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TG2: Ungrounded Weight Feedback in Virtual Reality Using Pendular Mechanical Actuation

Work presented in partial fulfillment of the requirements for the degree of Bachelor in Computer Engineering

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ABSTRACT

In this work, we introduce a new type of handheld haptic device capable of rendering forces by shifting a mass element on a hemisphere around the hand. The technique exploits gravity to recreate torque at the wrist, which generates the illusion of weight. With virtual reality becoming more popular, new ideas to increase the immersion in these environments start appearing. Devices capable of haptic feedback are being developed with different approaches to the same problem, generating force in the real world that increases immersion in a virtual world. Instead of using the traditional approach of a grounded mechanical actuated device, we used a lightweight 3D printed handheld device that utilizes an inverted pendulum driven by mechanical actuators to convey perception of different weights in VR as the user grabs virtual objects. To evaluate the quality of the stimulus provided, we designed a psycho-physical study composed of two tasks that consist of the user interacting with objects in a virtual environment. The first one was ordering a set of four cubes by weight, from lightest to heaviest. The second task was matching the weight of two bars with different densities by controlling their length and radius. We found that the stimulus allows to discriminate different weights that the response time is shorter as the weight difference between objects increases. We also found statistically significant differences in precision and response time between a pair of lightweight objects and a pair of heavyweight ones. Qualitatively, the users identify the stimulus as weight in most cases.

Keywords: Haptic. Mechanical actuation. 3D Printed Prop.

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1 INTRODUCTION

Virtual Reality (VR) head-mounted displays (HMD) evolved significantly in the last decade in such a way that visual and auditory immersion is now practically accomplished. Although the senses of sight and hearing are dominant for many human applications, the absence of an appropriate touch display for VR still hinders its effectiveness for several other applications.

While haptic displays have existed for decades, their use in VR is undermined by several factors. Successful force displays, such as phantom devices, haptic workbenches, exoskeletons, and alike, must be attached to the ground to counteract the user's physical action. They act on the proprioception part of the human haptics. However, their surface of action is restricted to the area around the ground attachment, limiting a VR user that needs to move around naturally. Besides force-displays, haptics also includes cutaneous displays. These, in turn, render vibrations, skin deformation (shear-force), heat, and so on. They convey important information through touch but cannot cause impulses on the user's limbs like the force displays. Finally, pseudo-haptic techniques combine visual illusions, body-mounted force actuators, vibrotactile actuators or external props to convey touch and force information.

We will review some of these approaches in Chapter 2, but, in summary, while force displays lack mobility, cutaneous displays lack the ability to counteract body actions. To circumvent such limitations, an ungrounded handheld or wearable haptic device must be able to produce thrust, similar to in-space rocket thrusters used to maneuver spacecrafts. Some approaches have been tried, which we illustrate with two examples: Shifty (ZENNER; KRÜGER, 2017) and Thor's Hammer (HEO et al., 2018) (see Fig. 2.1). The former shifts a weight position inside a long cylinder to convey changes in the weight of a virtual object being held. The latter uses a set of propellers within a handheld artifact to accelerate it in any direction.

In this work, we propose a new approach to apply forces on the user's hand that explores gravity, similarly to *Shifty*, but produces forces in different directions, similarly to *Thor's Hammer*. Moreover, by design, our approach gives faster responses than both previous works, enabling more dynamic interactions that are more applicable in VR. The concept of our device is based on a pendulum. The pendulum consists of a mass element attached to a rigid shaft that is rotated in two degrees of freedom by motors. The motor set is grounded on the user's hand, in such a way that each pose of the pendulum causes a different torque on the wrist joint and all the other joints in the human body hierarchy. While the total mass of the device does not change, the perceived weight may change according to the angles set to the pendulum. The design and development of the device and technique are described in Chapter 3.

The proposed device has the potential for several applications in VR where rotational impulses are needed, for example, games, applications where the user must be guided through a map or even a data visualization where an additional dimension is mapped to haptics. Such impulses are generated by the momentum of the moving mass at its tip when the pendulum is in acceleration (positive or negative). Nevertheless, when the pendulum is static at a given angular pose, gravity pull generates a constant torque.

Our central hypothesis for the use of this device is that it is able to inform the user about the weight of a virtual object being held. To assess the effectiveness of the approach as a means to convey weight information, we conducted two user experiments with a sample size of 9 (Chapter 4). The users were challenged to compare objects weights in Experiment 1 (Chapter 5), and to modify the weight of an object to mach a reference in Experiment 2 (Chapter 6). We discuss our contributions both in terms of the novel design and the experimental findings in Chapter 7 and conclude our work in Chapter 8.

2 RELATED WORK

The area of haptics in interactive systems is vast. It can be analyzed from different perspectives, and it is not in the interest of this work to provide a complete review. In the previous chapter we brought the understanding that some systems stimulate the cutaneous sensors while others stimulate human proprioception sensors in joints and muscles. In computer haptics we often denominate them tactile feedback and force-feedback respectively. Eventually, all haptic sensory information is processed in the somatosensory cortex in humans, integrating all these inputs plus visual aspects among other influences. Even the color and the temperature of objects affect how humans perceive the touch stimuli. Specifically for the study of weight perception, we expand the classification, organizing the types of haptic interaction into three categories:

- **Direct haptics** when actual forces and weights are rendered to the proprioceptive system
- **Indirect haptics** when tactile feedback is used to convey weight or force intensities (vibrotactile, skin-stretch)
- **Pseudo-haptics** when auditory or visual feedback replaces haptic stimuli in conveying touch information

While any of the haptic categories is able to convey weight information in a way or another, we leave the discussion on pseudo-haptics and indirect-haptics out of the scope of this work.

Numerous devices exist that are used to generate forces to provide users with weight perception. They essentially use mechanical actuators to transfer forces to human limbs. They range from grounded exoskeletons to stylus-based to hand-attached devices. Phantom-style devices (MASSIE; SALISBURY et al., 1994) with multiple degrees of freedom provide great force feedback, although the user must use the device near a fixed surface like a table. Grounded exoskeletons (Carignan; Tang; Roderick, 2009) can provide force feedback stimuli to the user's whole body. However, the device size hinders mobility and could create discomfort since it surrounds the whole limb.

With the evolution of VR, users no longer need and seldom want to be stationary when immerse in Virtual Environments. Thus, static grounded force devices are not really satisfactory as weight inducing peripherals, and researchers have been in the quest for a method to provide meaningful weight information for virtual objects in VR that is not attached to a static substrate. Here we review representative previous approaches before presenting our own technique.

Ungrounded direct force feedback approaches rely either on handheld or wearable devices. Wearable devices are actually body-grounded, as they are attached to a body part so that they can apply a force on another body part further down in the skeletal hierarchy. Most of the literature is focused on finger-attached actuators (SCHORR; OKAMURA, 2017; MAISTO et al., 2017). These are especially effective for grasping and to perceive stiffness. Other often favored attachment parts are around the wrist (SKORINA; LUO; ONAL, 2018), on the palm (TRINITATOVA; TSETSERUKOU, 2019; KOVACS et al., 2020), at the head (TEO et al., 2020), and the joints (GÜNTHER et al., 2019). Some of these interfaces have been used to convey weight (CHOI et al., 2017). An especially limiting aspect of wearable force devices is that they do not transfer force beyond the closed loop between the two attachment points.

Haptic interfaces based on handheld devices, also called prop-based interfaces, are created with the idea that changing the prop shape or weight, the haptic feedback would also change. They explore alternatives such as a mass shifting mechanical apparatus (ZENNER; KRÜGER, 2017), modulated air resistance or propellers (HEO et al., 2018; JE et al., 2019; JE et al., 2018; SASAKI et al., 2018), inertia (WINFREE et al., 2009), or apply a shear force on the skin where the device is held (SUCHOSKI et al., 2016; BEEK et al., 2020; CHOI et al., 2017) to pass the weight information. Skin stretching devices could be categorized as pseudo-haptics, but as they apply actual forces we decided to include them here. Some of these devices are even placed away from the hand, on the skin near joints or muscle locations, to modify the perception of dummy props that are handheld (BARK et al., 2009).

Figure 2.1 – Two illustrative related works: Shifty (ZENNER; KRÜGER, 2017) and Thor's Hammer (HEO et al., 2018) (pending permission).

Source: ZENNER; KRÜGER and HEO et al

In this overview of related works, we highlight two strategies to which our proposed technique represents an alternative. The first is the Thor's Hammer (HEO et al., 2018). It consists of using a cube-shaped handheld optically tracked device that uses propeller propulsion to generate three degrees of freedom force feedback. It has six motors and propellers that generate thrusts of air in controlled arbitrary directions that push and pull the user's hand around in 3 degrees of freedom, producing actual forces up to 4 N. These forces can be used to modulate the perception of weight among other stimuli. The authors illustrated the use of the device in several VR scenarios including walking a lamb by the leash, pushing buttons and feeling different weights with enhanced immersion. However, several limitations affect the applicability of the technique, such as high latency, the ability to render only slowly changing feedback, fatigue due to the heavy elements, among others.

The second technique we want to highlight and most related to our own is Shifty (ZENNER; KRÜGER, 2017). It consists of a tube-like device where a mass inside it moves in one axis. The user holds the device by one extremity, like a bat. The mass is displaced by a motor assisted by two pulleys. When the distance of the mass to the hand increases, an increased lever effect can be perceived as an increase of the virtual object's length, thickness or weight, depending on the visual feedback provided. Shifty was tested using specifically the length change and thickness change scenarios. The dynamic change of weight perception was a side effect, as the authors were interested in the static matching between visual and haptic feedbacks. To mitigate the visual-haptic mismatch when the mass was (slowly) moved between condition, the authors used progress bars, transparency, scaling and a magic smoke.

Although several of the devices and techniques reviewed here modify the perception of weight and potentially increase immersion for VR, they rely on cumbersome setups to provide actual force, or on illusions that require a mapping effort from the user. Our method detailed in Chapter 3, instead, stimulates cutaneous and proprioceptive sensors in muscles and joints of the whole biomechanical chain, from the hand to the toes, to build weight perception. Besides, our experimental evaluation focused on weight discrimination, both with visually equal objects of varying weights and equal weighted objects with varying shapes.

3 THE HAPTIC PENDULUM DEVICE

3.1 Concept

After studying the literature on weight perception in VR (Chapter 2), we came up with a list of requisites that would mitigate previous limitations:

- lightweight
- mounted on the VR controller
- capable of inducing both cutaneous and proprioceptive weight cues

These requisites pushed the design towards a mass shifting device type. We soon observed that people pick up physical objects at points on their surfaces, very often away from their centers-of-mass. We then realized that any object picked-up in that way will cause a torque on the immediate user's joints that is a feeling as expected as the actual weight of the object. We finally concluded that such torques will propagate throughout the body as far as the contact of the body with the solid ground, and will participate in the formation of a mental idea of weight.

To control torque induced by an ungrounded handheld device we propose to use the effect of gravity on a mass element that is mechanically displaced to different distances from the center of the hand. When the mass is at the center of the hand, the torque is zero, and as it moves away on the plane parallel to the ground, the torque around the axis orthogonal to the gravity vector and the mass location vector increases proportionally.

Displacing a mass quickly around the hand to different distances may require complex hardware. However, as gravity can be assumed to be the same at different altitudes, we can use a mass at any altitude and consider its projection on the plane parallel to the ground for any effects. This allowed us to simplify the mechanical actuation to a mass attached to a pendulum with fixed radius. The mass will move on the surface of a hemisphere as the pendulum is controlled with two angles.

Our design converged to an inverted pendulum (Fig. 3.1) that can be mounted on top of an HTC VIVE[1] controller. Motors can be used to displace the center of mass of the ensemble, which consequently modify the torque it applies to the user's hand, creating the perception of a heavier or lighter object being held. Although, the inverted pendulum could have three degrees of freedom, the mass moving up and down on its arm

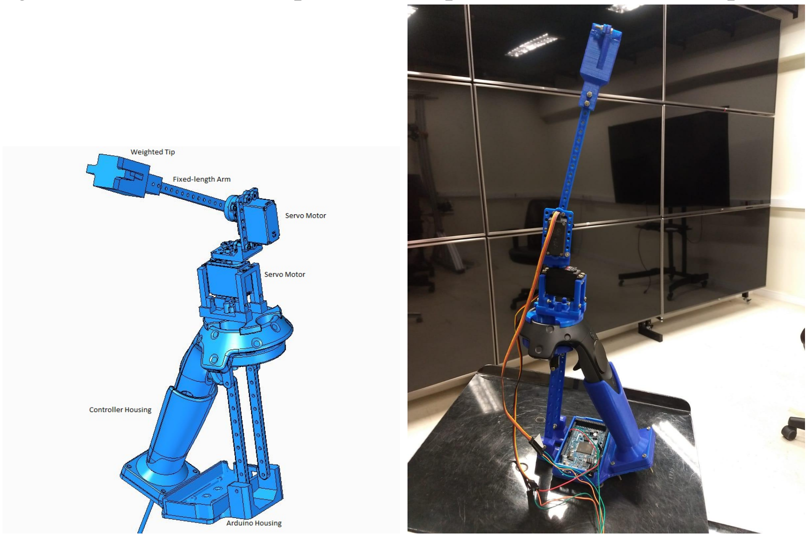
[1] https://www.vive.com/us/

being the third one, to simplify the device we opted for the mass being fixed at the tip of the pendulum's arm, leaving only two degrees of freedom. This simplification can be compensated with an appropriate computation of the inclination angles.

3.2 Hardware implementation

The device is a fixed length inverted pendulum with a stiff arm. We 3D printed the components needed to assemble the shell of the inverted pendulum as seen in Fig. 3.1.

Figure 3.1 – The inverted pendulum haptic device and finished product.

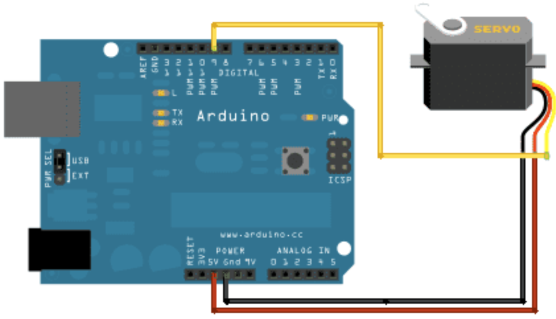


We control the position of the mass on a hemisphere using two 180-degrees servo motors controlled by an Arduino Due[2] board. Specifically, the motors are controlled using Arduino's PWM (circuit shown in Fig. 3.2). The two servo-motors demanded more current (1A-1.8A) than the Arduino could provide (800mA) if both were working at the same time. Therefore we opted for a 5.1V external power supply with a current of 2.1A. The servo motors have three wires: power, ground and signal. Both power wires were soldered to the 5.1V external power supply, the ground wires were also soldered to the ground of the power supply as well as connected with a jumper to the Arduino's ground pin. The signal wires were connected to pin 3 and 5 on the board, since these were the chosen PWM pins to relay the information to the motors.

With this design, we can control the mass relative position to maximize the user's perception of different weights being held in virtual reality.

[2] https://www.arduino.cc/

Figure 3.2 – Motor circuit

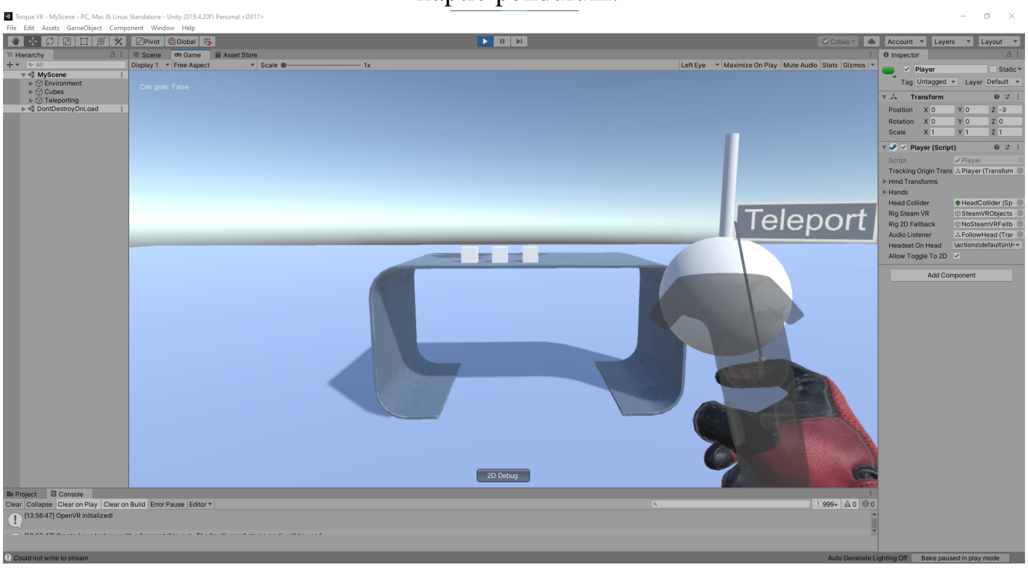


3.3 Virtual environment and angles computation

We used Unity[3] engine to create the virtual environment where we induce weight perception in the user holding virtual objects. Unity has an integration with SteamVR[4], which allows using the HMD and the controllers we need to attach the haptic device.

In the virtual environment, the user controls a virtual hand with the controller. For a quick feedback during development, and to make it easier to explain, the haptic pendulum was depicted as a sphere and a cylinder on top of it in the virtual environment, as shown in Fig. 3.3. That depiction represents how our physical inverted pendulum looks like in its current pose. Notice that it was removed later for the evaluation with users.

Figure 3.3 – Virtual environment showing the user's hand and the virtual representation of the haptic pendulum.

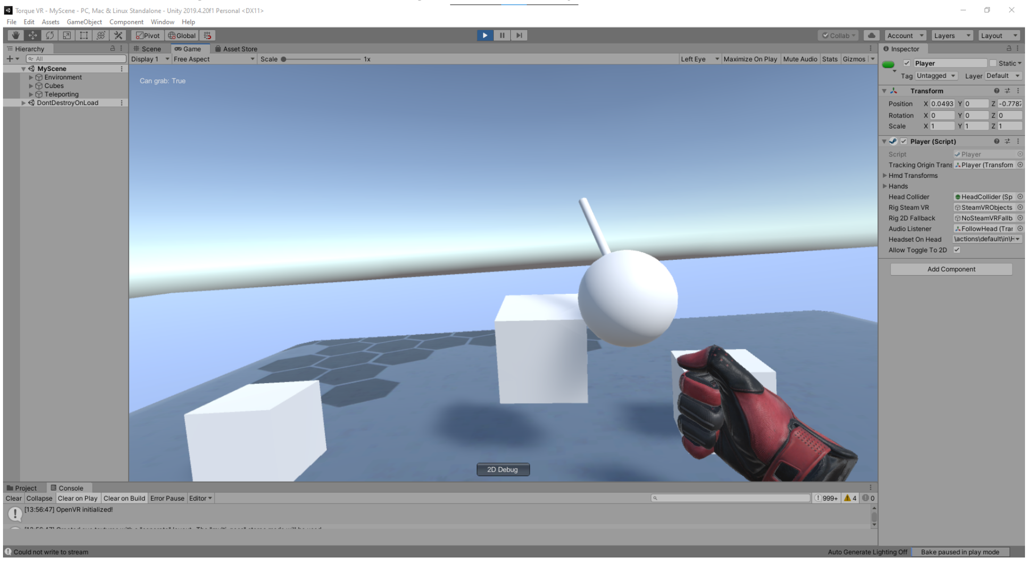


While no object is being held, the inverted pendulum is pointing upwards, which is its neutral position regardless of the user's hand position and rotation. The system

[3]https://unity.com/
[4]https://store.steampowered.com/app/250820/SteamVR/

keeps the pendulum vertical to avoid undesirable torques. The pendulum is activated whenever the user grabs an object. This is done by touching the virtual object with the hand while pressing a button on the controller. Fig. 3.4 shows the user holding an object. The pendulum moves to the angles corresponding to that object's weight. It will induce a maximum torque when its arm points horizontally (90° from the vertical). Thus, we set that angle to the maximum weight of an object in the scene. Lighter objects will generate smaller angles.

Figure 3.4 – Grabbing a virtual object with the virtual hand.



To control the servo-motors that should rotate the inverted pendulum to produce torque, we perform a series of angle computations as follows:

1. The contact point between the hand and the object is used to compute the distance between the hand and the center-of-mass of the virtual object (Eq. 3.1). After calculating the distance vector, we normalized it, since for the time being we only need its direction in the 3D space.

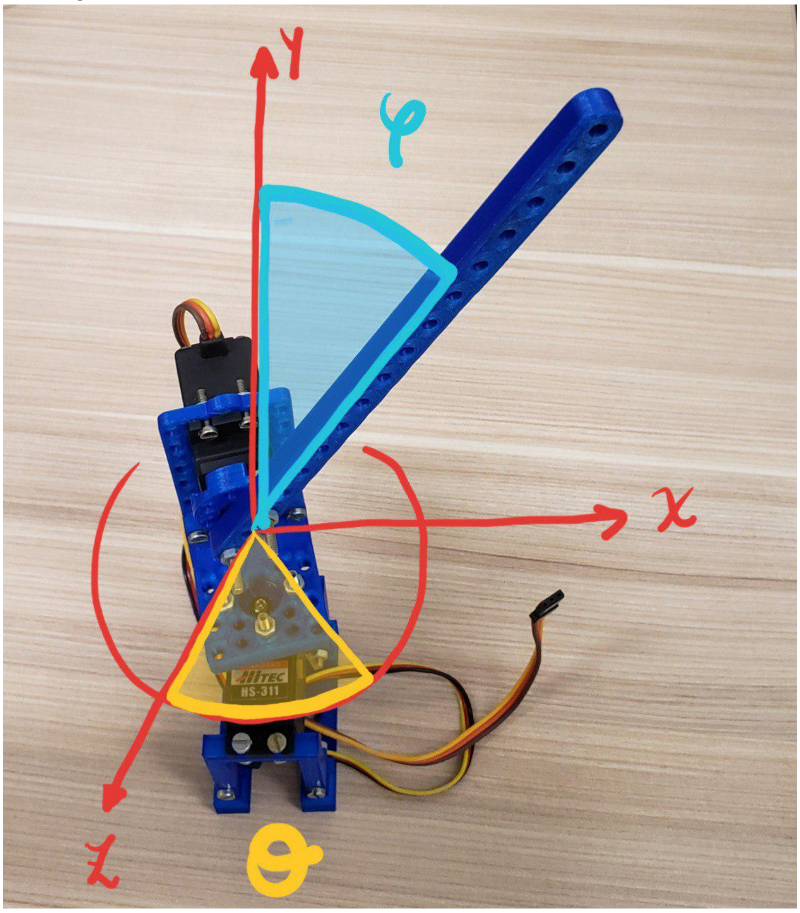
$$distNorm = \frac{objectCenter - contactPoint}{|objectCenter - contactPoint|} \tag{3.1}$$

2. At this moment, the distance vector has a magnitude of 1 after being normalized, and we still have to map the weight in relation to the maximum allowed. The new distance vector will have a magnitude equal to one if the object's weight is the heaviest one, or less than one otherwise (Eq. 3.2).

$$dist = distNorm * \frac{objectWeight}{maxWeight} \tag{3.2}$$

3. We need two angles to move the inverted pendulum tip to the designated location, θ and φ, as seen in Fig. 3.5. The first angle to be determined is θ, which is the angle in the plane parallel to the ground considering the world coordinate system.

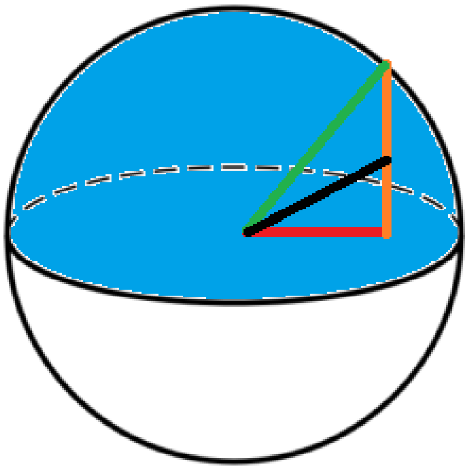
Figure 3.5 – Angles needed to control the servo motors and move the inverted pendulum



4. Since our pendulum can only move its tip on the surface of a hemisphere, distance vectors with magnitude less than one will end inside the hemisphere as seen in black in Fig. 3.6. This cannot be obtained in our device, so we use its projection onto the XZ plane, as seen in red and, with the sphere equation, we find the point on the sphere based on the height shown in orange in Fig. 3.6. With this new y, we create a new distance vector, shown in green in Fig. 3.6, and compute the angle φ.
5. We send Arduino both angles using its serial port. We opted for this approach since it is simple to implement, and the latency is minimal.

As already said, we keep the pendulum vertical when the user is not holding any object. The inverted pendulum always has a mass on its tip, and when it is pointing upwards, its torque is minimum. We wish to keep this mass pointing upwards regardless of how the user is holding the controller when no objects are being held. So, using the

Figure 3.6 – Computing the angle φ when the distance vector is smaller than one as seen in black. The new vector used, seen in green, is computed by the projection on the plane XZ, in red, and the sphere equation.



world up vector for reference, since it is the direction we wish to stay aligned with, we transform it from world coordinates to local coordinates. We normalize the vector and find φ and θ using Equations 3.3 and 3.4.

$$\varphi = \arccos y \tag{3.3}$$

$$\theta = \arctan -\frac{x}{z} \tag{3.4}$$

We use $-\frac{x}{z}$ because Unity uses a left handed coordinate system.

4 EVALUATION - OVERVIEW

To assess the use of our haptic device in providing weight perception, we created scenes using simple objects, 3D forms like cubes and bars, with different weights. The scene is composed of tables with objects on top of it. Each table has a set of interactive objects that can be manipulated. Fig. 5.1 and Fig. 6.1 show examples.

The next two chapters describe the two experiments that were conducted to evaluate our method. The target population was recruited on campus and was composed of 9 subjects (7 male, 2 female; average age of 25.8, ranging from 23 to 31). All of them gave their informed consent. Each subject performed the two experiments mentioned below using their right hand throughout the study.

The experiment was carried out in a 4 x 4 meters room. Although the users did not need to walk, they were aware of the space where they were immersed. After agreeing to participate, the users received a brief description of the environment and tasks. The instructions of using the handheld device were also given at this time.

A well-being questionnaire was applied pre- and post-study, as well as a subjective evaluation post-study. Before starting the experiments, we disabled the pendulum that can be displayed in VR, as this would coerce the users to rely on sight and not on perceiving the weights to realize each task. Each user received headphones that constantly reproduce the sound of pink noise to isolate noise from the servo motor gears.

To avoid the spread of COVID-19, all those involved wore a respiratory mask throughout the experiments, which took approximately 30 minutes, maintaining the appropriate distance between the examiner and the current participant. Additionally, the ventilation of the room was periodically activated and the hardware used was previously disinfected.

5 FIRST EXPERIMENT - ORDERING OBJECTS BY WEIGHT

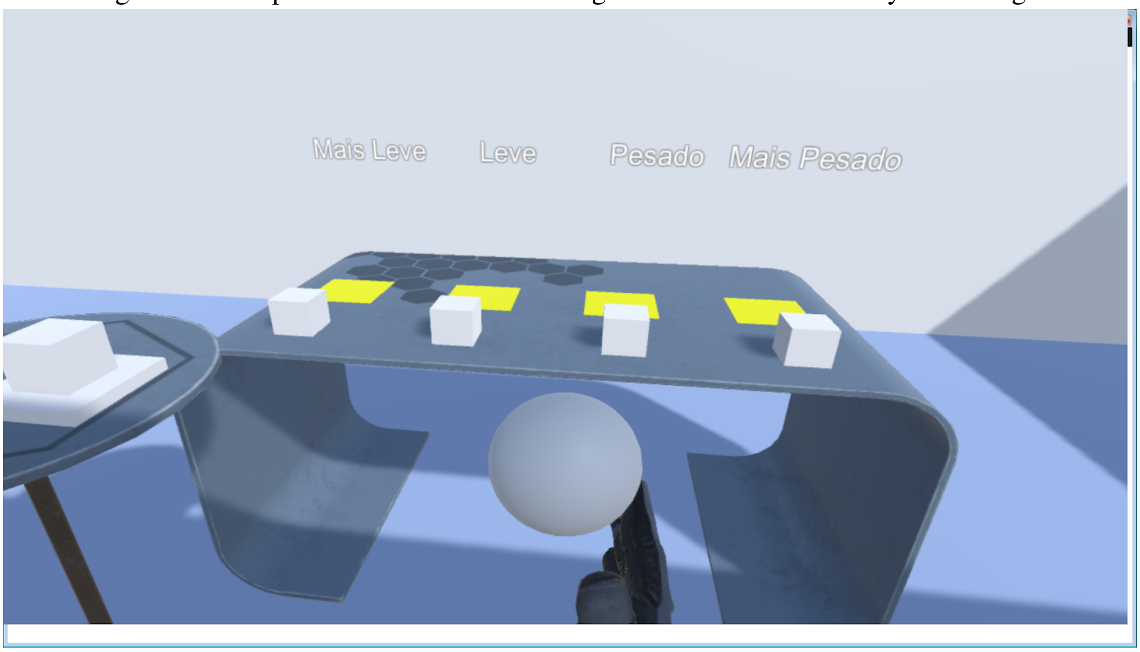
The objective of this experiment was to determine the validity of discrimination between a group of four different weights and to find a range of weights where the device had better psycho-physical results.

5.1 Experiment Design and Procedure

The users started with a training session where they explored the virtual environment holding the device, reporting their comfort with the handheld device and VR experience. With this, the subject learned to properly hold the device, grasp a cube in the virtual environment, and finish the task, thus ending the training session.

During the first estimation session, the subject experienced a virtual environment composed of a table with four cubes on top of it, four platforms on the table with their respective target label (lighter, light, heavy and heavier) and a confirmation button by the side of the table as seen on Fig. 5.1. All cubes share the same dimensions and material, but each one had a different mass. The user was then asked to place them on four yellow platforms, those being the slots the user must place each cube according to their weight, from lightest to heaviest.

Figure 5.1 – Experiment 1 scenario showing the cubes to be sorted by their weight



The masses of the cubes used range from 0.5 to 4.0 units with a step of 0.5, totaling

8 different weights. Using the combination Eq. 5.1 with n = 8 and r = 4, we have 70 arrangements without repetition.

$$C = \frac{n!}{r!(n-r)!} = \frac{8!}{4!(8-4)!} = 70 \tag{5.1}$$

For each user we designed 10 trials, to reach a total of 70 arrangements. So, at least 7 users were needed. For each user, a set of 10 arrangements were chosen. Each trial corresponded to one arrangement, so each trial is unique for a user. Furthermore, each set is unique to a user until we test with 7 users. After that the sets are reused. The weights have no correlation with the initial starting positions of the cubes, and the user was also informed about that.

The participant can grab each cube in any order for an unlimited amount of time. Eventually, the participant puts each cube in a platform and confirms the order by pressing the button. Before pressing the button, at any time, the user is free to reorder the cubes. The grabbing location on the object is always the point of the surface where the sphere held by the user touches the virtual object. Therefore grabbing by the side faces of the cube generate a different response from grabbing it by the front face.

After pressing the button, another trial of the experiment begins, with a new arrangement being loaded from the initial set. This repeats until all the set has been done, totaling 10 arrangements. This first experiment ends when the subject pressed the confirmation button on the 10th trial, and moves on to the next experiment.

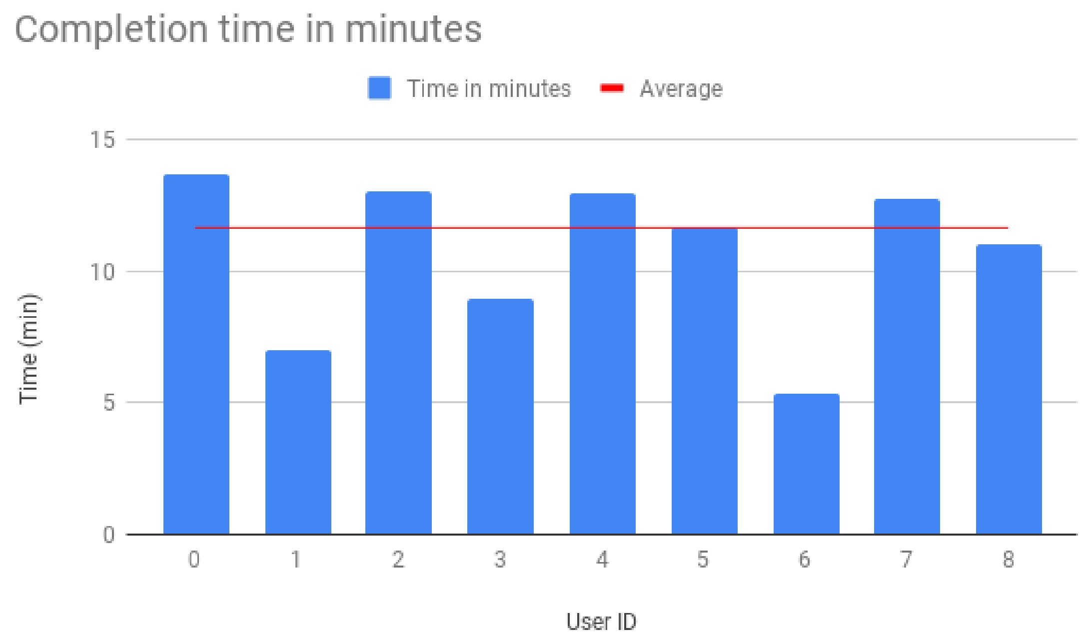
5.2 Results And Analysis

The average time per session was 12 minutes, with a standard deviation of 2.96 minutes. Fig. 5.2 shows completion time in minutes for each user.

The dependent variables analyzed in this study correspond to the final position of each cube (accuracy), completion time (s), distance error (DE), and mean square error (MSE) for each subject.

The accuracy is the percentage of success between the position of the cubes given by the participant and the ground-truth. Taking into account that the probability of placing each cube in its correct position is 1/4, we analyzed each pair of sequential cubes regarding weight.

Figure 5.2 – Completion time for experiment 1

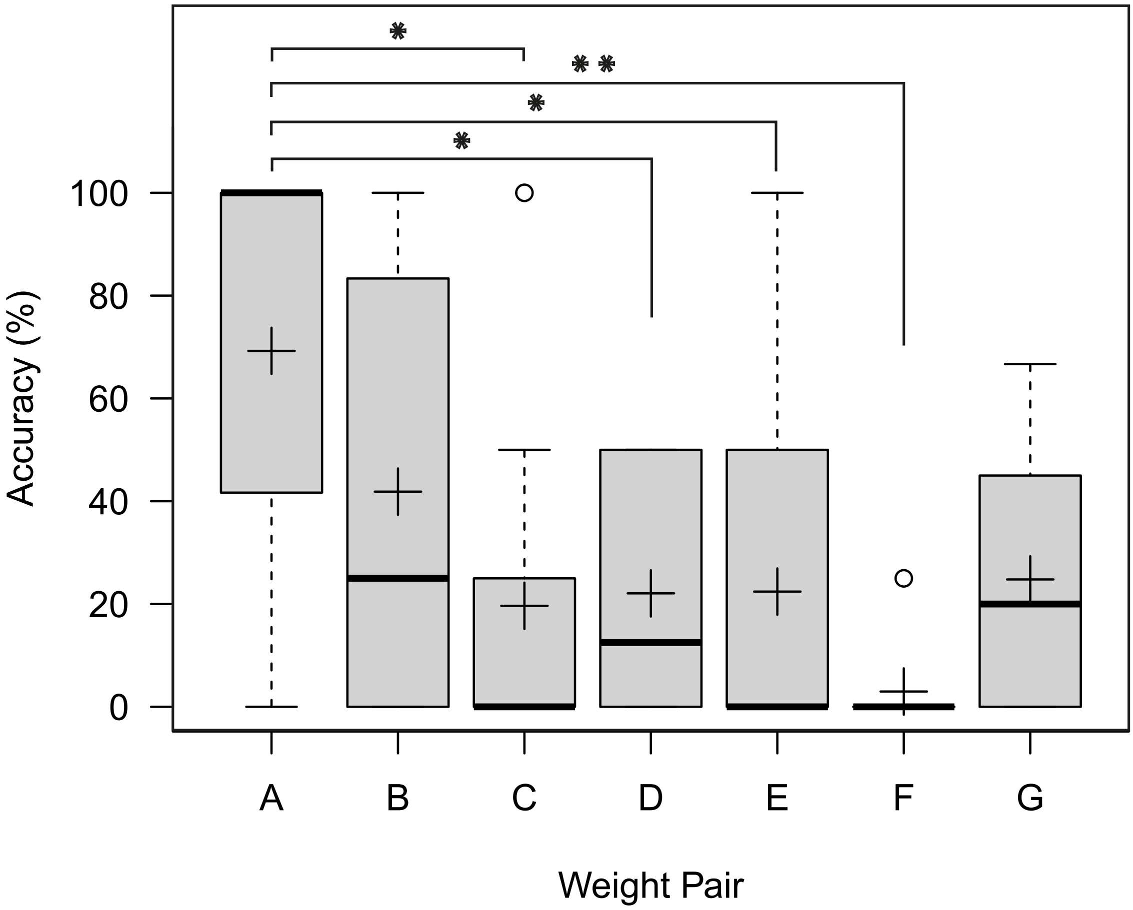


We assigned a new variable to each pair for better clarity (A: 0.5-1.0, B: 1.0-1.5, C: 1.5-2.0, D: 2.0-2.5, E: 2.5-3.0, F: 3.0-3.5, G: 3.5-4.0). To score a hit, both cubes of the pair must be in their correct position. This percentage score by group pair is shown in Fig. 5.3.

According to Shapiro-Wilks test the data was not normally distributed, so a non-parametric repeated-measures test was performed. Kruskal-Wallis test showed a significant difference in the group $[X^2(6) = 13.344, p = 0.03788]$. Post-hoc tests (Mann-Whitney) found significant differences on four pairwise comparisons out of 21 total comparisons which are the following pairs: A-B ($W = 51.5, p = 0.02838$); A-C ($W = 45.5, p = 0.04119$); A-D ($W = 50, p = 0.04252$) and A-F ($W = 58, p = 0.002212$).

Completion time is the time in seconds the subject takes to finish the test after the cubes were sorted, Fig 5.4. Shapiro-Wilks test showed that the collected completion time data was not normally distributed, so again a non-parametric repeated-measures test was performed. In this case, Kruskal-Wallis test did not show a significant difference among the pairs $[X^2(6) = 3.5384, p = 0.7389]$.

Figure 5.3 – Average percentage of correct weight pairs. Pairs grouped by asterisks were significantly different by Mann-Whitney test ($*: 0.01 < p < 0.05$, $**: p < 0.01$)



Subsequently, two groups of pairs (Lighter and Heavier) were analyzed, the two pairs of lightest weights (A and B) were taken as the Lighter group and the two pairs of heaviest weights (F and G) were taken as the Heavier group. This comparison aimed at observing the effects of perception on accuracy and completion time for both specific groups. The accuracy and completion time of both groups (Fig. 5.5 were evaluated again with the Mann-Whitney test, and a significant difference was found in the average percentage of correct weight pair ($W = 54.5, p = 0.006008$).

In the last analysis of this first experiment we observed the measurements of the Distance Error and the Mean Square Error in the Lighter and Heavier groups again as seen on Fig. 5.6. Distance Error (DE) is a simple metric to quantify how close to the correct order an answer was per trial according only to the position of each cube. The slots where the cubes were placed, were converted into index numbers from 0 for the lightest one, to 3, for the heaviest. The DE was computed adding the four absolute differences between the index of each object position in the answer i and the respective index j in the ground-truth

Figure 5.4 – Average percentage of completion time for each weight pair

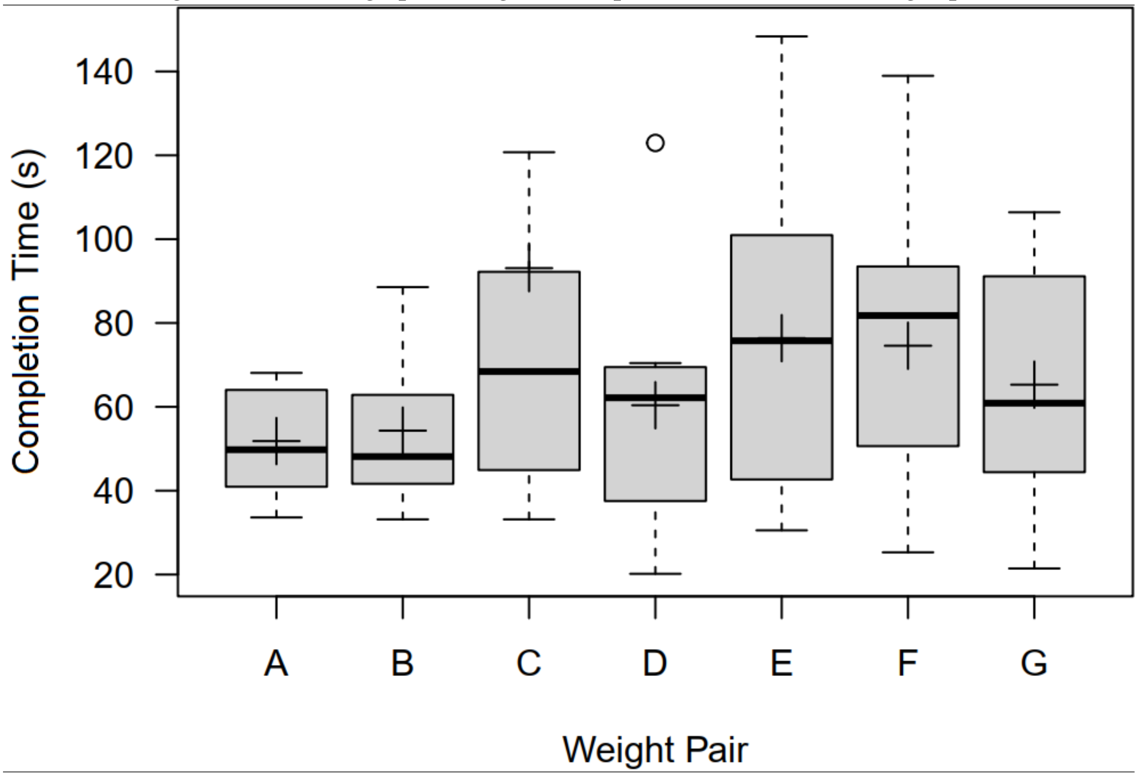
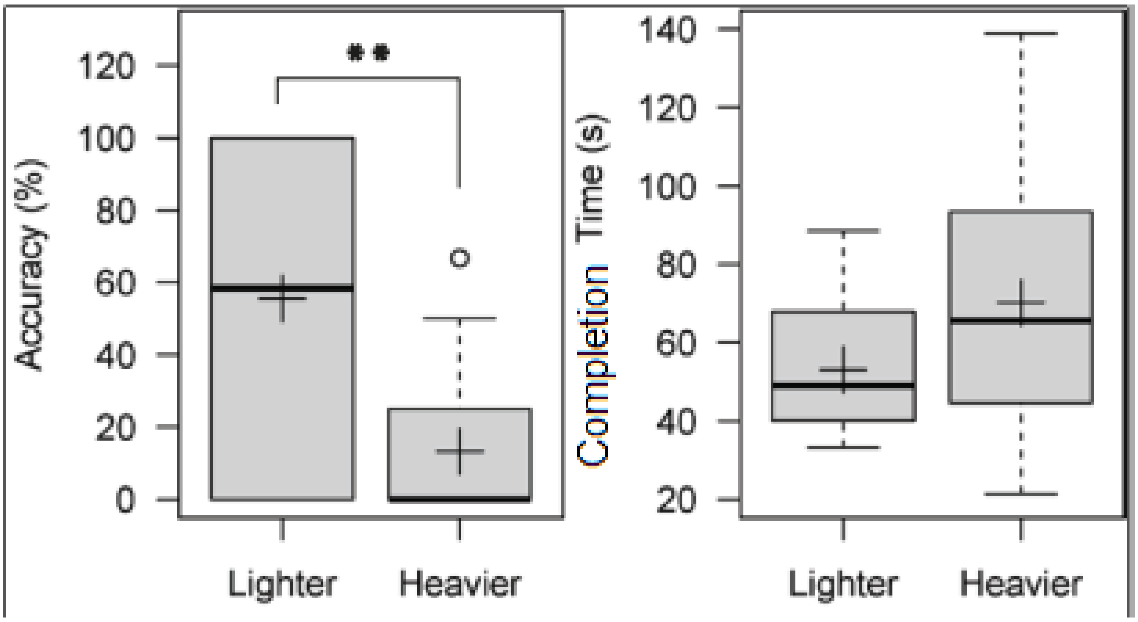


Figure 5.5 – Average percentage of correct hits and response time for each weight group. Pairs grouped by asterisks were significantly different by Mann-Whitney test ($* : 0.01 < p < 0.05$, $** : p < 0.01$))



as expressed in Eq. 5.2. Surprisingly, according to the Shapiro-Wilks test, the data was normally distributed, so we applied the Welch Two Sample t-test that showed a significant difference $t(2.7003) = 27.636, p = 0.01169$.

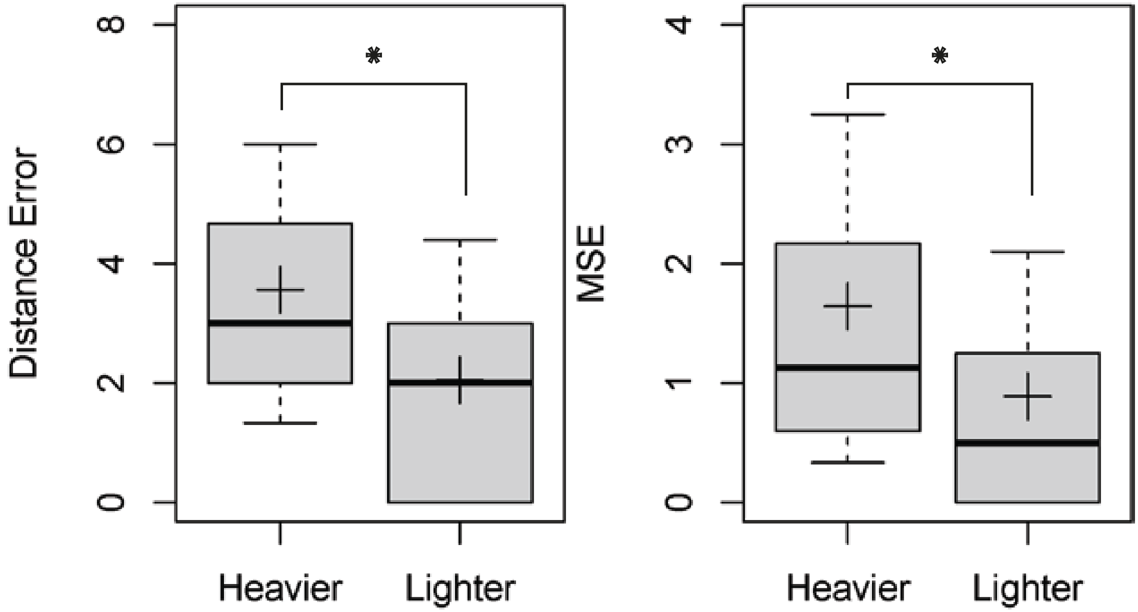
$$DE = \sum_{n=0}^{3} |i - j|_{n_i = n_j} \tag{5.2}$$

We also used the MSE metric to calculate the difference between the answer the participant gave and the correct answer, according to the cube's weight (Eq. 5.3). In this case, the Shapiro-Wilks test showed that the data of MSE was not normally distributed and the Mann-Whitney test found a statistical significance difference ($W = 177, p = 0.02201$)

$$MSE = \frac{1}{4} \sum_{0}^{3} (w - \hat{w})^2 \tag{5.3}$$

To measure if our device is indeed useful and creates a better sense of weight in VR, we compared the results obtained in this experiment with results we would have gotten if users performed the task without using the device. With this purpose in mind we measured the theoretical accuracy and compared it to our experimental accuracy. The theoretical accuracy is 4.16%, which is the probability of a correct answer (1 in 24). Our experiment yielded an accuracy of 26.6%, 24 correct answers out of 90 total trials.

Figure 5.6 – Distance Error and the Mean Square Error for each weight group. Pairs grouped by asterisks were significantly different by Mann-Whitney test ($*: 0.01 < p < 0.05$, $**: p < 0.01$))



6 SECOND EXPERIMENT - MATCHING MASS OF BARS

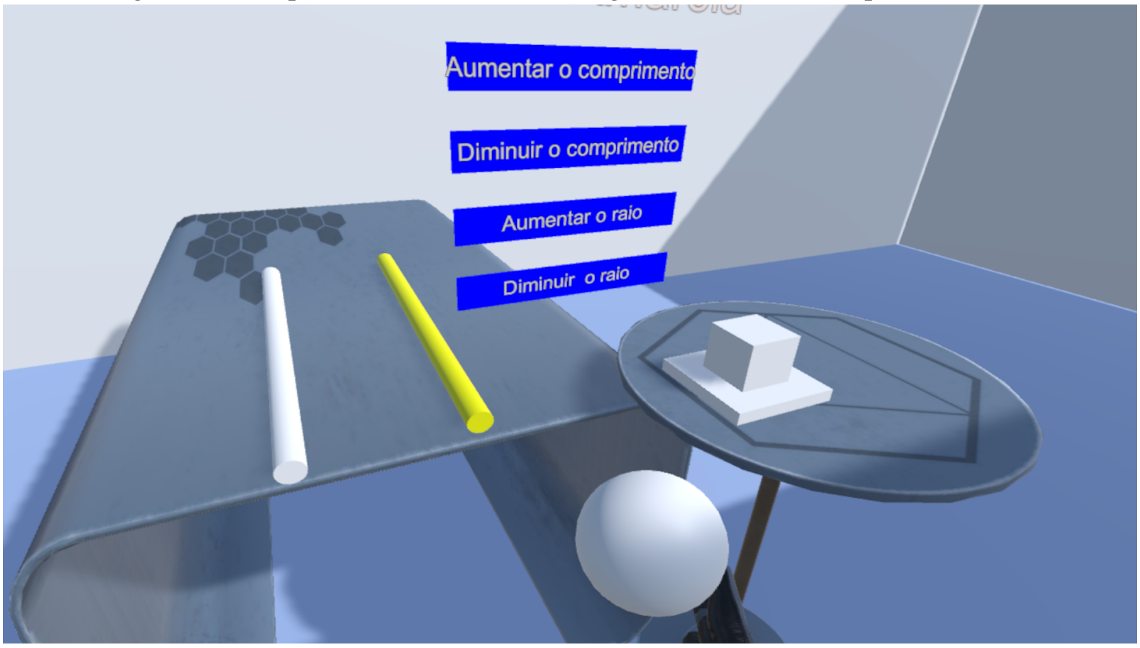
6.1 Experiment Design and Procedure

The second experiment consists of a table with 2 cylinder bars, a reference bar and an expandable one. Also, there is a confirmation button and buttons to change the expandable bar length and radius. Both bars have the same dimensions at first but different densities. The user task is to make both bars weigh the same by modifying the length and/or radius of the expandable bar to match its weight with that of the reference one. The reference bar is immutable and has a weight set at the beginning based on its density and volume, and the expandable bar can have its length and radius increased or decreased. For the reference bar, we used two densities of values 300 and 700, therefore the weights are 1.178 and 2.749 units and the expandable bar density ranges from 100 to 900 with a step of 200. Totaling 10 combinations, with each trial changing both bars densities. Each user will do all the 10 combinations, therefore 10 trials. The formula used for calculating both bars mass is presented at 6.1, where ρ is the bar density, r its radius and h its length. While the experiment was being conducted we perceived that the participants hold the controller more on a relaxed position, inclining the controller on a 35-45 degrees forward, instead of holding on a neutral position as we intended.

$$m = \rho * V = \rho * \pi * r^2 * h \tag{6.1}$$

For each trial, both bars start with the same dimensions. The participant can interact with both bars, holding them from any position. Then, the user may change the length and radius of the expandable bar to make its weight match or be as close as possible to the reference bar's weight. To change the length or radius of the bar, the user must press one of the 4 options that appear in front of him as shown on Fig. 6.1. When the user is satisfied with the expandable bar weight, the user presses the white button at the right and another trial starts, with both bars being moved to their original position and the expandable bar size changed to its original size. After completing the 10 trials, the second experiment is over.

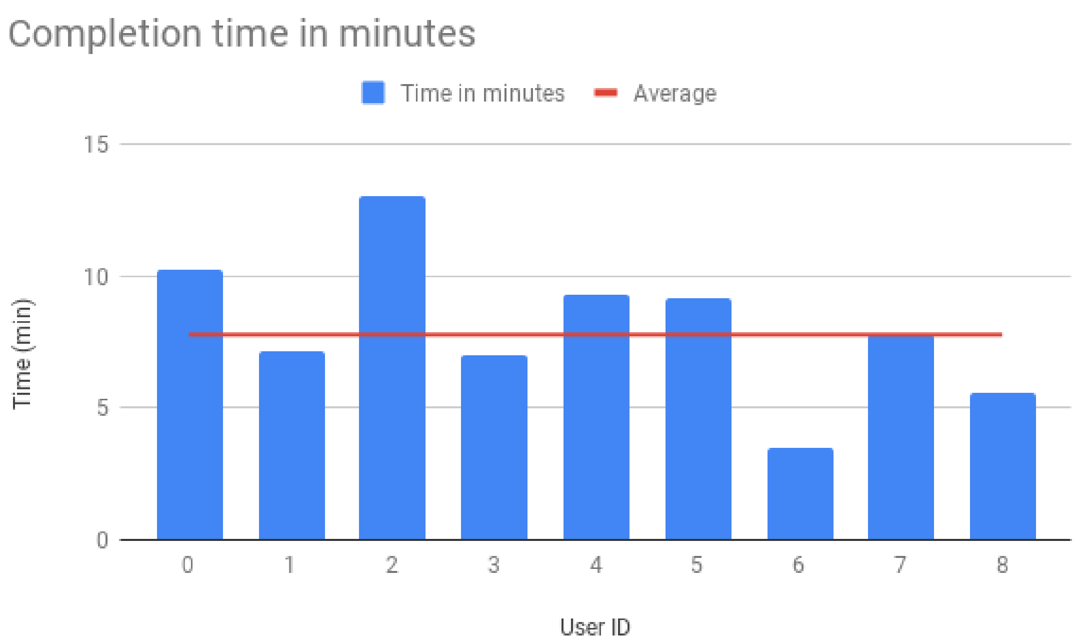
Figure 6.1 – Experiment 2 scenario showing the reference and expandable bars.



6.2 Results and Analysis

The average time per session was 8 minutes, with a standard deviation of 2.77 minutes. Fig. 5.2 shows completion time in minutes for each user.

Figure 6.2 – Completion Time for experiment 2

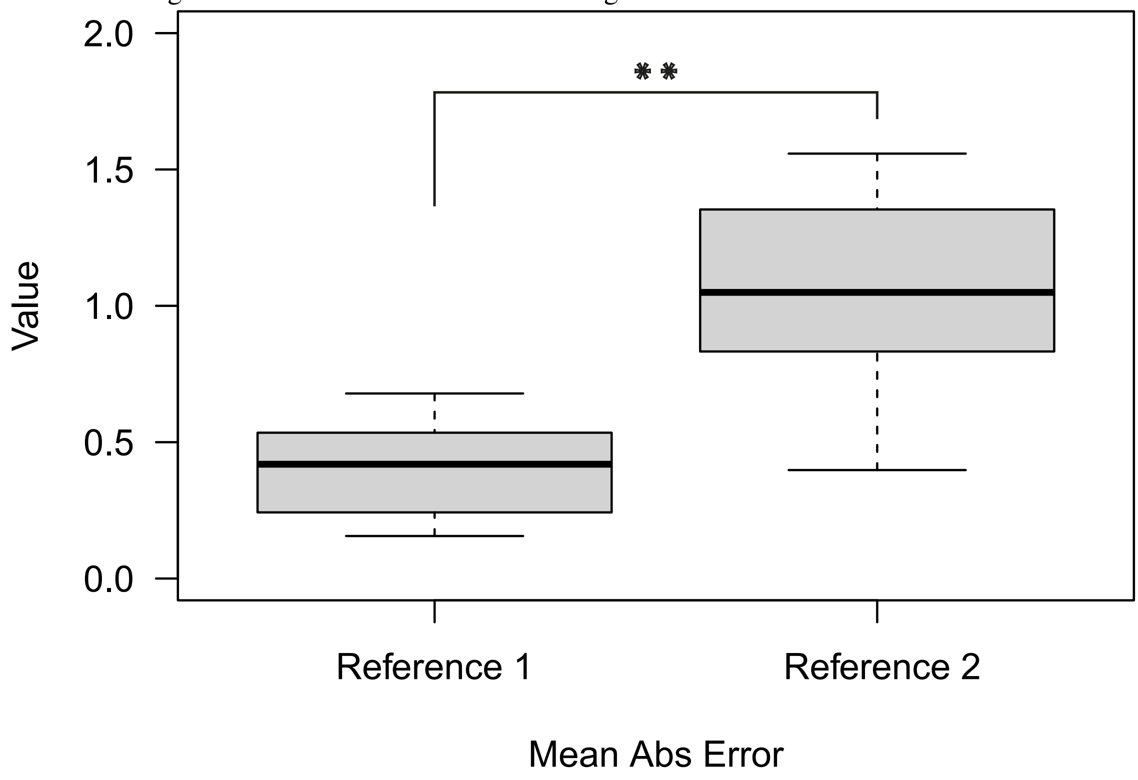


One of the questions we wanted to answer was which mass is easier to match, 1.178 or 2.749. We used Mean Absolute Error (MAE) to measure which reference weight yielded lower accuracy, with the lighter mass having a MAE of 0.418 and the heavier being 1.196. In Eq. 6.2 the x is the mass the user chose for the expandable bar and y is the closest or exact mass of the reference bar.

$$MAE = \sum_{i=i}^{n} |x_i - y_i| \tag{6.2}$$

Shapiro test showed that the data does not have a normal distribution. Therefore, we performed Wilcoxon signed-rank tests since we have unpaired data. We arrived at a result of ($W = 0, p = 0.003906$), which allowed us to conclude that there is a significant difference. Fig. 6.3 shows that the lighter mass, Reference 1, has a lower MAE. Then, when the participant needed to match the expandable bar's mass with the reference, and the reference was lighter, it had a lower error than matching with the reference 2 weight.

Figure 6.3 – Mean Absolute Error for lightest and heaviest reference bars

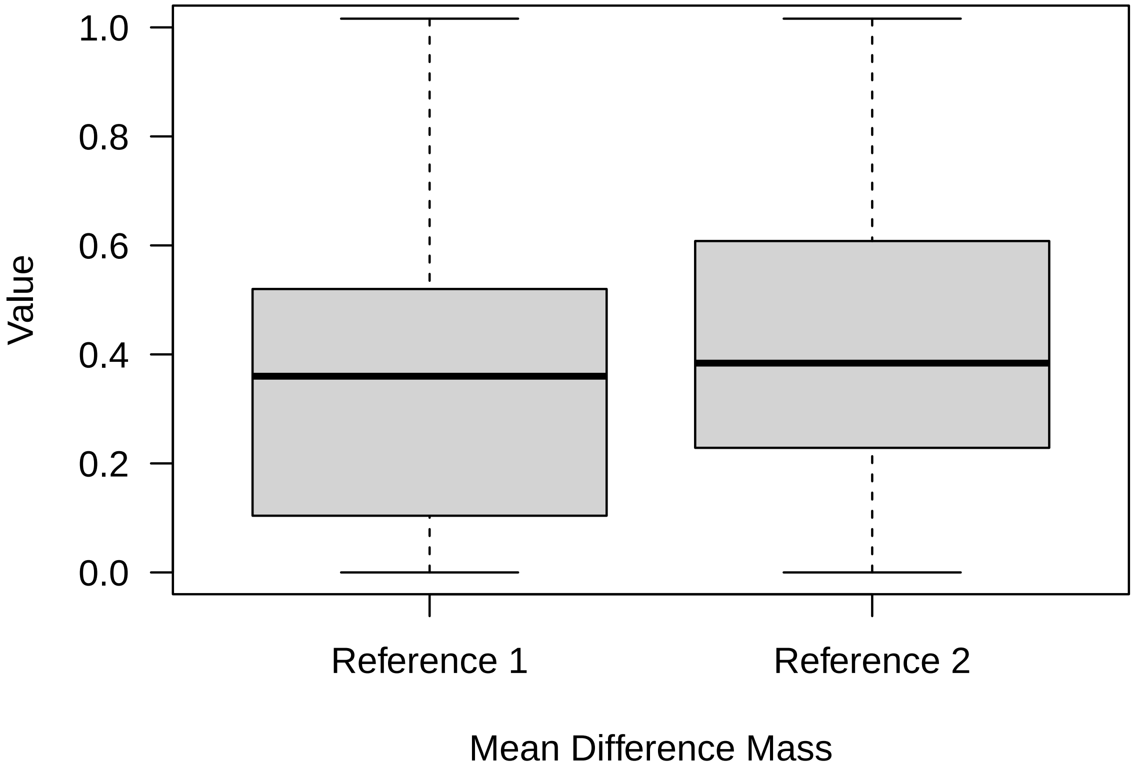


With Eq. 6.3 we measured the mean difference between the reference bar weight (y) and the mass that the user reached to answer the task.

$$MD = |x - y|/y \tag{6.3}$$

Then, we measured the accuracy of the experiment, coming to an 8.88% of accuracy (8 correct answers out of 90 trials). Again, as we did in experiment 1, we compared these results with the theoretical accuracy of 2.04%. To give the right answer, a user would have to guess the radius and length correctly, from a combination of 49 possible outcomes for the expandable bar weight. Since the user could change length and radius,

Figure 6.4 – Mean Difference Mass for lightest and heaviest reference bars



Source: The author

we wanted to identify if they would favor changing length or radius. Out of the 90 trials, 25 of them prioritized changing the radius and the 65 remaining, the length. We noticed that all the 8 correct answers we got in this experiment came from users that prioritized changing the expandable bar's length. However, we need further experiments to explain this result.

7 SUBJECTIVE RESULTS AND ANALYSIS

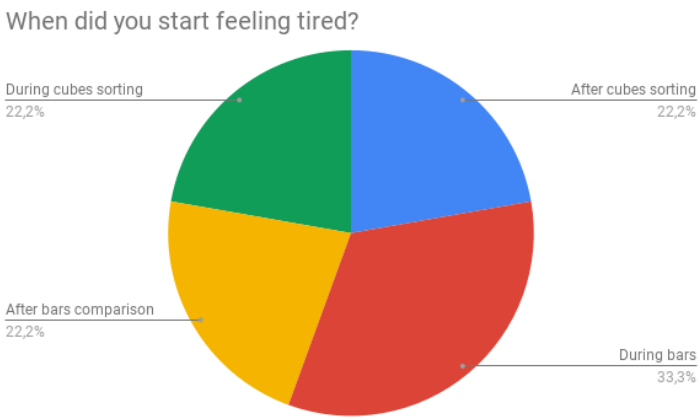
As mentioned before, we conducted a pre- and post-study well-being questionnaire as well as a subjective evaluation post-study. In the well-being questionnaire we asked how much each symptom was affecting the user, the answers could range from 1 (nothing) to 5 (severe). Almost all of them were feeling completely fine except for one that was feeling a bit dizzy.

After the experiments, we asked the participants to partake in another well-being questionnaire. Four users had a slight increase in dizziness and two had slight increase in headache. Also, we asked the participant subjective questions about the tasks that they had to complete. Two questions had a completely agree to completely disagree range of answer, where 1 means completely disagree and 5 completely agree. In Fig. 7.1 we can infer that most of the users slightly disagreed that the maximum sensation of weight caused any pain, but almost half of them answered that they felt that in some cases there was no weight.

Figure 7.1 – Weight Sensation

Since the handheld device has its own weight, we also wanted to track when the user would feel any fatigue while using it, with this in mind, we remembered the participants that they could take a break mid-experiment if they felt that their arm was feeling heavy or tired and the time they took resting was not counted towards the task completion time. Fig. 7.2 shows the amount of users that felt fatigue on each moment of the tasks they performed.

Figure 7.2 – Tiredness moment



We want to measure the confidence each user has on their own answers. We asked participants when the weight of two cubes felt the same (see Fig. 7.3). We also asked how many of the bar comparisons they think they got right (results is in Fig. 7.4).

Figure 7.3 – 2 cubes felt the same

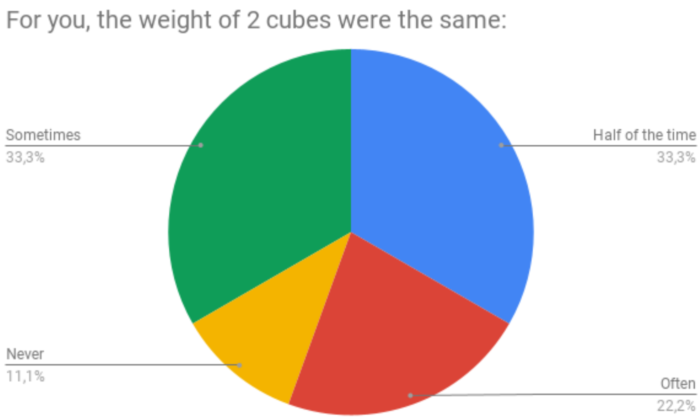
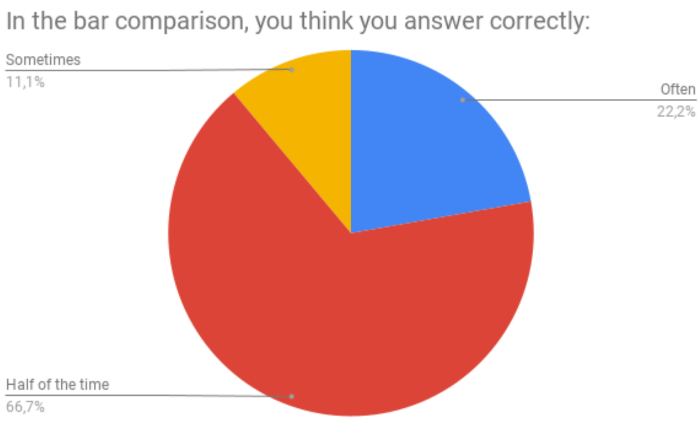
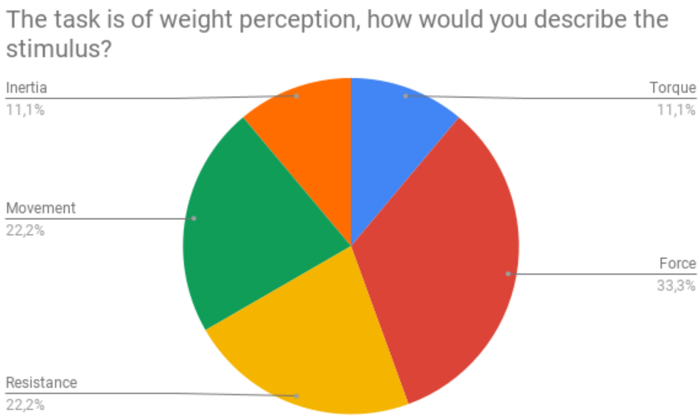


Figure 7.4 – Bar answer confidence



Finally, we needed to know which kind of stimulus the user comprehended while utilising our device. The task is of weight perception, but our device utilises torque as a way of transmitting the idea of weight. Fig. 7.5 has the answers of the participants when the question was how would they describe the stimulus the device created.

Figure 7.5 – Stimulus description



In Fig. 7.4 we can notice that most of the users believe they answered incorrectly half of their answers, indicating a high amount of uncertainty or low confidence. In Fig. 7.5 approximately half of the participants described the stimulus as force or resistance, both answers being compatible with weight sensation. The other two answers excluding torque are also acceptable and cohesive, since our device has to move to reach the designated spot for replication of weight, it can be perceived as inertia or movement, especially when the user grabs objects quickly.

8 CONCLUSIONS

In this work, we aimed at developing and evaluating a new type of handheld haptic device capable of inducing weight perception in users manipulating virtual objects. Instead of using the traditional approach of a grounded mechanical actuated device, we developed a lightweight 3D printed handheld device based on an inverted pendulum driven by mechanical actuators that rotate the pendulum to render forces by shifting a mass element on a hemisphere around the user's hand. The technique exploits gravity to recreate torque at the wrist, which conveys weight of virtual objects being grabbed by the user.

To evaluate the quality of the stimulus provided, we designed a psycho-physical study composed of two experiments, each one based on a single task that consists of the user interacting with objects in a virtual environment. In the first experiment, the user has to order a set of four cubes by weight, from lightest to heaviest. In the second experiment, the task was matching the weight of two bars with different densities by controlling the length and radius of one of them.

Results have shown that our device is capable of producing effects that allow users to discriminate different weights. Significant differences were found in accuracy when the users sort the cubes in the first experiment mostly when they compare objects with light weights. Also, we found out that the response time is shorter as the weight difference between objects increases. We also found statistically significant differences in precision and response time between a pair of lightweight objects and a pair of heavyweight ones.

Regarding the second experiment, an interesting finding was that accuracy was higher when the user had to match the two bars and the reference was lighter. Since one might expect better results for heaviest reference bars, this suggests that our device has a good precision in conveying weight. Also, although we had only 8.88% of correct answers, when compared to the theoretical success rate (2.04%), our results also suggest that our device is a good solution to convey weight of virtual objects.

While the experiments were being conducted, we noticed that the participants after grabbing an object would often move their hand and wrist to a position that would negate the torque applied on the user's hand, this greatly affects the user's perception of weight. With this in mind, one of our limitations is the angle at which the user holds the device. This could be solved by dynamically changing the pendulum's direction so the torque induced on the user's hand would be the same regardless of hand rotation.

As future work, we would like to perform further experiments with more complex scenes involving, for example, objects with different shapes to assess combinations of vision and haptic stimulus in weight perception.

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APPENDIX

Questionário - coleta de resultados

*Required

1. Email *

2. Teste (Preenchido pelo aplicador) *

   Mark only one oval.

   - Condição E
   - Condição P

3. Id do participante *

4. Esse é a sua primeira rodada do experimento? *

   Mark only one oval.

   - Sim
     Skip to section 2 (Pré-experimento: Indique o quanto cada sintoma abaixo está afetando você neste momento:)
   - Não *Skip to section 4 (Prossiga para o experimento)*

Pré-experimento: Indique o quanto cada sintoma abaixo está afetando você neste momento:

(1) Nada, (2) Levemente, (3) Moderado e (4) Severamente

Condições atuais

5. Mal-estar generalizado *

Mark only one oval.

	1	2	3	4	
Nada	◯	◯	◯	◯	Severamente

6. Dor de cabeça *

Mark only one oval.

	1	2	3	4	
Nada	◯	◯	◯	◯	Severamente

7. Náusea *

Mark only one oval.

	1	2	3	4	
Nada	◯	◯	◯	◯	Severamente

8. Tontura *

Mark only one oval.

	1	2	3	4	
Nada	◯	◯	◯	◯	Severamente

Prossiga para o experimento

Pós-experimento: Indique o quanto cada sintoma

(1) Nada, (2) Levemente, (3) Moderado e (4) Severamente

abaixo está afetando você neste momento:

9. Mal-estar generalizado *

Mark only one oval.

	1	2	3	4	
Nada	⬭	⬭	⬭	⬭	Severamente

10. Dor de cabeça *

Mark only one oval.

	1	2	3	4	
Nada	⬭	⬭	⬭	⬭	Severamente

11. Náusea *

Mark only one oval.

	1	2	3	4	
Nada	⬭	⬭	⬭	⬭	Severamente

12. Tontura *

Mark only one oval.

	1	2	3	4	
Nada	⬭	⬭	⬭	⬭	Severamente

Responda agora sobre sua

Responda em referência à sua experiência com a tarefa que você acabou de realizar percepção ao utilizar o sistema

13. O quanto você concorda com a seguinte afirmação: "A sensação de peso MÁXIMA que senti é tão intensa que causou um pouco de dor." *

Mark only one oval.

	1	2	3	4	5	
Discordo muito	⬭	⬭	⬭	⬭	⬭	Concordo muito

14. O quanto você concorda com a seguinte afirmação: "A sensação de peso em alguns casos é de que não há nenhum peso."

Mark only one oval.

	1	2	3	4	5	
Discordo muito	⬭	⬭	⬭	⬭	⬭	Concordo muito

15. Marque a partir de que momento sentiu cansaço:

Mark only one oval.

- ⬭ Durante o ordenamento de cubos
- ⬭ Após encerrar o ordenamento de cubos
- ⬭ Durante a comparação de cilindros
- ⬭ Após a comparação de cilindros
- ⬭ Não cansei

16. Para você, os pesos de dois cubos eram iguais:

Mark only one oval.

- nenhuma das vezes
- poucas vezes
- metade das vezes
- muitas vezes
- a maioria das vezes

17. Na comparação de cilindros você acha que acertou:

Mark only one oval.

- nenhuma das vezes
- poucas vezes
- metade das vezes
- muitas vezes
- a maioria das vezes
- todas as vezes

18. As tarefas são de percepção de peso. Caso possa interpretar o estímulo percebido de outra forma, interpretaria como? Marque apenas a opção que considerar mais provável:

    Mark only one oval.

    - nenhum - interpreto como peso mesmo
    - atrito
    - resistência
    - vibração
    - vento
    - força
    - torque
    - inércia
    - movimento
    - cócegas
    - choque elétrico

Muito obrigado por suas respostas!