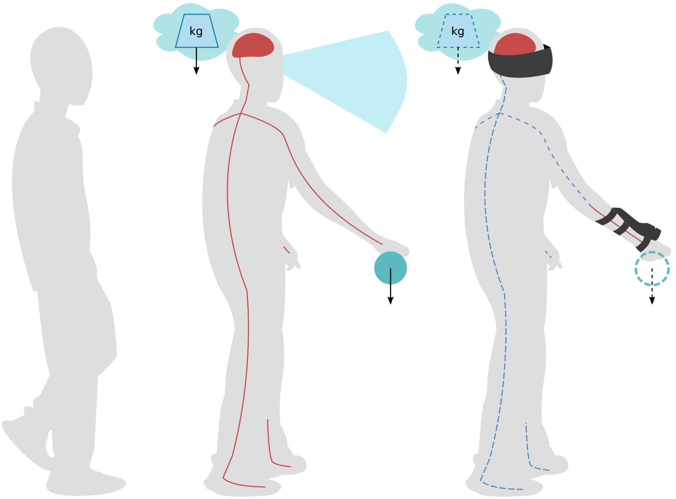
[1] https://exiii.jp/wrist-dk2/

perception?

Figure 1.1: The parallel between physical and virtual weight perceptions.



1.2 Overview and outline

We started our study with an application that involves balancing items. We describe this preliminary experiment designed to verify if the feedback can influence the perception of real objects weight with the same feedback used for virtual objects only. Then, to address the questions on how the body interprets the force feedback as the weight attributed to virtual objects, we designed and performed two experiments, exploring the feedback as a means to simulate their weight.

Besides testing viability, the experiments aim at uncovering details about the conditions necessary and the limits imposed on the discrimination of different weights. Furthermore, we introduce an experimental methodology that is also a contribution *per se*. We devised a collected hundreds of samples from a single user, who performed the tasks for several days, instead of short sessions with a population of several subjects. The method relies on redundancy and confrontation of the measurements.

The remainder of the dissertation is organized as follows. In Chapter 2, we explain in details the motivation coming from balance simulation, the design of a study regarding weight perception and other studies found in the literature related to our investigation. Chapter 3 brings a detailed description of the two experiments that were implemented and performed as the core of our contribution, as well as the analyses and discussion about the results we obtained. In Chapter 4, we draw conclusions upon our findings and propose what future research could be performed.

2 PREVIOUS AND RELATED WORK

Although our main focus on this work is weight perception, there are other tasks in VE that would benefit from wrist-centered stimuli. One of them is balance, and it was what provided the motivation for this work. In this chapter, we present an experiment that challenges the balance skills of the users, based on the haptic feedback provided around the wrist. Seeing the need for a better evaluation regarding the interaction with weight in a simpler approach, we have designed another experiment, which focused on altering the perception of physical objects. We describe this experiment and provide details on the evaluation and hypothesis we aim to test. We explain how the design was the base for the study proposed in this work. Finally, we discuss some of the related work regarding wearable and handheld devices that were used for simulating weight in virtual environments, and that inspired the design of the two experiments that are the core of this work.

2.1 Immersion and balance

Through the vestibular system, the human body is able to keep balance and spatial orientation (KANDEL et al., 2000, Part VI), but when we are immersed in virtual environments, it has to re-adapt to the new space, and sometimes this can cause side effects, like cybersickness. At the same time that throught this sense such side effects can be provoked, it is also through it that we can try to enhance the user's sense of presence, and engage balance.

Some previous works on this topic are based on bulky devices to physically change the user ground support (WAKITA; TAKANO; HADAMA, 2018), (BYRNE; MARSHALL; MUELLER, 2016), (YANG et al., 2011), which can limit the applications, increase simulation costs and require some effort for the users to get used to them. Some others use vibrotactile devices to guide users in space (OLIVEIRA; MACIEL, 2014), but not so much has been explored with force-feedback stimuli. For this reason, we proposed that we could influence balance, but using a wearable device that provides feedback on the wrist. When we talk about balance tasks here, one way to divide them is between the ones where the body needs to keep its balance, for instance in some exercising activities, and the ones where the goal is to keep an external object balanced, like when holding an object that is not stable. In our case we are considering only the last one, and our task involves holding a tray with an object that keeps moving on top of it.

Figure 2.1: The actuation-tracking loop that enables balance emulation.

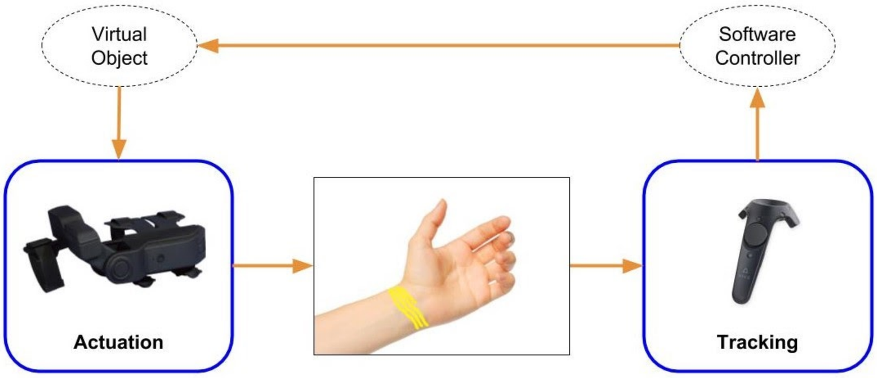
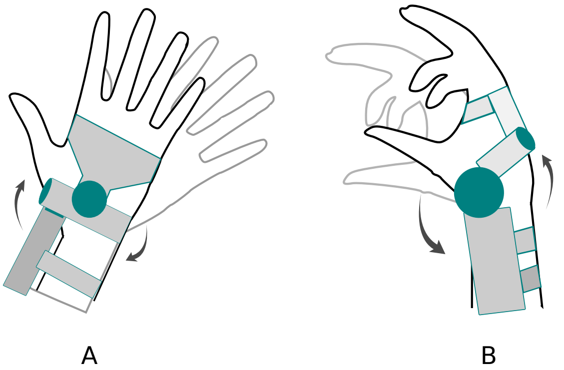


Figure 2.2: The two axes of force-feedback stimulus applied to the wrist by the haptic device: A) adduction/abduction; B) flexion/extension.



It is common to find tasks in our daily lives where our balance skills are required, for instance in rehabilitation situations, when we need to stimulate the body to recover locomotion functions. In this context, we proposed to bind the orientation of an unstable virtual object to both an actuation and a tracking mechanism, in such a way that they interact together within a feedback loop, like illustrated in Fig. 2.1.

2.1.1 Force Feedback Device

The haptic device used in all the applications presented in this work is the EXOS Wrist DK2 by exiii Inc.[1]. It delivers the force feedback using two servo-motors: one that provides rotational force on the *abduction/adduction* motion axis, as shown in Fig. 2.2(A); and the other one providing rotational force on the *flexion/extension* axis, as shown in Fig. 2.2(B).

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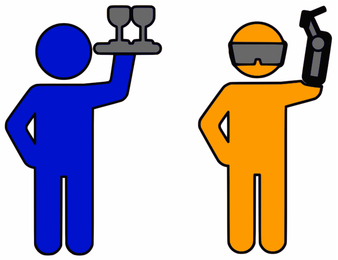
[1] https://exiii.jp/wrist-dk2/

Figure 2.3: Correspondence between virtual (left) and physical (right) scenarios when holding a tray



The device is attached to the arm using three velcro straps, one around the hand, and two around the lower arm, to ensure that the movement of the motors does not displace the device from the body. The device we had available is built for the right arm, so all the applications here described had users using it this way, even when they were left handed.

We hypothesize that combining the continuous haptic actuation-tracking cycle to the visualization of the balancing object can yield a realistic simulation of a balancing task such that the overall performance is increased, compared to the same task with visual stimuli only. Such simulation can have multiple applications, specially when we talk about rehabilitation of people who suffered some sort of trauma (like a stroke) and lost their motor abilities. The feedback can be provided both as a challenge, in case of real world balance tasks, or as an assistance, that would provide guidance to the equilibrium state of the limb.

2.1.2 Balance application demonstration

In this context, we propose an immersive application in which the participants have to walk, carrying a tray, from one place to another, following a line drawn on the ground. Fig 2.3 illustrates how the virtual world matches the the real world situation of holding a tray with objects on it. All the applications mentioned in this document were developed using Unity 2018.3.9f1 [2], SteamVR 1.11 and the Exos SDK for Unity, provided by exiii.

The tray has a spherical object on top of it, and the participant was told to try keeping it as close to the center of the tray as possible. Due to the sphere's shape and physical attributes (mass and material), it moves according to the inclination of the tray. The movement of the device's motors combined make it possible to simulate the move-

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[2] https://unity.com/

Figure 2.4: Participant carrying the virtual tray (left side) with the haptic feedback provided by the wearable device.

ment of the sphere on the surface, as it moves. To simulate the effect that the weight shift causes, we apply a force downwards, based on the weight value attributed to the sphere and its position to the center of the tray; the force applied and the distance are directly proportional, simulating the effect of torque. We chose a sphere because we wanted an object that could easily move on its own to make the task more dynamic. This was a pilot study, which was not formally evaluated, but we demonstrated it in two different large events, and between 200 and 300 participants tested it and provided us with verbal feedback.

All the participants worn the haptic device for the feedback and the HTC Vive Pro[3] headset when they tried the application. The controler was held on the right hand for tracking, like shown in Fig 2.4. In some cases we turned the device off, so they did not receive any force feedback, but still had it placed on the wrist. For many of the participants, this was their first contact with virtual reality, as one of the demonstrations was held in a event open to the public community. As we explained briefly how the system worked and they were not familiar with the haptic device, in most cases they did not know when it was activated or not. We asked the participants what they thought of the experience and if they were able to feel some influence on the balance, even knowing that the virtual tray did not exist as a physical prop.

Overall the feedback was positive; people felt engaged in the task and enjoyed the experience. Some of them mentioned that they could feel like the sphere was heavy and that it influenced the tray position depending on how they moved their wrist. From observing how the moved in the space, we saw that when the device was turned off,

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[3] https://www.vive.com/eu/product/vive-pro/

people tended to complete the task much faster and did not drop the object from the tray. In contrast, when the device was on, they were slower, but the stimuli also seemed to make them pay more attention to the task. This could indicate that either the feedback can help the users focus more on the task, or that it turns it more difficult. To analyse how this effect changes the experience, another study involving real objects of different weights would have to be performed. What we can say from our experience is that the force feedback affects the task, either in a helpful or not helpful way.

As already mentioned, we ran the two demonstrations as an informal evaluation of this application, which did not provide us with quantitative results from the tasks. One of this occasions was in the World Haptics Conference 2019, where this work was presented in the Student Innovation Challenge, and awarded as the winner. Balance is a complex mechanism in our body, so to tackle this matter in the immersive context, we decided to investigate first how the weight of virtual objects can be translated to the body through the use of force-feedback applied on the wrist. By studying how it works, we can understand better if balance applications can be explored using this weight rendering setup. Other devices with the same setting can take advantage of our evaluation and also applications that aim to stimulate the vestibular system can also integrate weight perception as a factor.

2.2 Experimental approach for altering the perception of physical props

From the previous experience, we realized it was important to understand how the body interpreted the simulated weight first, and then apply it to the balance context. To do that, we designed the preliminary study that is described here. We planned it towards evaluating how the same haptic feedback could be used to alter the physical perception of real objects. Here we present the design of a psychophysical experiment to verify how the stimuli can be extended to shifting the weight perception of objects with real physical properties.

This experiment was planned to be implemented and performed along with the other two that will be presented, but it was interrupted as a consequence of the Sars-Cov2 pandemic that is happening worldwide. Due to the psychophysical characteristic of the study, it would be necessary to conduct it with a large number of participants in order to guarantee reliable results. Since it would not be safe to expose participants during a pandemic situation, we decided to present its design here, as a contribution to a future implementation, and only perform the experiments where the one-participant setting could be used, which are described in Chapter 3.

With the results that would be obtained, we would have built a psychophysical curve and obtained the Just Noticeable Difference (JND) of the stimuli. JND is the minimum difference between two magnitudes for them to be noticeable as different. To measure how perceived force could be used, we proposed a task where the participants tell which of two physical objects is heavier, after holding and lifting them (one after the other) with their right hand. The participant movement is limited only to the wrist and fingers joints, and the physical objects weight ranges from a 350g to 550g, increasing in 50g from one object to the next, with a total of 5 objects. We planned to use Exos Wrist D2K to exert a force downwards when the participant holds the objects, in order to increase its weight.

2.2.1 Hypotheses

These are the hypotheses we aimed to test with an analysis of the data that would be obtained from the experiment.

- H_1 - It is possible to increase the perceived weight of tangible props by applying kinesthetic feedback in the final joint of the arm (Wrist)

- H_2 - Weight is perceived differently, depending on the axis of rotation of the joint.

To verify them, we would use the data collected from the participants to build a psychometric curve, using logistic regression.

For each axis, we would build a different curve, using the answers to calculate the probability of the participants to guess if the variable object was heavier than the reference or not. In an ideal scenario, taking H_1 as valid, for the case where the reference is compared to the object that weights 450g, we expected to have equal chances of yes or no answers, since the force combined with the weight would be equal to the reference. For heavier objects, the probability of answering yes should be higher, and the opposite for objects lighter than 450g.

The task would be repeated for several pairs of objects where the weight of one of the objects, called **reference**, is always the same, while the weight of the other, which we called **variable**, varies within the range of weights.

Each time the variable object is handled, a constant weight force is rendered by the haptic device attached to the user right wrist, while the object is being lifted. For the reference object, we would not apply any external force and the weight felt would be just the weight of the object itself. We wanted to find out if the artificially applied force makes the objects weight feel greater than it really is, having a reference parameter to allow the comparison.

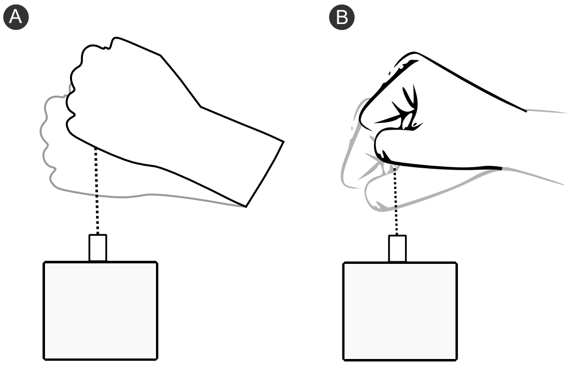
At the beginning of the experiment, the participant would be positioned seated, with her right arm partially fixed on the arm of the chair, as to allow only the wrist movement. This is important since the haptic device only actuates in the two wrist axes, therefore any movement from the arm could bias their perception. The arm of the chair is adjustable, so we would move it according the size of the participant's arm. The physical objects would be positioned near their hands in a reachable position on top of a surface. Participants would be equipped with a Head-mounted Display (HMD), which would not render a whole environment, but has two important roles: blocking the view of the real objects and showing the instructions that should be followed by the participant through the experiment. The subject also would wear a headphone with pink noise to isolate external noise. The device is capable of applying the feedback up or down for each axis independently. Therefore, when both are combined, it can provide a full **circumduction** movement resistance. When no force is being applied, the wrist is free to be moved in any direction. To apply the force only when the object is actually being lifted, the objects are tracked in space using a motion tracking system.

2.2.2 Study design

According to the device setting, we consider two independent variables: flexion and abduction movements, as represented in Figure 2.5. For each of them, we designed the experiment using five physical objects (levels) with weights of 350g, 400g, 450g, 500g and 550g, respectively. Among them, we selected the 500g object to be the **reference**, which means that, in every turn, this is the object that is going to be compared with one of the other weights. It is important to notice that the 500g object is also compared with itself during the turns, and that the execution order is shuffled with a Latin square or randomization as necessary for a fair comparison.

The choice of both the artificial force magnitude to be applied and the objects weight was made based on the Weber Fraction, which states that, as the ratio between the magnitudes of two stimuli increases, the easier it is to perceive the difference between the

Figure 2.5: Pulling movement executed during the tasks. Abduction/Adduction represented in (A) and Flexion/Extension in (B)



two stimuli. According to equation (2.1), where I is the weight and Δ is the difference between both objects, it is possible to calculate the JND based on the reference weight. According to (ROSS; BRODIE, 1987), 10% is the JND value (represented by K in the formula) for objects around 500 g. Following the equation, as we chose 500g as reference, the minimum difference between the weights was set as 50g (10% of the reference weight). This allowed us to have a balance between the weights not being too heavy to hold and the device being able to render the force correctly.

$$\frac{\Delta I}{I} = K \tag{2.1}$$

2.2.3 Procedure

Considering the two variables, we divided the test in two parts, one where they would hold the object like Figure 2.5(A) and the other as in Figure 2.5(B). Each participant would be assigned to start with one of the lifting positions (with the order being arbitrarily chosen in the first round, and then alternated for the following participants) and had their hands positioned according to it.

As we wanted every object to be compared 3 times per variable, each part of the test had 15 turns, resulting in 30 answers per participant. The procedure for each turn was:

- the reference object and a variable object are randomly assigned to A and B
- participant lift object A and then put it back to its original position.
- participant lift object B, and then put it back to its original position.
- when the object is the variable one, a force equivalent to 50g is rendered while

doing the movement

- the message: "Is object A heavier than object B? Press the right button for yes and left button for no" is prompted on the HMD screen.
- participant used a mouse positioned next to their left hand to select and then confirm their answer.

The order between the reference and variable objects would be randomized to avoid bias, so the first object would be alternated between either of them in each turn. In other words, if the chosen object had 400g and is set to be the first in the random process, the user would hold it and feel 400g, the real weight, plus 50g that is applied by Exos. Then, they would lift the reference object (500g), and after releasing it, answer whether the first one was heavier than the second one or not. It is important to highlight that if the answer was no, it could either mean that the second object was heavier or that both of them had the same weight.

The participant would never be aware of which object is the reference and which is the variable one, we named them A and B for them to be able to answer the question, but A could be any of the two.

After the first 15 turns are done, the experiment is paused for the participant to answer the questionnaire about the part already performed. Then, the arm is repositioned according to the other movement, and the following 15 turns are performed. After 30 turns, the participant answers the same questionnaire, this time regarding their experience with the second axis.

We also wanted to have baseline values to be able to compare our stimuli with no stimuli at all. Even considering Weber's Law, we think it is important to have values with and without the stimuli from the same participant, in order to have stronger parameters. The procedure is the same as the one we described above, the only difference is that in the baseline experiment there is no stimuli. We alternate between both of them in the turns, in order to reduce the bias. As the number of repetitions would double, we could split the experiment in two parts, and have them performed in different days to avoid any harm for the participant.

2.3 Weight perception from force-feedback devices

A number of VR systems support force-feedback when the user task is based on a workbench. With the user sitting or standing by a working surface, phantom-style devices (MASSIE; SALISBURY et al., 1994) of several sizes and degrees-of-freedom can be effectively used. Similarly, grounded exoskeletons (Carignan; Tang; Roderick, 2009) can provide a bodily involving set of force-feedback stimuli, while in some classes of virtual environments, passive haptics is applied as an affordable and effective solution (PALJIC; BURKHARDTT; COQUILLART, 2004; ACHIBET et al., 2015).

When the user cannot be constrained to a workbench or a small area around a grounded haptic device, the use of wearable or handheld haptic devices has been explored. When such ungrounded devices are used, the most important constraint is that they cannot render actual forces capable of stopping the user motion. Nevertheless, many approaches have been successful in providing several types of proprioceptive or kinesthetic stimuli that are applicable to VR interaction. Among them, we are especially interested in those that convey some kind of weight information. We discuss them below in two subsections that we organized according to the category of device used.

2.3.1 Prop-based handheld devices

Prop-based devices rely on the prop's shape, texture, and weight to provide their feedback. The simplest example is the interaction with a real object that is fixed or tracked and coupled with a virtual object. As in this work we are referring to changes in weight perception, we reviewed approaches that dynamically morph objects properties in order to change perception. They are usually held as controllers and are similar to the interaction we have with swords, bats, and wands.

One example, developed by Zenner and Kruger (ZENNER; KRÜGER, 2017), is a weight-shifting proxy, that is capable of changing the weight distribution along one axis to simulate virtual objects of different lengths and weights. Their device has a cylindrical shape and is held like a bat. As the user interacts with the environment, a motor inside the cylinder moves a weight up and down, displacing the center of mass. Together with visual feedback, they were able to simulate change in objects length, thickness and weight based on this technique.

White et al. (WHITE et al., 2019) proposed a prop setting to simulate hand-held real-world objects in the form of a VR controller and made assessments with simulation and training applications. They investigated if there was any advantage on giving the standard controllers a haptic feature. The application was a baseball game. They tested the interaction with a standard HTC Vive controller and the props they developed, which were three prototypes with a baseball bat shape: a standard bat, a weighted bat and a weighted bat with tactile haptic feedback. They concluded that, due to the decrease in cognitive dissonance, the participant's tension rate was lower when the task was performed using the weighted prop for holding a bat that had all the characteristics – shape, size, and weight – of a real one. The tasks performed with the weighted props also had a lower error rate, indicating that this aspect of the perception helped the participants to perform the task better.

In a more complex approach, Heo et al. (HEO et al., 2018) proposed a device capable of creating a force in any direction, allowing the simulation of changes in gravity and characteristics of different surfaces, like water resistance. Their device has a hammer shape: a cube where several propellers are placed in different positions and a handle for the participant's grip. Depending on how the propellers are activated, the force rendering changes, as well as the perception. The authors performed a qualitative study and, although the tasks were not focused on objects comparison, the feedback from users indicated that the change in weight was realistic.

Similarly, in Aero-plane (JE et al., 2019), the authors created the weight illusion of an object moving on a plane, in both axes. Along with VR, their device made the participants feel like the object they were holding was moving. The main principle is to use the wrist as a pivot and, by modulating the speed of two propellers, it is possible to apply torque on it and change the weight intensity and position perception.

Although these devices can alter the perception, have a good performance on providing a stronger feeling of immersion and also help in task performance, they rely on the participant's grasp, which sometimes is not desirable. Furthermore, the technology used to displace or create the weight can also become a problem when the system is too complex, limiting the interaction of the participant. Usually, they have to be developed for a specific purpose.

2.3.2 Wearable haptic devices

There are devices that interact more directly with our body, actively actuating on the joints or the skin.

Dexmo (GU et al., 2016) is an example of an exoskeleton attached to the hand back and coupled to the fingers. It uses a breaking component for each finger that stops the movement of the joints when there is a collision, bringing the feeling of interacting with a rigid body. Its simple functioning allows the device to be lighter and use less energy. It was tested in an archery application and, when compared to not having any haptic feedback, the device improved the performance. This result suggests that even with a simple type of feedback, it is possible to improve the immersion feeling and the performance in tasks.

Gurocak et al. (GUROCAK et al., 2003) proposed a device that consisted of tubes and a mechanical system to control the airflow, allowing the pressure created from the air shift to increase or decrease the weight sensation. It was designed to be placed between the elbow and the hand, with the function of applying a force in a specific point of the hand. The airflow inside the tubes controlled the magnitude and direction of the force. They performed studies to discover if the participants could identify objects based on their weights, using both tangible and virtual props. The results were satisfactory, but they concluded that the device was able to render a maximum force of $100gf$ (or $0.1N$).

Grabity (CHOI et al., 2017) is another wearable haptic interface used to assess touch, grasping, inertia and weight perception. Choi et al. attached a dynamic tangible device to the participants' fingers and performed two experiments. Firstly, they validated the design of the haptic device, and then, they tested the ability of the users to discriminate between different weights in VR. The authors combined skin stretching, vibrotactile feedback, and uni-directional brakes, generating opposing forces between the index finger and thumb to simulate contact, grasping, gravity and inertia, and were able to obtain satisfactory results. Their portable device shows to be a good approach, although the use of vibrotactile feedback still needs to be better explored for weight perception.

In a different application, a guidance approach using kinestetic feedback was proposed by Skorina et al. (SKORINA; LUO; ONAL, 2018), where the stimuli provided on the wrist joint was used to guide participants through a path. Through an experiment study, participants had to guide an agent to walk on a path, and they controlled it using the wrist and arm movements. The device used was a soft robotic wearable, that used pressure-driven actuators to apply a force on the wrist. They observed that the feedback helped the users had to control an agent to follow non-linear paths when comparing to having no feedback. This shows another type of application that can benefit from the stimuli applied on the wrist.

Designs, where the users themselves are the primary energy source, were also reported in the literature (PALJIC; BURKHARDTT; COQUILLART, 2004; ACHIBET et al., 2015), showing that even with simpler devices, which have the user as causing and receiving the feedback at the same time, there is an increase in the embodiment and confidence of experiments' participants. An example is Elastic-Arm (ACHIBET et al., 2015), a passive haptic feedback approach. Through a body-mounted elastic armature, it values portability and causes less discomfort for the participant while still augmenting the interaction level during the tasks. The authors integrated the device with 3D interaction metaphors and tested them in navigation and selection tasks. The two main advantages are that the user is the power source, which decreases the weight that a battery would add, and also that it does not rely on any static passive prop, which increases mobility.

From the works briefly surveyed in this section, we noticed that many alternatives have been proposed to study weight perception in virtual environments. This highlights the importance of this topic and its applications. Although more sophisticated pseudo-force feedback devices are a technology that is not available for ordinary users in most of the cases, they become more relevant when we think about training purposes, as the physical properties of the objects need to be taken into account, along with the audio-visual stimulus. Feedback on the hand and wrist movements combined are not easy to approach from the evaluation perspective, since there are many variables that could be considered, like exploring or not the joints in each finger, the fact that tactile and proprioceptive feedback can be used, and we also have to take into account the ergonomic aspect of the devices.

The present study contributes to the state-of-the-art with a methodology for assessing how force feedback is perceived in a specific situation, the perception of the weight of virtual objects.

3 WEIGHT PERCEPTION FROM LOCALIZED FORCE FEEDBACK

In this chapter we describe the experiments we performed to assess how force-feedback stimuli applied to the wrist are perceived as the weight of virtual objects in an immersive environment. We revised studies that analysed weight perception of real objects, without using any other device to influence it. Most of them tested Weber's Law (ROSS; BRODIE, 1987) in different weight ranges and different participants' characteristics. Such studies tried to understand how people discriminate between weights within a certain interval. In one of those experiments (KARWOWSKI et al., 1992), five boxes with different weights, but with the same shape and color, were presented for the participants that have to organize them from lighter to heavier. They analyzed the results regarding the load heaviness fraction and compared how the load differential can affect the error rate. Their conclusions were mostly regarding the maximum acceptable weight of lift for real objects, and how much the weight increase should be to enable the participants to discriminate the objects.

In our study, we used similar experiments based on simple tasks, as well as a similar analysis of the output data. In this section, we define our hypotheses and describe the general conditions we had for developing our experimental study.

3.1 Hypotheses

To break the problem down and facilitate the assessment through more straightforward tasks, we focus on the feedback that is applied directly on the wrist, instead of the whole hand or just the fingers, this last one being largely explored already (PACCHIEROTTI et al., 2017). It is known that the fingertip has much potential for stiffness and texture perception. However, when lifting objects, our weight perception is more related to the whole body (CULBERTSON; SCHORR; OKAMURA, 2018), becoming rather a complex task. We wanted to understand if the feedback provided on the wrist axis is enough to change how the objects are perceived regarding their weight.

To assess these capabilities, we adopted a wearable device composed of two servomotors that actuate on the two motion axes of the wrist. The device actually induces a controllable torque between the forearm and the hand (see Fig. 2.2).

We developed a system that computes the applicable torque at interactive frame rates depending on the user's actions in a virtual environment. Then, we designed two task-based psychometric experiments to measure the user's perception of weight, and test the following hypotheses:

H_1 - A torque applied on the wrist affects the subjective perception of the weight of the virtual objects being handled.

H_2 - The point where an object is grabbed by the user does not affect the subjective discrimination of two objects regarding their weights.

The first experiment aimed at testing hypothesis H_1 through a task where the participant had to order a group of four objects according to their weight. In the second experiment, the participant has to manipulate two objects and decide if one is heavier than the other, holding them at different positions, thus testing hypothesis H_2.

3.2 Boundary conditions

We used Exos Wrist to provide the feedback that will simulate the weight. We briefly explained that the combination of movements on the two joints creates the illusion of holding something heavy, and this is achived by using the motors to simulating torque. The servo-motors movement is based on an angle relative to an initial position, and the rotation happens with a force actuating from the initial angle to the new one. Despite not actually having any intensity control regarding the force, the larger the angle, the wider this movement is. When considering the context of the device we are using, if we have the wrist in a rest position, a longer movement means that the wrist is going to be forced into a wider position. When we put two of these motors together, this creates illusion of torque being applied. This is the principle to simulate weight.

Besides Exos, we used an HTC Vive as VR device, and as Exos does not have a tracking mechanism, an HTC Vive Controller was held by the participant during all the tests, on the right hand. While the position of the controller was used for tracking the Exos position, the two grip buttons were used to grab and release the cubes, and the controller was held in its standard position by the participant. Besides, no haptic feedback was provided by it. The participant also had a headphone playing pink noise during the experiments, in order to cancel the noise coming from the haptic device. Due to the design of the haptic device, the two experiments were made using the right hand.

Both of the experiments were developed using Unity 2018.3.9f1 [1], SteamVR 1.11 and the Exos SDK for Unity, provided by exiii.

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[1] https://unity.com/

The two experiments were intended for a single participant scenario. In contrast to the setting of multiple participants, where tasks are performed with a small combination of conditions regarding the independent variables, with a single participant we can vary the values of independent variables as many times as we want. For this reason, we tried to randomize the variable orders and increase the number of repetitions as much as possible. At the same time that this aspect brings disadvantages, it allowed us to explore different conditions that would not be feasible with a larger group of subjects, particularly in cases where the execution of experiments is limited by external factors, like social isolation. A similar approach was taken in other studies (STEINICKE; BRUDER, 2014). We think that the experience can be analysed in a slightly different approach, compared to a study involving more participants, since the assessment of the tasks and the prolonged exposure to the interaction methods can provide valuable information about its effects on the subject.

In order to diminish the bias created by the single-subject setting, the number of repetitions was increased, and the sessions of the whole study were distributed over 17 days. In both experiments, the objects and their appearance order were randomized as much as possible, making it uncertain enough to elude the participant of which condition was being presented. The author of this thesis volunteered as the participant. She is 25 years-old, right-handed, computer scientist, with about two years of experience in human-computer interaction, VR user interfaces as well as haptic devices, which enables valuation of certain effects that might have occurred.

For both experiments, we call *trial* each task instance where the participant evaluates the objects and provides an answer, and *session* each group of trials, that would represent a different participant if we were performing the test with multiple subjects. The number of trials in each session and the number of sessions are further discussed in the description of each experiment.

Also, in both experiments, the objects were attributed with a weight value, from 0.5 to 6, always increasing by 0.5 units. This value does not correspond to the real weight in metric system, but an input value to the Unity SDK. The value for the weight attributed to each object was based on an empirical observation, taking into account a range that was not uncomfortable for the participant, in order to avoid any physical harm for the wrist.

Figure 3.1: Screenshot of the first experiment. The user task is to order the four gray cubes by weight, placing them on the respective yellow slot. Pressing the button on the right confirms the conclusion of the trial.

3.3 First Experiment - Ordering Objects by Weight

This experiment aimed at testing H_1(*A torque applied on the wrist affects the subjective perception of the weight of the virtual objects being handled*), and was based on performing 495 trials of a single task. For each trial, the user was presented with four visually equal objects and was asked to place them on four slots ordered by their perceived weight, from the lightest to the heaviest. In this section, we describe the details of the first experiment.

3.3.1 Experiment Design and Procedure

For this experiment we kept the objects with the same shape, size, and color, varying just their weight.

Twelve different weights were assigned to the objects, ranging from 0.5 to 6.0, with a difference of 0.5 between each pair. As there were only four objects per trial, we selected them from this list of twelve weights, and each of the sequences appeared just once through all the sessions, in random order. To achieve this grouping, we calculated all possible combinations $C\binom{12}{4} = 495$, which were divided into sessions of 15 trials, resulting in 33 sessions. Thus, we ensure that each possible combination of weights was tested. We divided these 33 sessions in 10 consecutive days, using a Latin square based sequence, resulting in a schedule with the following number of sessions/day: [(1, 3, 5), (3, 5, 1), (5, 1, 3), (6)].

For each trial, a not-yet-used combination is randomly selected from the 495 combinations. The four weights are shuffled and then attributed to four cubes that are presented to the user on top of a surface. There is no association between position and weight between trials. The participant was informed that the positions had no relation with the weight.

We also display four slots where the cube objects are to be placed according to their weight. The participant can grab the objects, one at a time, as many times as she wants. She should eventually place each of them on one of the slots, as shown in Fig. 3.1. The participant is allowed to move the objects among slots freely, and is asked to press a button to confirm the ordering when she is satisfied. The grabbing location on the object is always its center of mass. A snap-to-center operation is carried out whenever the user touches the cube and activates the grabbing effect, avoiding interference of additional torques that a distance from the grabbing point to the center of mass could generate.

The NASA-Task Load Index (HART; STAVELAND, 1988) questionnaire was applied after each session, to measure how the experiment affected the participant regarding mental and physical effort. Additionally, some questions from the Simulator Sickness Questionnaire (SSQ) were selected. As our participant already had experience using VR applications we reduced the questions to: General discomfort, Headache, Nausea and Dizziness, which were the main symptoms that the participant usually experience. All factors were evaluated in a scale of 5 points for each question, ranging from 0 for "None" to 5 for "Severe". These questions were asked before and after each session.

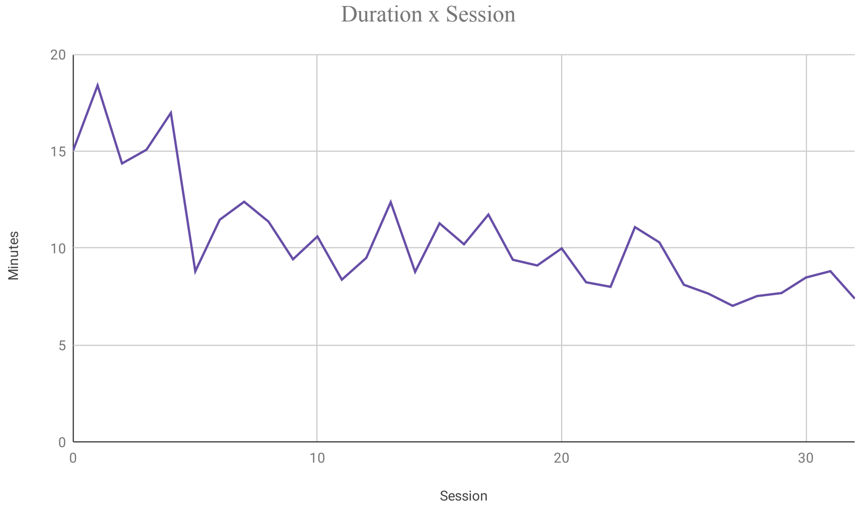
3.3.2 Results and Analysis

In total, the experiment took 5.7 hours over the course of 10 days. The average time per session was 10.4 minutes, with a standard deviation of 2.81 minutes. There was at least one-hour interval between sessions. We can see the distribution over the sessions in Fig. 3.2

The data obtained with this experiment consists of 495 ordered sequences of four elements, corresponding to the four objects ordered by the user in each trial. These sequences are firstly compared with the ground-truth, and two error metrics are computed: Distance Error (DE) and Mean Squared Error (MSE).

Distance Error (DE) is a simple metric we designed to quantify how close to the

Figure 3.2: Completion time (in minutes) for each of the 33 sessions of the first experiment. A learning period is observed during the first six sessions.



correct order an answer is. The slots were converted into index numbers from "0" for the heaviest one (left), to "3" for the lightest one (right). The DE is computed adding the four absolute differences between the index of each object position in the answer (i) and its respective index in the ground-truth (j), as expressed in eq. 3.1.

$$DE = \sum_{w=0}^{3} |i - j|_{(w_i = w_j)} \tag{3.1}$$

We also used the Mean Squared Error (MSE) metric to calculate the differences between the weights that were ordered by the participant and the weights of the correct order (eq. 3.2).

$$MSE = \frac{1}{4} \sum_{0}^{3} (w - \hat{w})^2 \tag{3.2}$$

While the DE allows us to assess how much out of order the answer is considering just the positions, the MSE allows us to account for the difference in weight between each cube and the one that was placed on its destination slot. If an error is due to a swap of two objects, for example, DE penalizes equally, regardless of the weight difference, while MSE penalizes more if the difference between weights is greater and vice-versa.

We computed both error metrics for each of the 495 answers, and analyzed first the overall data. Then, we also grouped the trials according to several features for further analysis, following the approach by Karwowski et al. (KARWOWSKI et al., 1992), e.g., by sessions completed on the same day and by trials including the lightest-half of the objects only and the heaviest-half only.

In the following, we analyze our findings.

3.3.2.1 The stimulus is perceived as weight

For the first analysis we took the whole set of answers. We aim at comparing it with a user who was not receiving any stimulus. Instead of performing such a tedious task, we applied the theoretical assumption that without force stimulation the user responses would be random. Thus, we generated an equal number of entries (495) with random answers, and computed DE and MSE on this answers distribution.

A Shapiro-Wilk test showed that the distribution was not normal, so we performed a Wilcoxon signed-rank test that indicated that both error measures for the random sample, $m_{de} = 1.12$ and $m_{mse} = 1.75$, were significantly higher than the errors calculated from the participant answers, $m_{de} = 0$ and $m_{mse} = 0.375$, with Z_{de} = 7681, $Z_{mse} = 10151$ and p $<$ 0.001 in both cases, where m_{de}, m_{mse} are the median value for DE and MSE variables respectively.

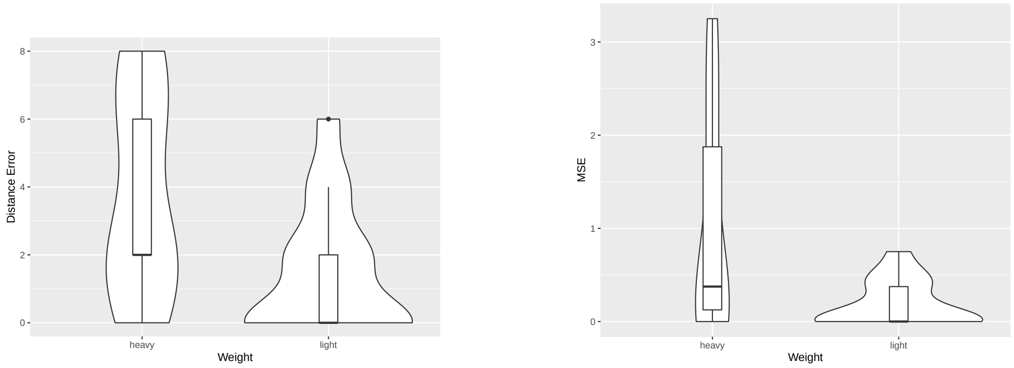
3.3.2.2 Lighter objects are more accurately weighted

We also grouped the trials according to the range of weights they contain. A low-weight group is defined as having all four weights between 0.5 and 3, named 'light'. On the other hand, a high-weight group, containing only weights from 3.5 to 6.0, named 'heavy'. For each group, a set of 15 input sequences were available. We analyzed the DE and MSE for these 30 sequences. The medians for the light and heavy groups were respectively (m_{de} = m_{mse} = 0) and (m_{de} = 2, m_{mse} = 0.375). A Mann-Whitney test indicated that the error was significantly larger for heavy weights than light weights, with U_{de} = 163.5, U_{mse} = 162, p_{de} = .0291 and p_{mse} = .0362. Fig. 3.3 shows the data distribution. It is noticeable that both error metrics were lower in the group of light weights.

3.3.2.3 Effect from period of the day and number of session was not detected

To investigate the influence of the period of the day when the session was performed (morning, afternoon or night) on the results, we grouped the sessions by this condition. This could be important, especially due to possible variation on the levels of alertness or fatigue imposed to the participant. A Kruskal-Wallis test indicated that there was no significant difference in the median of the errors between periods of the day,

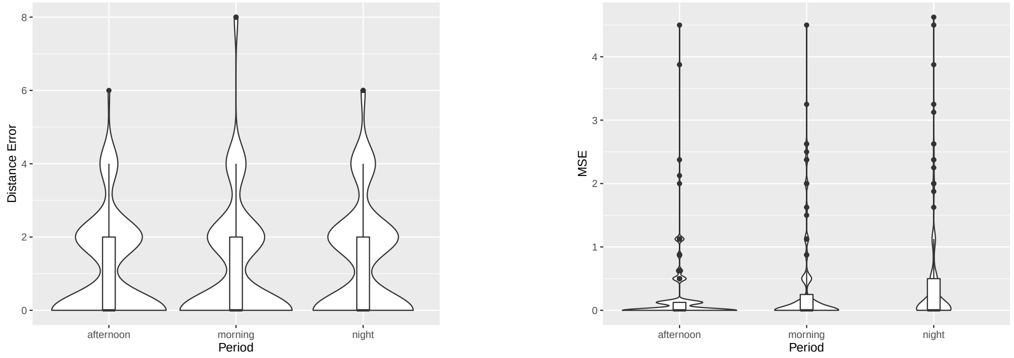
Figure 3.3: Error metrics computed for pairs within the groups of heavier ($w > 3$) and lighter ($w <= 3$) objects. The comparison shows a finer discrimination among lighter objects.



(a) Distance Error (DE)

(b) Mean Squared Error (MSE)

Figure 3.4: Error metrics computed for the periods of the day when the trial was performed. The comparison shows only a slight variation on the distribution, with no significant difference on the medians.



(a) Distance Error (DE)

(b) Mean Squared Error (MSE)

($m_{de} = 0$ in all three groups), U_{de} = 0.87704, p_{de} = 0.25, although the distribution slightly varies, as shown in Fig. 3.4.

Similarly, as the sessions were distributed among several days, we investigated the possible influence of the number of sessions in the same day on the participant's answers. We assembled the results in five groups, the first containing all the first sessions of each day, the second group with all the second sessions of the each day, and so on. The first group was the largest, as there was at least one session everyday, and the last group was formed by all the last sessions performed each day when there were five sessions. A Kruskal-Wallis test indicated that there was no significant difference between the five groups ($m = 0$ in all categories for all groups), $H_{de} = 2.85$, $H_{mse} = 1.36$, p_{de} = 0.9719, p_{mse} = 0.9503, where m is the median for all groups.

3.3.2.4 Learning effect from sessions over the days

To investigate if the participant's performance improved over the days due to learning effects, a Friedman test was performed, which showed that there were no significant changes in the error metrics between the sessions for both DE (Chi-squared = 37.9, p = 0.21) and MSE (Chi-squared = 42.4, p = 0.1). Also, we observed that the sessions' completion time became more stable after the sixth session (Fig. 3.2).

3.3.2.5 Difference in discrimination between two objects

Herein, we call Δ_W the weight difference between two successive objects in the sequence that they are presented to the participant. Although the participant can examine each object in any order and as many times she wants, we examined if the presentation order is a factor that affects the discrimination between objects, we selected groups of objects with each of the possible differences to compare. As we used 12 weights starting from 0.5, and varying in intervals of 0.5 until 6.0, we can generate several groups with $\Delta_W = [0.5, 1.0, ..., 5.5]$.

We selected from the 495 quadruples presented to the participants those where the four objects ordered by weight have the same Δ_W between neighbors. We were able to make three groups with the exact differences of 0.5, 1.0, and 1.5 between each of the four objects. As only few combinations respect these conditions, these groups are small, with 9, 6, and 3 entries respectively. To improve our sampling, we added the quadruples with $\Delta_W = 1.0$ and $\Delta_W = 1.5$ into one single group, and compared them with the $\Delta W = 0.5$ group. A Mann-Whitney test indicated that there was no significant difference in distance error (DE) between the [0.5] ($m_{0.5} = 2$) and [1.0, 1.5] ($m_{[1.0,1.5]} = 0$) groups, $U = 23.5$, $p = 0.12$. It should be noticed that $DE = 2$ means a simple neighbors swap. As for MSE, the results were similar ($m_{0.5} = 0.125$) and [1.0, 1.5] ($m_{[1.0,1.5]} = 0$) groups, $W = 38$, $p = 0.854$.

As the quadruple sampling is small and limited in terms of Δ_W, we also followed another approach to analyze discrimination power. We looked into how correctly each pair of weights is ordered in all 495 quadruples. There are six pairs for quadruple, resulting in 2,970 pairs with Δ_W varying from 0.5 to 5.5. As the error metrics only make sense when we analyze all elements of the quadruple, here we just counted whether or not the two objects were in the right order when comparing their positions in the answer. The number of hits and misses was compared and can be observed in Fig. 3.5

Figure 3.5: Difference between miss and hit when comparing pairs with equal Δ_W. Notice the sharp trend of higher hit-rates when Δ_W increases.

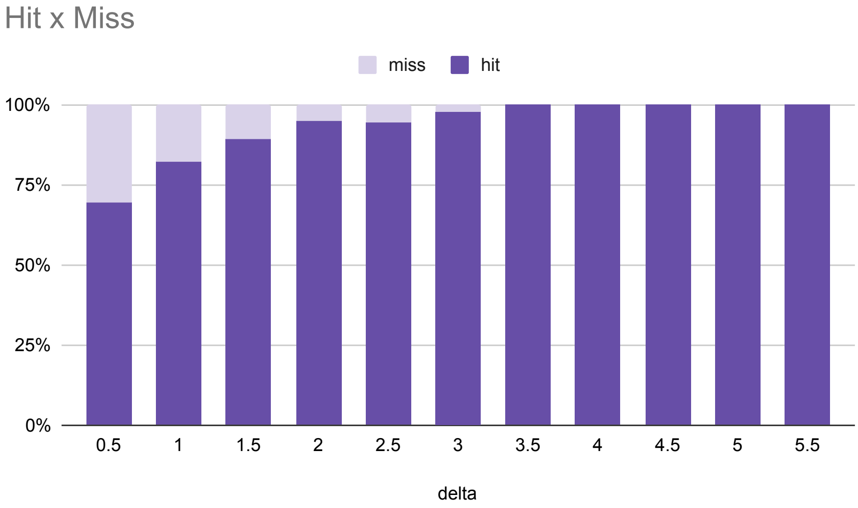


Table 3.1: Hit and Miss frequencies in pair grouping

Δ_W	**hit**	**miss**	**total**	**hit (%)**
0.5	345	150	495	69.70%
1	371	79	450	82.44%
1.5	361	44	405	89.14%
2	341	19	360	94.72%
2.5	298	17	315	94.60%
3	264	6	270	97.78%
3.5	225	0	225	100%
4	180	0	180	100%
4.5	135	0	135	100%
5	90	0	90	100%
5.5	45	0	45	100%

Here again, we had a larger number of pairs with $\Delta_W = 0.5$ (495) than with $\Delta_W = 5.5$ (45), but the total count for each level is fairly higher. Table 3.1 shows the frequencies obtained, and in Fig. 3.5, we can see how the miss rate decrease when Δ_W increases.

3.3.3 Discussion

Regarding the analysis of the results of the whole sample concerning the error metrics, it was expected that the feedback would increase the hit rate when compared to the context with no feedback. This assumption was confirmed (Sec. 3.3.2.1), thus supporting H_1, and therefore we can say that the feedback provided on the wrist generates some tendency on the perception of weights. The results of the comparison between the groups of heavy and light objects (Sec. 3.3.2.2) showed that the lighter the group of objects, the more accurate the perception is, regardless Δ_W, when considering the maximum difference we had in our range. This phenomenon was already observed previously when physical props were tested (KARWOWSKI et al., 1992), which indicates that the wrist stimulus reproduces the effects we have for real weight perception. This is also a common behaviour according to Steeven's power law (STEVENS, 1957), which basically states that the higher the stimulus, the harder it is to perceive differences in sensation.

Complementary to this, when we look at the results that compared an equal Δ_W, we observed that there was no significant difference between the two groups, even with different median values (Sec. 3.3.2.5). This could be due to the low number of samples in each group or also to a small Δ_W. More sessions involving these groups would have to be performed to confirm whether it is easier or not to differentiate between objects with larger Δ_W.

As we did not get significant results from the quadruple grouping, we decided to group the objects in pairs, and as shown in Table 3.1, we can see that there is a inverse relationship between the number of hits and Δ_W. We explored better the comparison between a pair of objects in the second experiment, but it is already possible to see that the influence the device causes is similar to the reality.

Regarding the time analysis, we can argue that the learning curve is relatively fast, as the time spent in each session varied more in the first ones and stabilized around the sixth session (see Fig. 3.2). However, no learning effect was found considering the error metrics (Sec. 3.3.2.4).

Regarding the grouping based on the period of the day (Sec. 3.3.2.3), there was no significant difference in the error metrics, which also happened in the grouping by session order on the same day. In this last case, it could mean that the effort necessary to complete the task was not enough to influence the next session. Moreover, as we discuss later (Sec. 3.5), the results for the low subjective simulation sickness are compatible with the fact that the participant was already familiar to VR, and also that the task did not require much spatial locomotion and visual search.

3.4 Second Experiment - Weight Perception regarding the Grabbing Position

In the second experiment, we also evaluate weight perception, using the same system setup. However, this time a cylindrical object is presented, and the user is forced to grab it at specifically assigned areas. A lever-effect is produced, which might influence the user judgment of the actual weight. The task is to compare two objects, manipulating them successively, and tell if one is heavier than the other. This is then a complementary approach to test H_1 (*It is possible to increase the perceived weight of tangible props by applyingkinesthetic feedback on the*). Besides, we use this experiment to evaluate how weight perception is affected when grabbing the object at different points, thus testing H_2 (*Weight is perceived differently, depending on the axis of rotation of the joint.*).

3.4.1 Experiment Design and Procedure

In this experiment, the two objects to be compared are presented one after the other, opposite to the simultaneous approach of the first experiment.

Each of them is a cylinder with exactly the same dimensions and appearance. The use of a cylinder, instead of a cube, is interesting for this experiment as we can control where, in the cylinder, the user can grab as if it was a line, with the long axis being the single dimension used to define points. We then defined five grabbing positions: at both ends, at the center and between the ends and the center. They are indicated by a red ring, as shown in Fig. 3.6 with their respective labels. Each time the object is shown in the scene, one of these circles is displayed, indicating the position where the participant should grab the object.

We tested all paired arrangements of grabbing points, excluding the pairs where the same grabbing point is assigned to both objects. This resulted in (5 * 5) - 5 = 20 pairs of grabbing points. The weight of each object is chosen from a list of six values, from 1 to 6, increasing in one unit. These values correspond to the integer ones used in the first experiment. We include all combinations of these six values in pairs, $C\binom{6}{2} = 15$, plus the six pairs containing the same weight twice, resulting in 21 distinct pairs of weights. The 20 pairs of grabbing points applied to the 21 pairs of weights result in 420 unique trials. These trials are shuffled and grouped into 21 sessions of 20 trials. The sessions were spread over seven days as in the Latin square based sequence: [(1, 3, 5), (3, 5, 1), (3)].

Figure 3.6: Object of the second experiment. The user is forced to grab at one of the indicated points for each object presented. In the example, R1 is the active grabbing point.

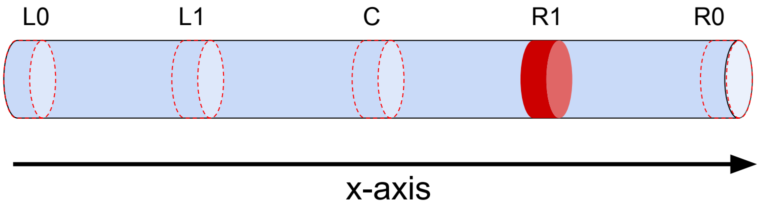
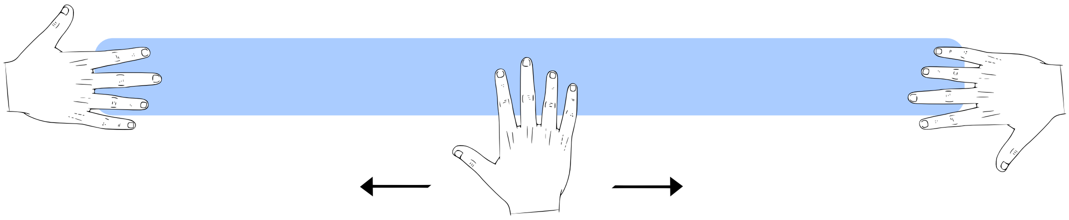


Figure 3.7: The user is constrained to remain at the same side of the table while manipulating the cylinder. The schematic indicates the hand poses allowed.



One last detail of the design is that the participant is instructed to stay at the same side of the table and always grab the object with the palm of the hand facing down. Once the object is held, the participant can move it freely, but return it to the same orientation it was initially placed. In all cases, but especially for the endpoints, the participant was allowed to place the hand at a maximum angle of 90° between the thumb and the x-axis of the cylinder, as shown in Fig. 3.7. These precautions were taken to enforce the distinction between left and right for the cylinder that would otherwise be symmetric, i.e., left becomes right when a 180° rotation happens around the vertical axis.

As the experimental session starts, the first object appears in the scene, and the user is asked to manipulate it using just the indicated grabbing point. After the user considers she has manipulated the object enough to perceive its weight, she presses a confirmation button to proceed to the second object, which appears in the same position as the first one. The only apparent difference is that the grabbing point is in a different position. Then, she manipulates the second object in the same way as the first, and has to answer the question: "Is the previous object heavier than this one?". Two buttons are displayed, corresponding to the "Yes" and "No" answers. The participant's answer is recorded, and the trial is concluded. Then, she is presented with the next object to start another trial. This process is repeated 20 times per session. Fig. 3.8 shows the experiment scenario, at the moment where the second object of a trial is presented to the user, and the grabbing point is at the position L0. The user interacts with the buttons to the right to answer the

Figure 3.8: Scenario of the second experiment. The caption on the top indicates that this is the second object presented in the current trial. The user has to press one of the "Yes" and "No" buttons shown on the right side of the table, to answer the question.

question and to switch between objects.

Like in the first experiment, the participant answered the NASA-Task Load Index questionnaire after each session, and the same questions selected from the Simulator Sickness Questionnaire regarding General discomfort, Headache, Nausea, and Dizziness were asked before and after each session.

3.4.2 Results and Analysis

The experiment took 2.8 hours in total, with an average of 8 minutes per session ($22.9s$ per trial) and a standard deviation of 0.99 minutes. Fig. 3.9 shows the duration of sessions over time, where we can see that the duration is very stable indeed.

Similar to the results from the first experiment, we noticed low subjective simulation sickness and low effort taken to accomplish the task. The overall results regarding these analyses are discussed in Sec. 3.5.

Based on the answers, we generated a confusion matrix, illustrated in Fig 3.10. Analyzing the results, we obtained an average accuracy = 67.1%, error = 32.8%, precision = 51%, and MCC (Matthews correlation coefficient) = 0.3, indicating that the performance was above the chance level. An MCC of 0.3 means that the stimulus is positively correlated with the perception showing that the user can distinguish weights despite grabbing the objects at different points. As this result, *per se*, does not prove $H2$, we proceed

Figure 3.9: Completion time (in minutes) for each of the 20 sessions of the second experiment. A learning effect is not observed.

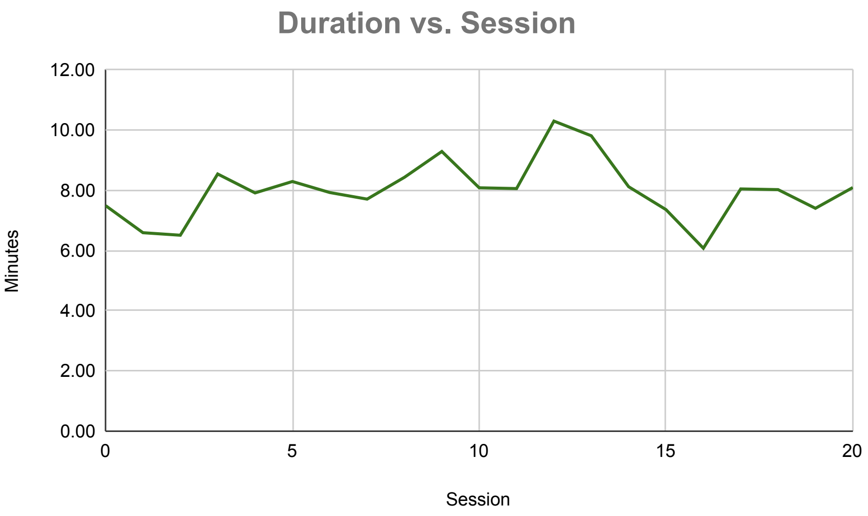
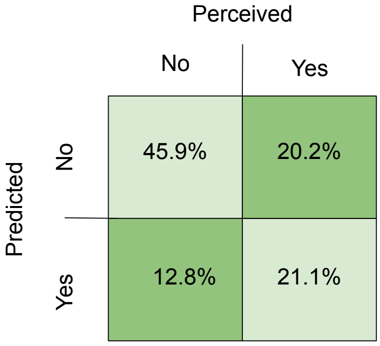


Figure 3.10: Confusion matrix based on the results of the second experiment. The stimulus is positively correlated with the perception with $MCC = 0.3$ and accuracy of 67.1%.



Predicted \ Perceived	No	Yes
No	45.9%	20.2%
Yes	12.8%	21.1%

with the analysis below.

3.4.2.1 Weight difference between paired objects

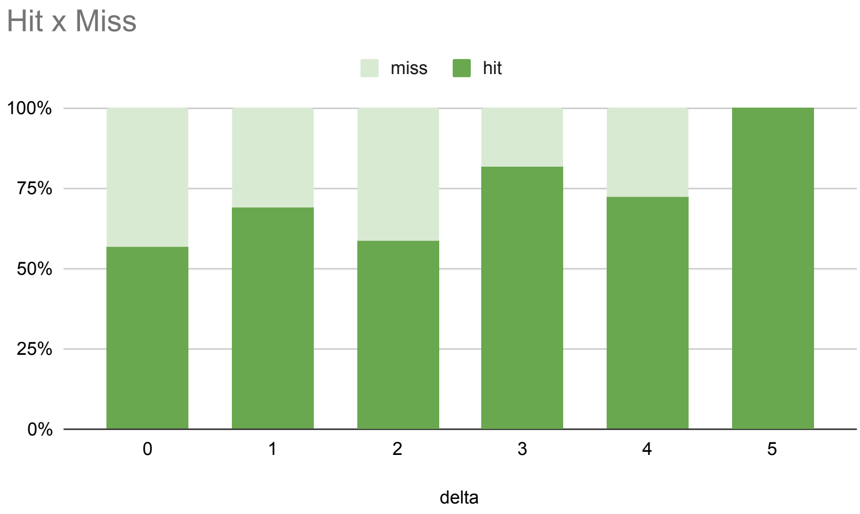
We analyzed the frequency of hits and misses in relation to the difference in weight (Δ_w) within each pair. This analysis is the same we did for pairs of objects in the first experiment. The grouped results are presented in Table 3.2. As in this experiment the weights go from 1 to 6, the number of Δ_w's decreased to 6, generating the groups $\Delta_w = [0, 1, ..., 5]$. The group where $\Delta_w = 0$ is the largest one, and it includes all the pairs with the same weight. Following the pattern from the previous experiment, $\Delta_w = 5$ only contains 20 entries, which come from the trials involving the weights 1 and 6 only.

In Fig. 3.11, we can see that there seems to be an inverse relation between Δ_w and the number of hits, similar to the first experiment. The trend is not as evident as it is in

Table 3.2: Hit and Miss frequencies regarding weight difference (Δ_w) between the objects in the same pair.

Δ_w	**hit**	**miss**	**total**	**hit (%)**
0	68	52	120	56.67%
1	69	31	100	69.00%
2	47	33	80	58.75%
3	49	11	60	81.67%
4	29	11	40	72.50%
5	20	0	20	100.00%

Figure 3.11: Difference between miss and hit when comparing pairs with equal Δ_w. Notice the trend of higher hit-rates when Δ_W increases.



the first experiment, though (compare with Fig. 3.5), revealing a probable influence of the different grabbing points.

3.4.2.2 Analyzing the hits and misses

Even though the confusion matrix and the weight difference analyses above show that different grabbing positions do not impede the user to distinguish weights, they suggest that the grabbing positions have some influence. Then, we proceeded with a more in-depth analysis of the hits and misses. The goal is to find out the main factor causing the 139 wrong answers from the total 420.

We noticed that the grabbing style imposed in the experimental setup favors a torque on the user's forearm, diminishing the influence of the wrist axes. Remember that the Exos device actuates on the flexion/extension and adduction/abduction axes of the wrist only, while the axial pronation/supination motion occurs on the elbow, out of the

Table 3.3: Frequency of hits and misses when comparing the grabbing positions

Grabbing	**Hit**	**Miss**	**Sides**	**Total Hits/Misses per side**
[R0-R1]	18	3	4*equal	4*57/27
[R1-R0]	13	8		
[L1-L0]	13	8		
[L0-L1]	13	8		
[R0-L1]	12	9	8*different	8*98/70
[L0-R1]	11	10		
[R0-L0]	10	11		
[R1-L1]	10	11		
[R1-L0]	12	9		
[L1-R0]	13	8		
[L1-R1]	15	6		
[L0-R0]	15	6		

Exos range. Still, none of these three motions can be easily isolated by the user, which implies that they all contribute to the hand pose and the perceived weight. These contributions seem to vary considerably with the grabbing point due to a lever effect when grabbing a cylinder out of its center of mass. While the user naturally compensates, searching the angle that provides a satisfying weight stimulus, it is arguable that the grabbing points at one half of the cylinder are explored with a fairly different range of angles than the other. Therefore, we looked at the frequency of hits and misses, and calculated the $hit/miss$ ratio for the group of pairs with grabbing points at *equal* sides, and the group of pairs with grabbing points at *different* sides. Table 3.3 shows the number of correct and wrong answers for each pair of grabbing points. R0 and L0 are equivalent to the extreme right and left positions, and R1 and L1 to the mid points right and left points (as seen in Fig. 3.6). The ratios for equal and different sides are respectively 2.11 and 1.4, showing a higher rate of success when the grabbing points are at the same side.

To further analyze this grabbing-side effect on the misses with respect to the levels of weight, we took only the pairs with grabbing points at different sides. Then, we grouped them by the grabbing side of the heavier weight in the pair, excluding the cases where both weights were equal. There were 62 combinations with the *lighter* object grabbed at the right side, and from them, in 58 cases (93%) the answer was wrong. On the other hand, from a total of 58 pairs where the *heavier* object was grabbed on the right, all 58 responses were correct. This strongly indicates that there is a bias towards perceiving more weight when the object's center of mass is to the left of the grabbing point.

3.4.3 Discussion

The analysis of the results summarized in the confusion matrix, suggests that the participant could distinguish the different weights of two objects presented as a pair, even when the grabbing point of each object was different. When we analyzed the number of errors in relation to the weight difference, we found that it decreases with the greater weight differences, similar to what happened in the first experiment, which was expected. However, the error rate is overall higher than in experiment 1. These results confirm H_1, but are not conclusive regarding H_2, as the discrimination seems to be influenced by some factor in this experiment (Sec. 3.4.2.1).

In a further analysis, splitting the trials into groups regarding the side of the grabbing points, and in which side the heavier object is grabbed, the results demonstrated that the objects grabbed by their left side felt lighter than the paired ones. (Sec. 3.4.2.2). As we used an Exos device designed for the right hand, when the cylinder is grabbed at a point on the left, the weight is felt as torque in the supine direction. Opposingly, when the cylinder is grabbed at a point on the right-side, the torque direction is towards the pronated position.

We believe that there are two main aspects regarding this effect: the abduction movement of the wrist is wider to the right than to the left (considering wearing Exos Wrist) and also, as we limited the hand position, when the center of mass was placed to the right side with respect to the thumb, the natural response would also involve the elbow joint rotation, which, in this case, had no stimulus applied on. Even so, the frequency of wrong answers decreased as the Δ_w between the two objects increased. This result indicates that, even in positions that would require more body joints to be stimulated to have a better perception, to a certain degree, the force feedback when applied only on the wrist was enough to allow differentiation between two objects with distinct virtual weights.

This eventually refutes H_2 and indicate that pronating forces on the forearm are better conveyed by the wrist axes than supinning forces. Interaction designers should consider this when designing their environments that use this kind of stimulus.

Table 3.4: Summary of results from both experiments

	First Experiment	Second Experiment	Total
Sessions	33	21	54
Trials per session	15	20	-
Total trials	495	420	915
Hits (%)	54.7%	67.1%	-
Total time (hour)	5.7	2.8	8.5

3.5 Summary of our Findings

As the two experiments measure similar effects, here we present the discussion regarding the common aspects found on the results between them. In Table 3.4 we can see the summary of the results obtained from both experiments. We discuss in more details further on how the second experiment had a simpler task to perform, but this is already reflected here when we compare the number of trials and the total time spent in each experiment.

3.5.1 About the Hypotheses

When we gather the results from the two experiments together, we find that the force-feedback provided on the wrist joint conveys weight information in VR that the user perceives and understands. The stimuli are then comparable to those of the physical world and can function as appropriate surrogates. While the discriminability measured from each experiment differs, it is rather due to the increased cognitive difficulty of the second experiment task. Nevertheless, the results corroborate to confirm H_1, and can conclude that the applied feedback on the wrist is a valid alternative to the rendering of weight in VR environments.

We did not perform a baseline task with virtual objects in the real world for any of the experiments. Doing that could be interesting to emphasize the significance of our findings, as it is known that people have difficulty in discriminating weights precisely, even with all the tactile and proprioceptive senses in place. Furthermore, when the objects are grabbed by points distant to their centers of mass, the task becomes even harder. From the results of our second experiment, we found, nevertheless, that the force-rendering approach based on the wrist conveys sufficient information to distinguish weights even in that case. We noticed, however, that the different grabbing points do influence the results, especially biasing the subjective perception due to the design of the device in combination with the arm's biomechanics, thus refuting H_2. With this knowledge, interaction designers can think about alternatives to avoid or to mitigate the bias.

3.5.2 Duration

The total time taken to perform the experiments was 8.6 hours, and the sessions were distributed over 17 days (10 days for the first experiment, and 7 for the second one). Observing the same participant over time, we could notice that there was no significant change on the results among the sessions performed in different periods of the day or regarding the number of sessions performed on the same day. Moreover, the performance regarding errors did not improve over time.

3.5.3 Discomfort and Workload

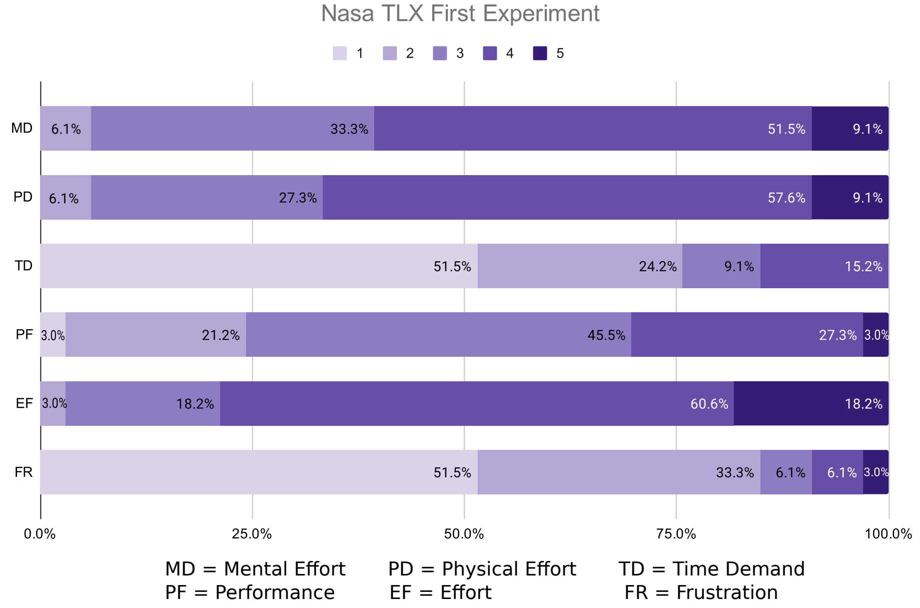
The experience of performing the study with just one participant also brought some aspects that can be discussed.

We applied an SSQ-based, which can be found in Appendix A, questionnaire to check for cybersickness effects, but none was observed. Since the participant was experienced in VR, and we set the device force in a range that was considered safe, we did not expect different results. Regarding the influence of the device on the participant's body, further analyses could be done with an ergonomic study to observe different movement patterns and how they relate to the workload.

As for how demanding the sessions were, we base our analyses on the Raw NASA TLX questionnaire, applied after the sessions in both experiments, using a scale from 1 to 5 for each factor. Even though having just one participant is not enough to extend these results to a standard behavior, we thought it would be interesting to check the scores. The questionnaire is also in Appendix A. Figs. 3.12 and 3.13 show the scores for the categories in each experiment.

Mental and Physical demands were high, which could indicate engagement in doing the task. The goal was to perform the task as accurately as possible, regardless of the time taken. Thus, Temporal Demand was low in both experiments, which can be attributed to the absence of time constraints during the trials. Performance results were

Figure 3.12: Overview of NASA TLX answers from the first experiment



also above the average, since the number of correct answers were overall higher than the wrong ones. Effort and Frustration were higher in the first experiment, and this can be explained by the number of objects that were manipulated in each trial. Ordering four different objects is more complex than just choosing between two, and these results suggest that the first experiment was slightly more difficult than the second one for the participant, even if the discrimination is more error-prone when different grabbing points are used.

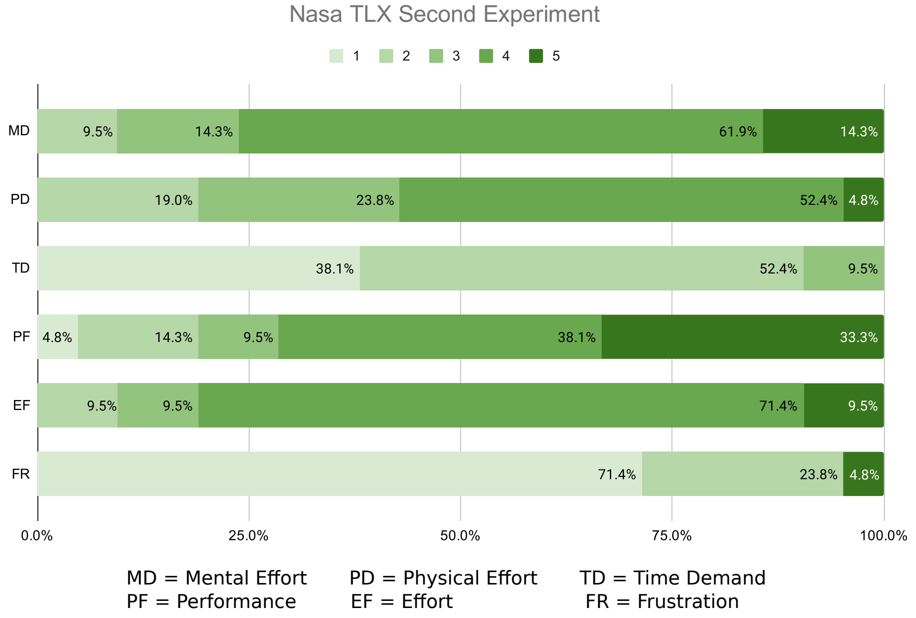
3.6 Final comments

Considering that the only participant of this study was also part of the development process, we can highlight some of the main comments from her personal experience, both as user and as researcher.

3.6.1 From the researcher point of view

As researchers, it can be very interesting to actually be on the other side of the study. When we develop a user application and test it, we always have to look for flaws and things that could be improved in order to deliver a better experience. This role is very important, but we end up not really experiencing what the users will. In other fields, self-

Figure 3.13: Overview of NASA TLX answers from the second experiment



experiments are more common, but it all depends on the conditions. Testing immersive applications usually requires a considerably space and expensive equipment. Regarding the conditions we are studying, there is also the fact that we know what hypotheses we want to test, so a lot of attention has to be put on trying to trick ourselves. This model cannot be adapted to all scenarios, but it is something that can be considered for some setups. Other variables could also be explored in future work, like the shape and color of the objects, as they would probably influence the perception. As we wanted to make sure we were testing all the possible combinations of comparison in both experiments, adding another variable would increase the number of repetitions in an exponential way, which was not feasible for us in this study.

3.6.2 From the subject point of view

When we show our application to people who did not try it, the main question we receive is: *does it feel realistic?* The answer is complicated, since *realistic* depends on each person's perception, but we can say that, for the participant, the experience felt real, and that this is mainly due to the integration with the visual stimuli. Only getting the force feedback, without seeing the object, does not make much sense in terms of weight sensation, but when both stimuli are coupled then it feels like something real is being held.

When playing the participant role, it is possible to forget about the possible problems that can occur within the experiment environment and actually experience it. We believe that knowing that the results would be used in the analysis helped the shifting process from researcher to participant role.

This is something that can contribute even to studies where the researcher is not taking part of the evaluation; trying to put yourself in the participants' shoes can help realize aspects that are not obvious from the technical point of view.

4 CONCLUSION

We proposed a method based on two experimental approaches for evaluating the weight perception of virtual objects applying force-feedback on the wrist only, using a wearable device to render the stimuli.

4.1 Main contribution

The results demonstrated that the stimulus on the wrist influences the weight perception of virtual objects in an immersive environment and that such influence reflects the human perception of real props. Even though other aspects would be required to provide a fully immersive experience, we came up with evidence that the stimulus applied to the last joint of the arm chain is already capable of influencing the weight perception.

Regarding the design of the experiments, we also demonstrated that, when taking the necessary precautions, increasing repetitions, and randomizing the variables, it is possible to perform a single-participant experiment and obtain statistically significant results that are comparable to other studies. This is especially important when dealing with hard constraints to experimental research, such as during the ongoing Sars-Cov2 pandemic.

4.2 Limitations

Our main limitation in the analysis was the insufficient number of answers for some specific cases, for instance when the weight difference between two objects was the same, so to overcome it more trials would be necessary. Another important point us that in the current experiments, we did not relate the weight value of the virtual prop with a real-world measure, e.g., in kilograms. To do that, we would have to either perform a study with multiple users, comparing real weights with the device stimuli, or understand the process of conversion that the device's development kit does by itself. Even without this equivalence, our comparison was relative to values within a numeric scale, which increased and decreased according to the feedback given to the participant. Observing the results, we found similar trends to those found in the literature of weight perception with physical objects.

4.3 Future Work

An extension of this work could include tests involving a wider range of weight values, and weight differences between the objects. It would also be interesting to study the weight difference between the objects to analyse the Just Noticeable Difference value in a certain range and compare it to the perception in real weights.

Following the design for a user study we proposed in Chapter 2, other further analysis could involve the concomitant use of the wearable wrist device and real props, to assess the possibility of modifying the perception of the real weight, and to analyse the psychometric functions obtained.

We also explained that our motivation for this study came from balance applications, and now that we understand better how the body interprets the force feedback on the wrist as the weight of virtual objects, a future study involving balance applications could take advantage of our findings.

Another aspect worth mentioning is the fact that the feedback provided by Exos Wrist was interpreted as weight because the experiments' scenarios were designed with this purpose. It might be the case that it is possible to simulate the same effect with other types of haptic feedback, like vibrotactile. Further studies could explore this possibility.

5 RESUMO EXPANDIDO

5.1 Introdução

Esse trabalho explora a renderização de um estimulo háptico de força no punho, através de um dispositivo vestível, com a intenção de influenciar a percepção de peso de objetos em ambientes de realidade virtual. Nossa motivação para essa avaliação vem de tarefas que envolvem habilidades de equilíbrio de objetos. A percepção de peso dos objetos é um fator relevante nesse tipo de tarefa, pois sua variabilidade pode afetar diretamente o desempenho do usuário.

A avaliação da eficácia da técnica é feita através de dois tipos de experimentos que, de maneiras diferentes, buscam avaliar se é possível simular a percepção de peso usando o estímulo háptico de retorno de força. Nesse trabalho nós consideramos apenas um participante para ambos os experimentos, o que também é uma contribuição para futuros trabalhos que tenham limitações no número de usuários disponíveis.

5.2 Método de Avaliação

Para avaliar a capacidade do feedback de força com relação à simulação de peso, propomos o design de um experimento onde o estímulo háptico é usado para alterar a percepção de peso de objetos físicos. Além do design proposto, também apresentamos e implementamos dois experimentos diferentes que simulam o peso de objetos totalmente virtuais. O primeiro consiste em ordenar quatro objetos visualmente iguais, que diferem somente no peso virtual. A tarefa dada ao usuário é ordená-los do mais leve ao mais pesado, sempre segurando o objeto pelo seu centro de massa. No segunto experimento, a tarefa dada é comparar dois objetos diferentes, um de cada vez, segurando-os em diferentes pontos com relação ao centro de massa. Com os resultados obtidos a partir das respostas das duas tarefas buscamos:

- Avaliar se o feedback pode simular a percepção de peso em objetos virtuais
- Verificar se existe alguma diferença entre os pontos de pegada dos objetos em relação à percepção de peso.

5.2.1 Ordenando objetos com base em seu peso

O primeiro experimento foi divido em 33 seções de teste, que foram realizadas ao longo de 10 dias. Em cada seção o participante ordenou 4 objetos 15 vezes, gerando um total de 495 ordenações. Cada seção durou em média 10 minutos. No total temos 12 pesos diferentes, onde a cada ordenação 4 deles eram selecionados de maneira aleatória. Testamos todas as combinações possíveis de 4 objetos entre os 12 da lista.

5.2.2 Comparando dois objetos com diferentes pontos de pegada

No segundo experimento a tarefa proposta é a comparação entre dois objetos também visualmente iguais, mas com pesos diferentes. Dessa vez reduzimos o número de objetos analisados em cada seção e variamos a posição na qual o objeto é segurado em relação ao seu centro de massa. Com a redução do número de objetos pela metade, também reduzimos o número de objetos na lista para 6 pesos distintos. Em cada seção 20 combinações de diferentes posições foram apresentadas, e 21 seções de testes foram realizadas. No total obtivemos 420 respostas do usuário.

5.2.3 Resultados

Com base nas análises das respostas obtidas dos dois experimentos, agrupamos os resultados e observamos dois pontos principais. Ao olhar a diferença de peso entre dois objetos, constamos que quanto maior essa diferença é, mais acertos foram obtidos. Também observamos que o discernimento entre dois objetos de pesos menores é mais preciso do que quando os pesos aumentam, mantendo a mesma diferença de peso entre os dois. Esse resultado é o mesmo observado na percepção de pesos reais.

Também foi possível constatar que diferentes pontos de pegada em relação ao centro de massa alteram a percepção de peso. Isso provavelmente se deve ao fato de que, como a percepção de peso é um processo complexo que contempla todo o corpo, o estímulo aplicado apenas ao punho não é suficiente para simular uma experiência realistica completa.

5.3 Considerações Finais

Pelos resultados obtidos, conseguimos concluir que, dentro do intervalo de peso dos objetos testados, foi possível ter resultados similares de percepção de peso em relação ao que é tido com a percepção de objetos reais. Também concluimos que o ponto de pegada dos objetos é um fator importante a ser observado quando o estímulo de força é aplicado somente no punho. Com os resultados observados, podemos usar o feedback de força aplicado ao punho sabendo que o comportamento é similar a percepção de pesos reais, dentro das limitações dos dispositivos. Aplicações futuras podem envolver simulações, aplicações médicas e outros tipos de aplicações envolvendo equilibrio.

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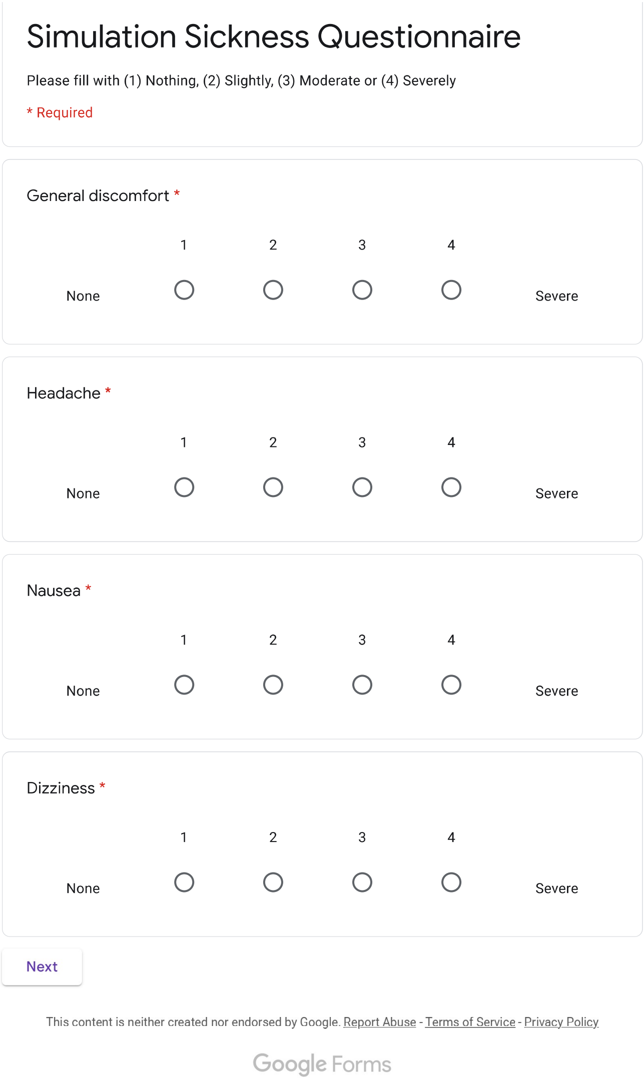
APPENDIX A — QUESTIONNAIRES



Simulation Sickness Questionnaire

Please fill with (1) Nothing, (2) Slightly, (3) Moderate or (4) Severely

* Required

General discomfort *

	1	2	3	4	
None	○	○	○	○	Severe

Headache *

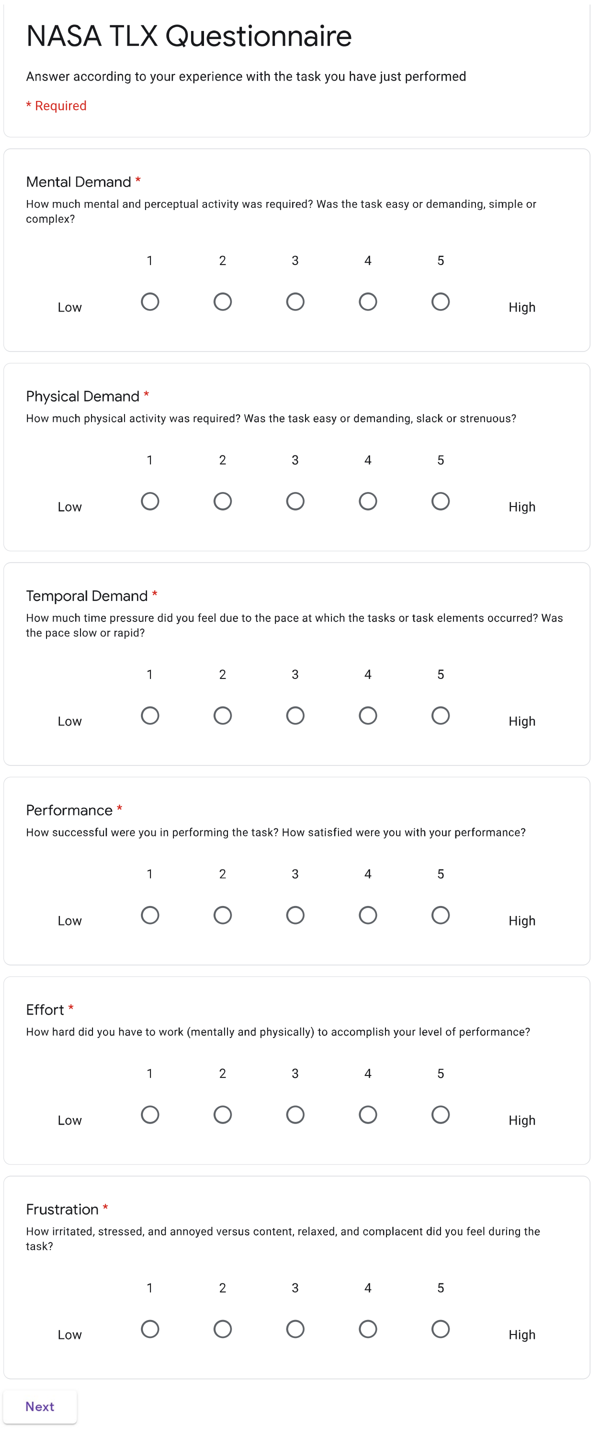
	1	2	3	4	
None	○	○	○	○	Severe

Nausea *

	1	2	3	4	
None	○	○	○	○	Severe

Dizziness *

	1	2	3	4	
None	○	○	○	○	Severe



NASA TLX Questionnaire

Answer according to your experience with the task you have just performed

* Required

Mental Demand *

How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?

	1	2	3	4	5	
Low	○	○	○	○	○	High

Physical Demand *

How much physical activity was required? Was the task easy or demanding, slack or strenuous?

	1	2	3	4	5	
Low	○	○	○	○	○	High

Temporal Demand *

How much time pressure did you feel due to the pace at which the tasks or task elements occurred? Was the pace slow or rapid?

	1	2	3	4	5	
Low	○	○	○	○	○	High

Performance *

How successful were you in performing the task? How satisfied were you with your performance?

	1	2	3	4	5	
Low	○	○	○	○	○	High

Effort *

How hard did you have to work (mentally and physically) to accomplish your level of performance?

	1	2	3	4	5	
Low	○	○	○	○	○	High

Frustration *

How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?

	1	2	3	4	5	
Low	○	○	○	○	○	High