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Size and Distance Estimation in Virtual Reality

Bachelor's Thesis
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ABSTRACT

Interest in virtual reality (VR) has been on the rise in the recent few years. However, it is difficult to create virtual environments which provide realistic perception of scale for their users. We wanted to study how humans perceive scale in VR and ways to improve VR scale perception.

We did a pilot test to see how design choices affect distance and height estimation in VR. For pilot tests we had nine test participants.

Based on the experience gathered from the pilot test, we designed the main test. For the main test we had 44 participants. The main test showed similar results for distance estimating as earlier studies. Humans underestimated distances and heights in VR. Having a familiar size object cue, a VR model of a milk carton, next to the object improved height estimations.

Keywords: Virtual reality, VR, Virtual environment, HTC Vive, Scale perception, Distance estimation, Height estimation, Depth perception

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TIIVISTELMÄ

Kiinnostus virtuaalitodellisuuteen (VT) on ollut kasvavaa muutaman viime vuoden aikana. On kuitenkin vaikeaa tehdä virtuaalinen ympäristö, joka luo käyttäjilleen luonnollisen aistimuksen mittakaavasta. Halusimme tutkia, miten ihmiset hahmottavat skaalaa VR:ssä ja kuinka sitä voi parantaa.

Teimme pilottitestejä, jotta näkisimme kuinka erilaiset suunnittelupäätökset vaikuttavat etäisyyden ja korkeuden arviointiin virtuaalitodellisuudessa. Pilottitesteissä oli yhdeksän osallistujaa.

Pilottitestien pohjalta teimme laajemman testin, jossa hyödynsimme pilottitesteistä saatuja kokemuksia. Laajemmassa testissä oli 44 osallistujaa. Tämä testi tuotti samankaltaisia tuloksia etäisyyden arvioinnissa kuin aikaisemmat tutkimukset. Ihmiset aliarvioivat etäisyyksiä ja korkeuksia virtuaalitodellisuudessa. Kun esineen vieressä oli tunnetun kokoinen esine, maitopurkin virtuaalimalli, korkeuden arviointi parani.

Avainsanat: Virtuaalitodellisuus, VR, HTC Vive, Mittakaavan hahmottaminen, etäisyyden arviointi, korkeuden arviointi, syvyyden hahmottaminen

TABLE OF CONTENTS

FOREWORD

We would like to thank our teaching assistants Prof. Steven M. LaValle and PhD Anna LaValle, and also PhD student Katherine Mimnaugh for their great help and assistance during the making of this project.

We would also like to thank our Applied Computing Project I course supervisors Adj. Prof. Simo Hosio and PhD Matti Pouke for their help and guidance with writing a bachelor's thesis.

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ABBREVIATIONS

VR	Virtual Reality
VE	Virtual Environment
HMD	Head-Mounted Display
LCD	Liquid Crystal Display
FSO	Familiar Size Object
IPD	Interpupillary Distance

1. INTRODUCTION

Interest in virtual reality has risen in the last few years. This is most likely due to the increasing availability of consumer devices and the decrease in their prices [1]. Virtual reality can be defined as, for example, “Inducing targeted behavior in an organism by using sensorial stimulation, while the organism has little or no awareness of the interference” [1, pp. 2]. Making a virtual environment so that the user has no awareness of the environment not being natural is challenging, because humans have many methods to observe their surroundings [2]. Nowadays the virtual reality environments are implemented with light-weight head mounted displays (HMD), their assisting devices and computers or gaming consoles.

The way the human eye works is quite well understood. The light enters through the cornea and pupil to the lens, from where it is refracted to the photoreceptor sheet known as retina. From the retina, the information is transported to the brain via the optic nerve [3]. However, the science of human perception is a lot more complex subject than human vision. Humans perceive scale and depth in many ways, both with just a single eye and with two eyes. In visual science, the ways that help us perceive depth and scale are called “cues”. Single-eye cues are called monocular cues, whereas two-eye cues are called binocular cues [4]. “Human spatial behavior depends on correctly perceived distances” [5, pp. 9].

In this project, we performed a study about scale with human subjects by utilizing parts and assets from the virtual reality (VR) version of the Virtual Zoological Museum of the University of Oulu, which was made after the physical museum was decommissioned. The goal is to determine ways to help people perceive the scale better in virtual environments (VE). The project involves creating little experiments for human subjects, making and executing pilot tests, creating a main test with the knowledge that we got from the pilot tests and evaluating the main tests. We believe that generating familiar size cues will help people perceive scale and depth better.

1.1. Motivation

Why is it important to get the scale right and ensure that the scale is perceived correctly? Thinking about virtual reality museums, for example, to get the right experience to the users, it is crucial to get the scale perceived right so that it corresponds to reality. If the size of the objects compared to each other and to reality is incorrect, the virtual museum is not realistic. The problem is that often when making a VR environment there might not be a good way to check the scales and even if the objects size is correct, we still might perceive it to look wrong. In this study we are trying to figure out how to implement a cue to increase the similarity to reality, and implement a few experiments to test if the cue makes it easier for the user to perceive scale right, so that they might be able to figure out the correct size of an object from virtual reality without seeing its counterpart in real world. What we find in these experiments can then be used to help with scaling of the museum and other possible projects.

1.2. Contributions

All participants in the thesis group did approximately an equal amount of work for the thesis. For the most part we worked by assembling to a single location and working on the thesis together by either discussing what to write on the thesis or writing at the same time.

During reading related work, Jouni gathered general information about VR and about the technologies, problems and challenges. Petteri gathered information about history and experimenting with human subjects. Aleksi gathered information about cues.

During pilot test design, Petteri focused on making the milk carton. At the same time Aleksi and Jouni discussed and planned the details of the test environment. The test environment was made collaboratively.

During main test design, Aleksi designed the boxes while Petteri and Jouni made changes to the environment based on finding from the pilot tests.

During the tests, both the pilot and main test, Jouni directed the experiment by telling the participants what to do and asked the questions, Aleksi took down the participants' answers, and Petteri took notes on things that the participants had commented and how they acted during the tests.

Table 1. The number of hours that each group member used to the thesis.

Group member	Number of hours
Jouni Lammi	257
Petteri Moilanen	252
Aleksi Sierilä	249

2. RELATED WORK AND MOTIVATION

2.1. Virtual reality

2.1.1. General

As said earlier, VR could be defined as "Inducing targeted behavior in an organism by using sensorial stimulation, while the organism has little or no awareness of the interference" [1, pp. 2]. VR is mostly created with an HMD that has a small screen to produce the simulation for you. VR is used, for example, for gaming, design, teaching [6] and brain recovery [7, 8]; there is almost an infinite number of possible use cases. Another source describes VR in terms of functionality: It is a simulation in which computer graphics is used to create a realistic-looking world. The world is not static; it responds to the user's input, which may be gestural, verbal command or so on. A key feature of VR is real-time interactivity [9]. Head tracking provides necessary information for positional visual and aural presentation of the virtual world. Controller tracking allows user to interact with the virtual world using real world actions. Head tracking and controller tracking are an important part of a VR system to ensure the immersion.

2.1.2. Problems and challenges

There are some problems with VR. It is challenging to make a virtual environment where the users do not notice that they are in a virtual environment. For example, a natural scale of objects is not easy to produce. Wrong-sized everyday objects can make you unsure about the scale of the environment and can break the immersion. If VR is used for virtual prototyping, for example, precepting the scale and depth falsely could lead to design flaws in products. VR sickness is another challenge. It can make you feel very uncomfortable and must be avoided as much as possible when designing a virtual environment (VE) or a VR device. A great deal of research has been put to lessen VR sickness. VR sickness is caused by visual and bodily senses being in conflict [10, 11]. Motion that happens in virtual world but not in real world is a great example of this. Particularly during acceleration inner ear vestibular organ does not sense acceleration, but it is conveyed visually.

2.1.3. Technologies and devices

The VR system usually consists of the following devices: the VR headset, base station(s), controllers and a PC or a gaming console. On PC, Oculus with its products Oculus Rift and HTC with its products HTC Vive and HTC Vive Pro are the most popular manufacturers. [12] In addition, lately some other manufacturers, such as HP, Samsung and Acer have published their VR or Mixed Reality headset [13].

Figure 1. Oculus Rift HMD, Oculus sensors and Oculus Touch controllers. Picture taken by thesis group.

Figure 2. HTC Vive HMD, HTC Vive base stations and HTC Vive controllers. Picture taken by thesis group.

Sony with its product PlayStation VR is the most popular manufacturer in console VR [12, 14]. Also smartphones have been used to produce a VR environment: Google Cardboard, Google Daydream and Samsung Gear VR are good examples of this technology. Virtual reality can also be achieved using a stereoscopic image projected to a wall combined with shutter glasses that the user must wear [15]. However, for achieving a realistic scale, an HMD is suited better [16]. During this research we are going to use HMDs to produce the VR environment.

Figure 3. PlayStation VR HMD. Picture taken by thesis group.

While virtual reality can be coded with many engines, during this research we are using Unity to interact and customize our VR environment. Developing a VR environment is very similar to normal Unity development, but there are a few things to consider. Firstly, when viewing the project in the editor and not in VR, you are likely to experience some lag and tremor as the content is being rendered twice by your computer. While rendering there might be overhead, so it is wise to run and check the environment on your device in short intervals to avoid that. In Unity, you cannot move the camera directly, but you need to attach your camera into a specific object to move. You will also need to create InputTracking classes for the left and right eye cameras to get their position [17].

Since VR projects render the images twice, some image effects might be too expensive, and some effects do not make sense to use. Examples of effects that do not make sense are depth of field, blurs, and lens flares since those effects are not viewed in real life. Some effects are useful to use to make the images better for example anti-aliasing, color grading and bloom in some games. Lastly, depending on the complexity of your scene and hardware, you may want to modify the render scale, which means that we get sharpness but lose performance or vice versa [17].

2.1.4. History

First patent for an HMD like those used today, was issued to Morton Heilig back in 1960 [9]. In 1962 Heilig was issued a patent for the first virtual reality arcade, which simulated riding through New York in a motorcycle. The arcade had a vibrating seat for road feel, small fans for wind effect, and you could even smell food when passing a store. Ivan Sutherland continued Heilig's work on HMDs. In 1966 Sutherland tested a device that used head mounted Cathode Ray Tubes (CRTs). The device needed a mechanical arm for support because the displays used were heavy. There were also potentiometers in the mechanical arm for head tracking, since noncontact position tracking was not available. In 1968, he introduced an HMD that was hung from the ceiling, it was called Sword of Damocles [1]. While working on his HMD, Sutherland realized that he could use computer generated scenes, instead of images taken by a camera. In 1973 Sutherland and Evans produced an early graphics scene generator which generated simple scenes of 200-400 polygons in 20 FPS, more complex scenes resulted in less FPS and animation smoothness suffered [9].

In 1981 National Aeronautics and Space Administration (NASA) created the first Liquid Crystal Display (LCD) based HMD called Virtual Visual Environment Display (VIVED). The displays used were taken from Sony Watchman TVs and paired with optics. VIVED used Polhemus noncontact tracking to measure head motion. In late 1980s VPL Inc. introduced the first commercial HMD called EyePhone. The LCDs used by this device had a resolution of 360x240 pixels, resulting in blurry virtual scenes. Weight (2,4 kg) and cost ($11,000) were also drawbacks, but this device allowed researchers to start developing applications. Progress was hindered by low computing power and high cost of hardware. In 1998 Sony's Glasstron had a resolution of 800x600 and weighed only 310 grams, after that Kaiser Electro-Optics introduced an HMD with resolution of 1024x768. These resolution improvements made the image sharper [9].

2.2. Depth perception and scale perception

Humans use a combination of one or more different visual cues, that can work alone or in unison to make us perceive depth and make us able to differentiate between objects that are in different distances to us. Those cues are separated into monocular and binocular cues, in other words, cues that require only one eye and cues that use both eyes. For estimating depth of 3D objects in VR binocular cues improve accuracy compared to only using monocular cues [18].

Scale perception and depth perception are interrelated [19], so the depth cues also work as scale cues. Perceiving sizes in VR can be improved if user is first presented a virtual version of a familiar environment, so called transitional environment, however this was not used in this paper's research [20]. Previous studies mention size underestimation in virtual environments [21]. Previous studies have also shown that people give more accurate results in real environment compared to estimating distances in VR on a VE that replicates the real one [22, 23]. In VR the perceived distances were smaller than in real life. Also studies only done in VR show the same underestimations of distances [24, 25].

2.2.1. Monocular cues

Occlusion is a cue that occurs when object is partially hidden behind another object, which helps us discern that the hidden object is further away than the object it hides behind. Occlusion alone cannot give us the absolution distance, only relative. An example of this is when looking at a queue of people from the front, you can only see the first person fully and smaller and smaller parts of the people behind the first person [19, 26].

Relative size. When viewing two objects that we know are the same size then the object that takes more of our field of view is seen to be closer to us. This can be easily seen by holding your hands at different distances to your face [19, 4, 26].

Familiar size. When figuring out the distance of an object we use our prior knowledge of the objects size to figure out how far away it is. This can be used by the object alone or by comparing unfamiliar object to familiar objects [19, 26].

Atmospheric perspective is when an object appears less sharp, blurry with less details and often with a blue hue. This happens because there are particles in the air and the further an object is the more of those particles there are in front of the object [19, 4].

Texture gradient. When objects that are spaced together with relatively same space in between them, the further the objects are viewed the more tightly packed they seem to be. This is closely related to the cue relative size [19].

Shadows can provide us information of distance by the way of an object’s shadow is formed. If the shadow rests on the ground with the object but is higher than the other objects, we can see that the object is farther away. In the case that the object and its shadow are apart from each other we can incur that the object is off the ground, then in the previous case this object maybe be the same distance away but levitating [19].

Motion parallax is a depth cue that occurs when the observer is in motion. When moving and looking at stationary objects that seem to move at different speeds in relation to other objects in the background. The closer objects move faster than the objects farther away [19, 27].

Image blur. When looking at an object or a scene happening, the part we focus on becomes a point. Objects that are in between the viewer and the point are seen clearly with full detail, but the objects beyond this point and on the edges of our field of view become blurred [3].

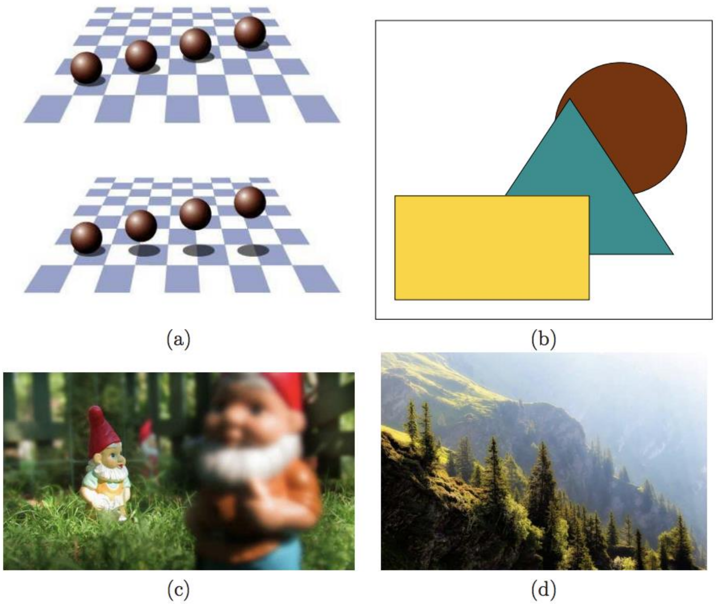

Figure 4. a) Shadows as a cue. b) Occlusion of objects. c) Image blur. d) Atmospheric perspective.

Picture credit: Steve M. Lavalle, Virtual Reality, page 157: "Several more monocular depth cues". Cambridge University Press, 2017. Available: http://vr.cs.uiuc.edu/

2.2.2. Binocular cues

Vergence. When viewing both of our eyes focus on the same object, the axis of both eyes must converge so that an image can appear on the both eyes' fovea. The angle of the axes depends on the distance of the object viewed [3].

Binocular disparity. When the image is formed in the fovea of each eye, the images have slight differences because of the lateral separation of the eyes [28] and when the differences are sufficiently small an effect called stereopsis occurs, also called stereo vision. This effect makes objects appear in 3D [3].

2.3. Experiments

2.3.1. Experimenting with human subjects

Doing experiments where the subjects are humans brings out many difficulties. Participant-predisposition effect is known to impact how subjects behave in an experiment. There are at least three different groups of participants. People belonging to the first group tend to try help the researcher by providing data that supports the researcher's hypothesis. Second group are people that try to disturb the study by providing invalid data. This behavior may come from previous bad experiences, disliking the researcher, being forced to participate in the experiment, being tired or not understanding the instructions. Third group is people that are uneasy about being studied. Demand characteristic is another threat to the result of the experiment. It means that since humans are natural problem solvers, subjects try to figure out what is expected of them and behave accordingly. For the validity of data, the subject should not know what the purpose of the experiment is [29].

Since the researcher is also a human, he/she is also prone to altering the results by their actions. This kind of behavior falls under experimenter-expectancy effects. The expectations of the researcher can affect the way they record the data, and they may unintentionally guide the subject towards a wanted result, for example tone of voice and body language can subtly give away what kind of results are expected. When analyzing the data expectations can alter the way things are interpreted, things that are against their hypothesis may be double-checked and things that favor it may not. Unintentional small errors made by the researcher tend to favor the hypothesis [29].

2.3.2. Planned experiments

First, we planned the possible pilot experiments to execute during the pilot tests. The goal was to examine how to help people perceive the scale better in VR environment using familiar size cues and the animals in the VR Zoological museum of University of Oulu. The ideal situation would have been to use animals that you rarely meet, such as bears, lynxes and wolves, because the test participants would have most likely had little knowledge about their size, and therefore they would be affected less by their previous knowledge. These were the possible pilot experiments.

The impact of the observer moving. What if the person could move or could not move? How would it affect the precision and the perception of scale?

The impact of a Familiar Size Object (FSO). First, the person would be shown an animal without any cues. Then, an FSO would be attached to the controller the person was holding. Finally, an animal would be shown to the person and an FSO was statically next to the animal. How would an FSO affect the precision and perception of scale? How would it be different when the person held the FSO or when the FSO was static? This experiment could also have been done with a row of different animals instead of just one animal, which would have combined an FSO and the relative size cue.

Using an animal as a relative size cue. The person would be asked to estimate the size of an animal and then another animal was placed behind the estimated animal. How would a relative size cue affect the precision and perception of scale?

Animal behind an FSO. The person would estimate an animal when the FSO is between the person and the animal. How would this affect the precision and perception of scale?

Relative size when estimating a group of animals. The person would estimate a group of animals one at a time and they would be asked in the end if they wanted to change some of their answers. How would the relative size affect the precision, when the person did not see the animals at the same time?

The impact of distance. How would changing the distance affect the precision and perception of scale? What if the person was given an FSO?

The impact of the moving object. The estimated animal would be moved. How would this affect the precision and the perception of scale?

The impact of environment. First, the person would estimate the animal in an empty space. Then the room and some objects would be added. How would this affect the precision and the perception of scale?

The realism of the FSO. First, the FSO used would be first designed very roughly, and then it was changed to a very detailed model. How would this affect the precision and perception of scale?

The difference between a VR environment and the real world. First, the person would be asked to estimate the size of an animal in VR. Then, the person would be shown a real stuffed and they were asked to update their estimate.

3. PILOT TESTS

3.1. Considerations

As mentioned before, we used parts of the VR Zoological museum as a framework for the project. It was made with Unity, so we stuck to it. An HTC Vive VR system was used to generate the VR environment, with resolution of 1080x1200 pixels for each eye, field of view (FOV) 110 degrees and tracking was done with SteamVR.

In the VR museum, there was a ready-made simple room that we thought is good for our test use. We considered both making a big room where all the experiments happen and making many rooms, so each experiment has their own room and scene. We decided to make one scene and one room for each of the pilot tests. Moving from scene to scene was done with modifying the portals that were already in the rooms.

From the beginning our idea was to prevent the test participant from moving around the room, because changing the position would make the test different between the test participant. Because the test participant could not move, the teleports had to be close to the test participant's spawning point in the room. This led to problems, because the user teleported through multiple rooms at once, which would make the testing ridiculously hard and in addition often crash the whole program, because the scenes were not loaded and unloaded correctly. A key press had to be implemented to the teleports to prevent moving through multiple scenes at once.

3.2. Problems and their solutions during design

We had a 3D scanner in our use, so our first idea was to scan our familiar-size-object, milk carton in our case, with it. The 3D scanned model did not come out as detailed as we wished and it was in such condition that it was very hard to customize to our liking, because of that we decided to make the model ourselves or use a ready model. Since making 3D models from scratch is time-consuming, we looked for 3D models from online libraries. We found a model of a smaller milk carton, about two deciliters, from Microsoft's Remix 3D library. We customized the model to be a one-liter carton. The texture for the milk carton was purchased from the CGTrader online store.

Perhaps our first and largest problem was that by the beginning of this project none of us had any prior experience using Unity and Blender, which made this phase of our project last longer as we had to learn everything at the same time as the project went by.

The way of moving between scenes was by having the user move their headset on a teleporter on top of a pillar. We saw that as not ideal way since our test participants would have to do unnecessary moving during the tests and they might accidentally move to another scene before the test in the previous room was ready, so we wanted to make moving between the scenes by having us, the testers, press a button on a keyboard. We figured out that we had to write some script for it and found help on doing that from Unity forums.

A frequent problem we had was that when we moved between the rooms, the objects (animals) within the room disappeared completely and we had to place them again and again in to the rooms. After a while we noticed that when moving from a room to room the scenes loaded multiple times, when we moved by our implemented button pressing, and that seemed to cause the disappearing animals. The problem was fixed by customizing the button pressing movement between the scenes by placing the small piece of code to a different place where it did not run multiple times and putting a limiter so it could not run multiple times.

A problem with making our VR test objects (animals) sizes match reality was that we did not have a proper way to measure them. To measure their sizes in VR we compared them to a ready-made 1 m^3 cube with a texture that consisted of white and grey squares. The texture had squares that were 10 cm * 10 cm which we could resize to 1 cm * 1 cm squares. A problem with the ready-made cube was that it was hard to make sure that its size was exactly 1 m^3 and did not deviate from it by much. We measured the cube to be around 102 cm in height and therefore we multiplied all the measured objects by $100/102 \approx 0.9804$. But that measurement could have been off also, because we are not sure how precisely the controllers were tracked.

3.3. Pilot test strategy and test plan

The research questions during our pilot tests were:

1. How good are people at estimating the distance of an unfamiliar object from themselves in a virtual environment?
2. At a known distance, how good are people at estimating the height of an unfamiliar object?
3. At a known distance, how good are people at estimating the height of an unfamiliar object if a known object is present in the scene?

The first of our experiments was designed to answer question one. The second, third and the beginning of fourth experiments answered question two. The fourth experiment answered question three.

We changed the floor material from dark and light grey tiles to a marble-like material that wouldn’t give any cues of the scale, removed paintings from the walls and adjusted the room height to match the testing room. The controller bodies were hidden for the whole time during the experiment. We agreed that simple experiments provide the most reliable data, which led us to the experiments listed below.

3.4. Test protocol

In the beginning of the experiments we measured the Interpupillary Distance (IPD) of the test participant and adjusted the HTC Vive headset accordingly. The test participants were told not to move around during the experiments.

In total, we had nine people that took part in our pilot tests. All the pilot tests were held in the same demo room at University of Oulu. There were seven men and two women in our sample.

3.5. First experiment

One bird (Lesser white-fronted goose) was first placed at 12 meters, then at six meters and then at three meters. The test participant estimates the bird and was then taken to the next room and same spot, the only difference being that the distance to the bird has changed. The first experiment was meant to test depth perception. The question presented to the participant was: “In front of you is a bird. How far is the bird?”

The figure 5 below shows the average percentage of the estimations from the correct distance in the first pilot experiment. The table 2 below shows the average of absolute errors and the lowest and highest estimation related to the correct distance in the first pilot experiment.

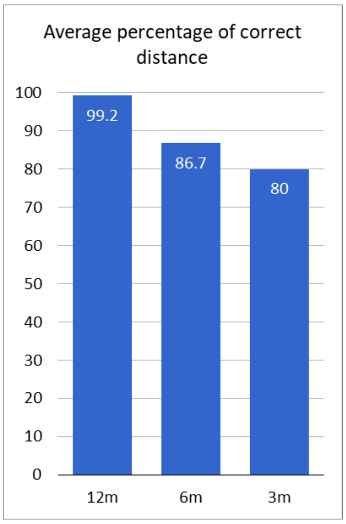

Figure 5. Data from first pilot experiment.

Table 2. Data from first pilot experiment.

Distance - m	Average of absolute errors - %	Lowest estimation - %	Highest estimation - %
12	21.3	-33.3	41.7
6	16.7	-33.3	16.7
3	20.4	-33.3	0.0

Analysis: The distances of the different birds were guessed correctly by one person and only on two out of three distances. Others guessed the distances to the closest number divisible by five, for example, the correct distance was 12 meters and they guessed 10 meters. Five out of nine underestimated the distances, three overestimated the furthest distances but underestimated the two closer distances. Absolute error on their guesses was from -4 meters to 5 meters on the 12-meter experiment (from -33.3 to 41.7 %), -2 to 1 meter on the six-meter experiment (from -33.3 to 16.7 %) and from -1 to 0 meters on the three-meter experiment (from -33.3 to 0 %).

Figure 6. First pilot experiment, distance is six meters.

3.6. Second experiment

First room had two birds which were two and four meters away, then the test participant estimated their heights. Then for the second part, the participant was taken to the next room. In the second room was two different birds than in the first one, and they were one and three meters away. In both cases, smaller of the two birds was closer to the participant. The second experiment was meant to test the effect of the relative size cue. The birds for the first part were Lesser white-fronted goose and Great cormorant. For the second part, Boreal owl and Great grey owl. We placed the birds at different distances to make comparing them to each other more difficult.

The question presented to the participant was: “The two birds in front of you are X and Y meters away, please tell their heights.”

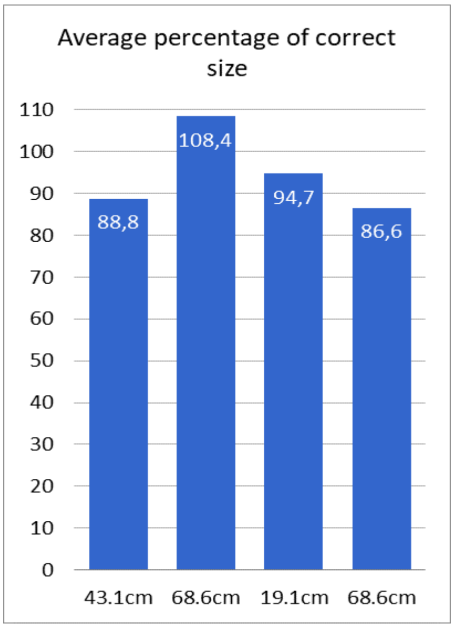

Figure 7. Data from second pilot experiment.

Table 3. Data from second pilot experiment.

Height - cm	Average of absolute errors - %	Lowest estimation - %	Highest estimation - %
43.1	19.8	-30.4	39.1
68.6	23.3	-27.1	45.7
19.1	31.6	-47.7	109.2
68.6	29.6	-49.0	45.7

Analysis: During the first part, mean for the estimates of the smaller bird (43.1 cm) was 11,2% smaller than the actual size, and for the bigger bird (68.6 cm) 8,4% bigger than the actual size. During the second part mean of the estimates for the smaller bird (19.1cm) 5,3% smaller than the actual size and for the bigger bird (68.6cm) 13,4% smaller. The first smaller bird was estimated only a little bit smaller by four, considerably smaller by four and bigger by one of the test subjects. The first bigger bird was estimated smaller by three subjects and bigger by four subjects, while two gave the correct answer, with just a few percentages of deviation. The second smaller bird was estimated smaller by six subjects, a lot bigger by one and roughly correct by two. The second bigger bird was estimated smaller by five subjects, bigger by two subjects, one was correct, and one answer was dismissed because of an error during the testing.

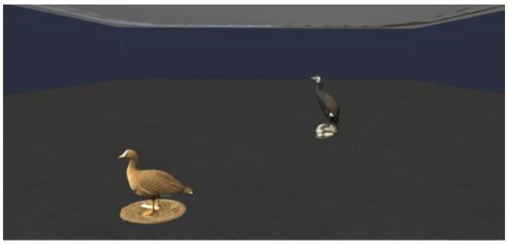

Figure 8. Second pilot experiment, first part.

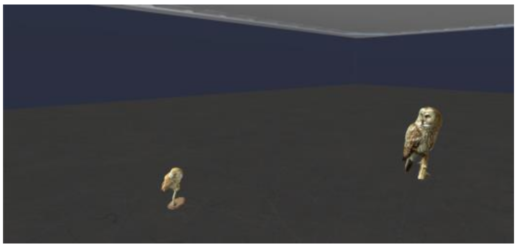

Figure 9. Second pilot experiment, second part. Side view.

3.7. Third experiment

Around the test participant was six different birds in a semicircle. They were three meters away. The participant estimated their individual heights and sorted them from shortest to tallest. The birds from left to right were Common eider, Eurasian bittern, Boreal owl, Gadwall, Northern goshawk and Great grey owl. The birds were placed at the same distance so you can easily compare them to each other.

The question presented to the participant was: “There are six birds around you, they are three meters away from you. Tell their heights and sort them from smallest to biggest.”

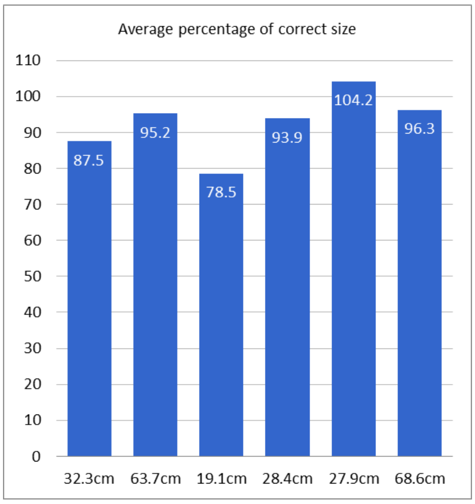

Figure 10. Data from third pilot experiment.

Table 4. Data from third pilot experiment.

Height - cm	Average of absolute errors - %	Lowest estimation - %	Highest estimation - %
32.4	19.5	-38.2	23.6
63.7	24.4	-37.2	56.9
19.1	24.6	-47.7	4.6
28.4	22.8	-47.2	40.7
27.9	17.5	-28.4	43.2
68.6	28.1	-41.7	89.4

Analysis: When putting the birds in order from shortest to tallest, no one got the order entirely correct. Everyone guessed the smallest bird correctly but when guessing the second smallest, no one got it right. The two largest birds were about the same size and most guessed it right and some said the birds were the same size, so they had to just answer which was the larger one.

Figure 11. Third pilot experiment, side view.

3.8. Fourth experiment

Two birds (Northern shoveler and Rough-legged buzzard) were placed two meters away from the test participant, the birds were next to each other. participant estimated their heights from the beginning of the legs to the top of the bird's head. Then a virtual milk carton was given to the participant. Then they were asked if they wanted to change their answer. After that the milk carton was taken from their hand and placed between the birds. Then they were asked again if they wanted to change their answer. Then the milk carton was again handed to the participant and now they were asked to estimate the cartons height. Then the HMD is taken off and a real milk carton was shown, and they estimated its height. The birds and the carton were placed at the same distance so they can be compared easily.

The question presented to the participant was: “The two birds in front of you are two meters away. Tell the heights of the birds from the beginning of the legs to the top of the bird’s head.” Then the controller and the VR milk carton were handed to the participant. “There is a milk carton in your hand, do you want to change your answers?” Then the controller was taken away and the VR milk carton was moved to in between the birds. “The milk carton is now between the birds; do you want to change your answers? What is the height of the virtual milk carton? What is the height of the real milk carton?”

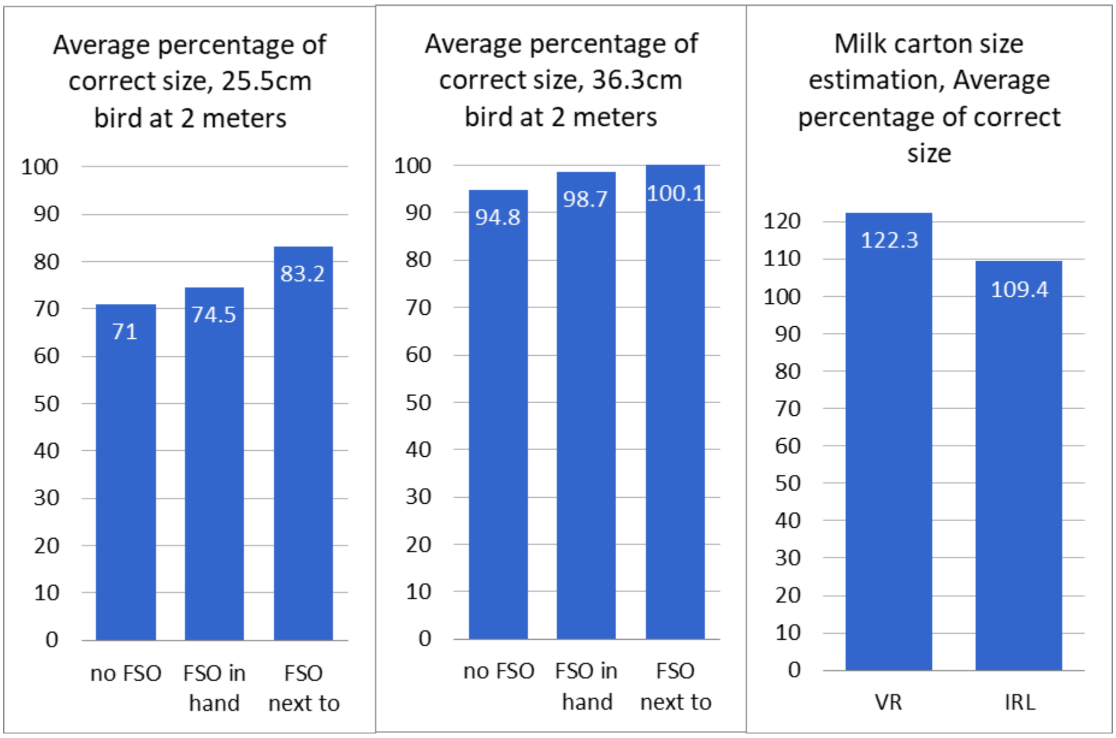

Figure 12. Data from fourth pilot experiment.

Table 5. Data from fourth pilot experiment.

Height - cm	Average of absolute errors - %	Lowest estimation - %	Highest estimation - %
25.5	18.1	-60.8	-1.9
36.3	34.4	-44.9	92.9
25.5 FSO hand	19.0	-41.2	17.7
36.3 FSO hand	35.8	-31.1	65.4
25.5 FSO ground	21.2	-41.2	56.9
36.3 FSO ground	36.3	-31.1	65.4
22.3 VR Milk carton	27.3	-23.9	79.1
23.4 IRL Milk carton	25.6	-14.5	92.3

Analysis: Height of the smaller bird was underestimated in all situations by almost everyone. Mean height of the bigger bird was close to the actual size, but the individual answers varied between -45% and +93%. Having the FSO as a help, the means of the answers got closer to the actual size. two out of nine did not change their answer at all. Out of the seven that changed their answer, five changed in the first phase and two of them changed it again for the second phase. For the milk cartons, means of the answers were bigger than the actual sizes. For virtual carton six out of nine answers were between -24% and +12% of the actual size and three were overestimates by over 65.7%. For the real carton eight answers were within -14.5% and +28.2% and one was +92.3%.

Figure 13. Fourth pilot experiment, second part.

Figure 14. Fourth pilot experiment, third part. Side view.

3.9. Answering pilot test questions, observations, lessons learned

The first test question was “How good are people at estimating the distance of an unfamiliar object from themselves in a virtual environment?”. The pilot test data shows that on average the people are quite good at estimating distances, but individually the answers vary quite a lot. During our tests people tended to slightly underestimate the distances.

Our second test question was “At a known distance, how good are people at estimating the height of an unfamiliar object?”. The pilot test data shows that people have a hint of the heights, but they lack the exact precision. While the means are quite close, the answers varied quite a lot. In most cases the heights were underestimated.

Our third test question was “At a known distance, how good are people at estimating the height of an unfamiliar object if a known object is present in the scene?”. The pilot test data shows that in about half of the cases having a familiar object in hand made the estimates more accurate and in the other half it made the estimates worse. When the FSO was placed in between the animals the estimates in some test participant became more accurate. In both cases, there were participant who did not change their answers regardless of having the FSO in hand or in scene. Whether the test participant could accurately estimate the size of the FSO did not seem to influence the estimates.

For the main tests, there were some things to consider. The environment must be made better by fixing some little things: The SteamVR’s blue circle that surrounds the user was still in the ground when the pilot tests were done, because our understanding was that it could not be easily removed. The scale of the environment may still be off by little, because measuring the objects precisely was quite hard. After completing the tests, we found out that the milk cartons in hand and in between the two birds in experiment four were not quite the same in terms of size; the handheld carton was 22.3 centimeters, while the one in the ground was 23.4 centimeters.

Three out of nine test participants reported feeling too short in the VR environment. The cause of this is not quite clear, but it may have affected the people’s estimates.

All in all, the pilot tests gave a good insight in what things to consider when making and executing the main tests, and what things should be fixed or changed in the future experiments. The sample of nine people was too small to draw any big conclusions, so a wider test is needed to achieve anything scientifically valuable.

3.10. Humans as test subjects

Based on our observation, the test participants seemed to have a strong tendency to center their answers around a number that is divisible by five and mostly liked to underestimate the sizes. With the tendency to answer with a number divisible by five it creates some of the errors in their estimation.

For the distance, the way the participants came to their estimates based on open-ended questions that we gave them after the experiment, some imagined how long their step is and counted the distance from that, some imagined a one-meter ruler, compared to own height and the others used intuition. The heights were estimated by comparing to the given distance, steps or own height, or imagining a ruler and intuition, only one had prior knowledge on birds. Generally, the participants said that estimating the distances or heights was somewhat harder in VR than real life, but not by much. But they said it would not be easy in real life either. Lack of cues was said to make the task more difficult.

3.11. Pictures of pilot tests

Figure 15. Test participant performing pilot tests with an HTC Vive HMD. Picture taken by thesis group.

Figure 16. Measuring the $1m^3$ cube during pilot test development. Tower was not present during the tests. Picture taken by thesis group.

4. MAIN TESTS

Based on what we learned from the pilot tests, we planned better experiments that would give better and easier to read results. The main tests consisted of 44 test participants (F=8, M=36). The test questions for the main tests remained largely the same than with minor modifications.

The test questions for the main tests were:

1. How good are people at estimating the distance of an unfamiliar object from themselves in a virtual environment?
2. At a known distance, how good are people at estimating the height of an unfamiliar object?
3. At a known distance, how good are people at estimating the height of an unfamiliar object if a known object is present in the scene? How does the answer differ when having the known object versus not having a known object?

The first of our experiments was designed to answer to question one, the second and third experiments to question two and the third experiment to question three.

4.1. Changes after pilot tests

For the main tests, the VR environment was modified a bit. The birds were changed to red, plain, red boxes without texture because we did not want the test participants to have any prior knowledge of the objects' sizes. The blue circle which was present in the pilot tests was hidden. The second experiment from the pilot test was removed as it was very similar to experiment three of pilot tests. In the main tests the participant was shown the milk carton before the test and were told its height. The scale was measured again and applied to the milk cartons and room height, and this time we believe the scale to match the real world. The hand-held milk carton was modified so that the milk carton on the floor and the hand-held milk carton were the same size. The floor was lowered a bit to get the VR floor to match the real floor and to see if it fixes the feeling of being too short in VR. The participants were explicitly told not to take steps or crouch during the experiments. A point was marked on the floor where the test participant will stand, so the tracking point is the same for everyone. This was done to eliminate issues with height tracking being inconsistent in different positions inside the tracking area [30].

The controller bodies were hidden for the whole time during the experiment. The environment was kept simple to get the most reliable data, since we thought that having more content in the room may affect each test participants' answers in different ways.

4.2. Test protocol

The tests were held either in English or in Finnish, according to the test participant's preference.

In the beginning of the tests the test participant read the research description and read and signed a consent form. Then the test participant's interpupillary distance (IPD) was measured and the HTC Vive headset was set accordingly. The following information is read to the test participant:

"We will be asking how big you think things are in VR. Just to calibrate your estimations, here is a milk carton that is 23.4 centimeters tall (a milk carton is shown to the participant). If you see a milk carton inside VR, you can assume that it is the same size. You can assume that your height is about the same in VR than it is in real life and that the height of the room the about the same in VR than it is in real life. Please stand still during the experiment."

When the participant had placed the HTC Vive headset on their head, the test started, and the participant was teleported to the first experiment. Movement between the experiments was handled by us by pressing a button on the keyboard.

4.3. First experiment

In the room, there was a single box in front of the participant, first the box was 11 meters away. In the second room the box was seven meters away and in the last room it was three meters away. While in each of the rooms and before they were moved to a next room, the participant was asked: "You see a box in front of you, please estimate the distance between you and the box. Please give the answer in meters as precisely as possible."

The figure 17 below shows the average percentage of the estimations from the correct distance in the first pilot experiment. The table 6 below shows the average of absolute errors and the lowest and highest estimation related to the correct distance in the first main experiment.

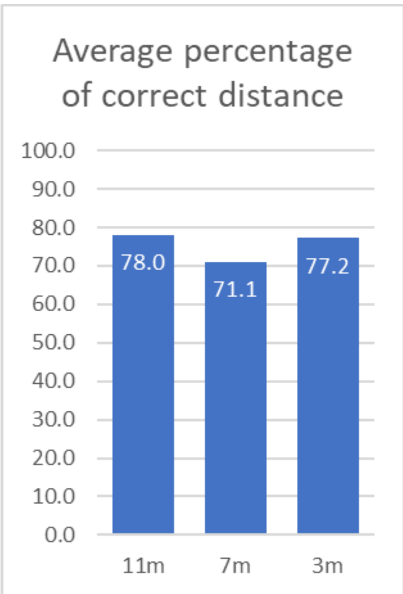

Figure 17. Data from first experiment.

Table 6. Data from first experiment.

Distance - m	Average of absolute errors - %	Lowest estimation - %	Highest estimation - %
11	34.4	-72.7	81.8
7	36.0	-71.4	71.4
3	28.5	-66.7	33.3

Analysis: Test participants had a strong tendency to underestimate distances during the first experiment. The averages were over 20% smaller than the correct distance was in each of the three evaluated distances. The answers also varied a lot: As seen in the table 6 above, the variation was over 100% for each of the distances.

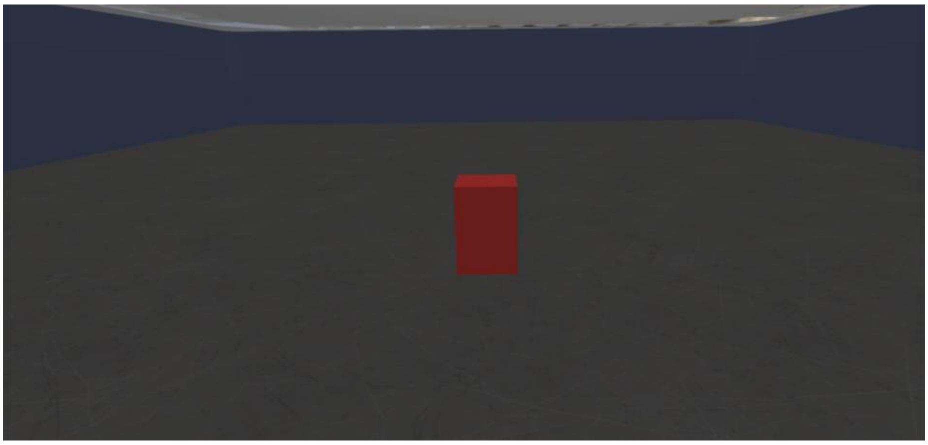

Figure 18. First experiment. Picture taken from the participant's perspective.

4.4. Second experiment

In the room, there were six boxes, placed around the participant in a semi-circle, the distance to each box was three meters, which was told to the participant. The heights of the boxes were 17, 58, 30, 100, 13 and 74 centimeters from left to right. In the room the participant was told "There are six boxes around you, please put them in order from shortest to tallest and when giving the answers name the boxes as second from the right, second from the left and so on." After giving their answer, the participant was asked "Now estimate the height of each box in centimeters. You can give the answers for example in the same order than you did just previously"

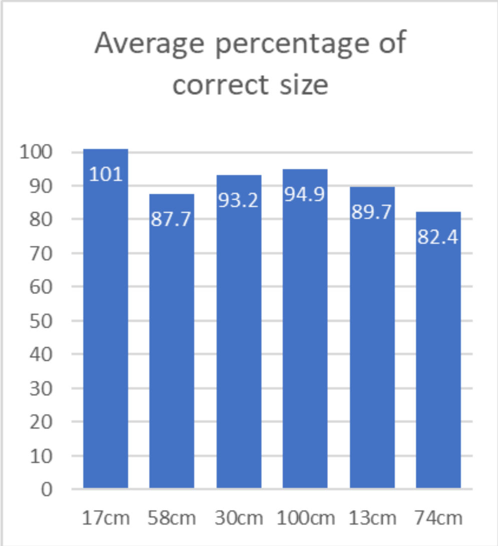

Figure 19. Data from second experiment.

Table 7. Data from second experiment.

Height - cm	Average of absolute errors - %	Lowest estimation - %	Highest estimation - %
17	23.1	-52.9	76.5
58	23.9	-74.1	89.7
30	22.4	-66.7	66.7
100	16.3	-53.0	50.0
13	25.5	-61.5	92.3
74	24.3	-66.2	62.2

Analysis: When putting the boxes in order from shortest to tallest, 43 out of 44 got the order correctly. The one person who put boxes is wrong order, mixed two boxes which heights were 58 and 74 centimeters. Every size aside from the 17cm box was on average underestimated, while the 17cm box was overestimated by 1%.

When estimating the heights of the boxes the percentage errors from the actual size were: for 17cm: -52.94% to +76.47%, for 58cm: -74.14% to +89.66%, for 30cm: -66.67% to +66.67%, for 100cm: -53.00% to +50.00%, for 13cm: -61.54% to +92.31% and for 74cm: -66.22% to +62.16%.

There were two outlier participants whose answers were left out as single-construct outliers. Where normal test participants answer ranged from around -50% to +50%, but these outliers' answers were around 60 to 300% from the correct answer. One participant's answer had to be left out because of a human error during the tests.

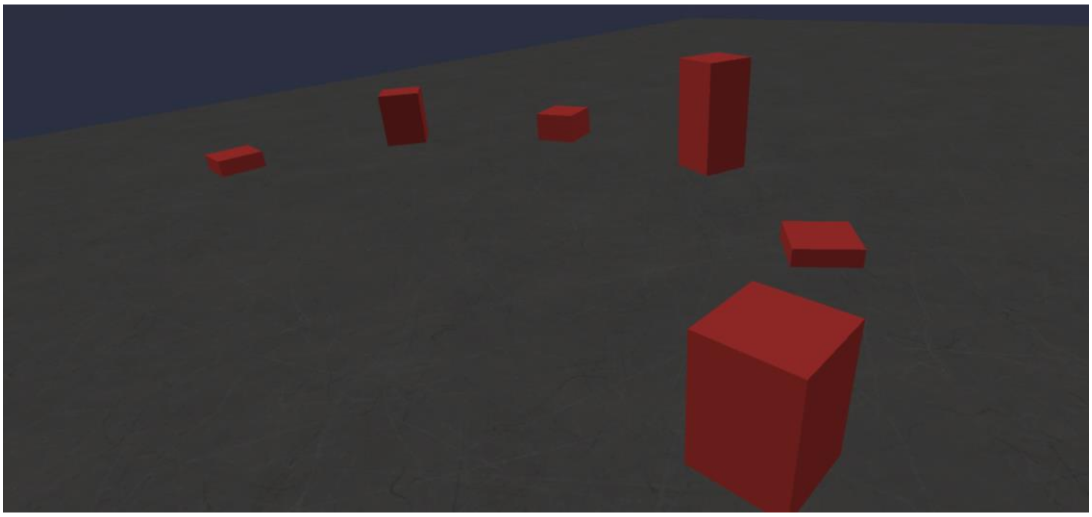

Figure 20. Second experiment, picture taken from side. Participant stands in a position in the middle that is at an equal distance from all the boxes.

4.5. Third experiment

In the room, there was two boxes in front of the participant and the distance to the boxes was two meters, which was told to the participant. The height of the boxes were 34 and 46 centimeters. The participant was asked “There are two boxes in front of you, please estimate their height in centimeters.”. After answering the question, the participant was handed a controller, which now showed a milk carton in the virtual environment, and a question was asked “Now with milk carton in your hand, do you want to change your estimate or leave your answer the same?”. After answering the second question, the controller was taken from the participant, the milk carton was hidden and in the next room was place in between the boxes. When in the last room, the participant was asked “Now the milk carton is in between the boxes, do you again want to change your estimate or leave your answer the same?”

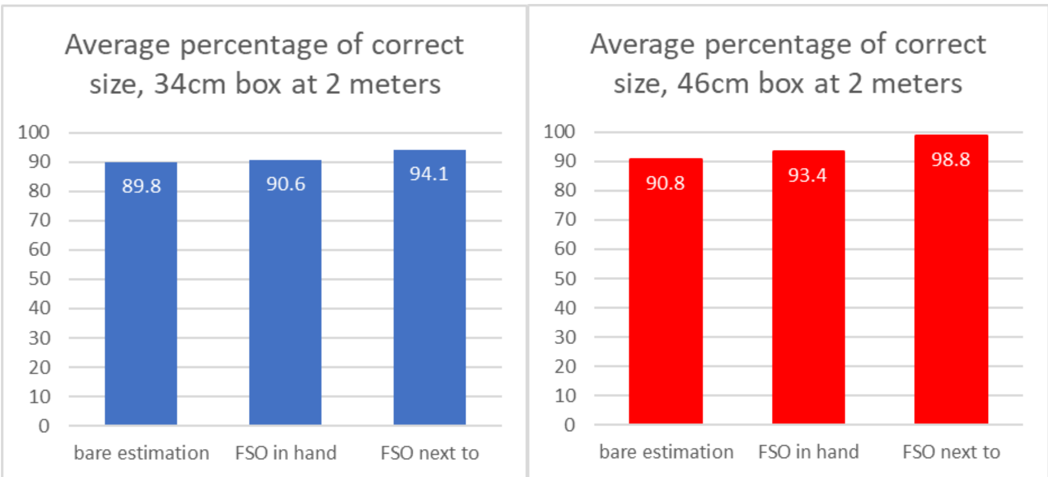

Figure 21. Data from third experiment.

Table 8. Data from third experiment.

Height - cm	Average of absolute errors - %	Lowest estimation - %	Highest estimation - %
34	22.5	-55.9	76.5
46	22.1	-56.5	73.9
34 FSO hand	20.3	-55.9	76.5
46 FSO hand	19.4	-45.7	73.9
34 FSO ground	15.0	-26.5	47.1
46 FSO ground	12.6	-30.4	52.2

Analysis: During the first part the average error for the 34cm box was -10.23% and for the 46cm box -9.22%. When the FSO was in the participants hand the errors were -9.38% and -6.59%. When the FSO was on the ground between the boxes, the errors were -5.92% and -1.25%. Having the FSO in hand improved the individual estimates on average by 2.22% and 2.63% (See appendix 3). When the FSO was in between the boxes, the improvements were 7.59% and 9.51% (See appendix 3).

For the 34cm box estimate errors varied between -55.88% and +76.47%, having the FSO in hand did not change these errors. When the FSO was between the boxes, the errors were between -26.47% and +47.06%. For the 46cm box the initial estimate errors varied -56.52% and +73.91%, having the FSO in hand improved the lower error to -45.65%. With the FSO between the boxes, the estimate errors were between -30.43% and +52.17%.

There was one outlier participant whose answers were left out as a single-construct outlier. Where normal test participants answer ranged from around -50% to +50%, the outlier's answers were around 60 to 300% from the correct answer.

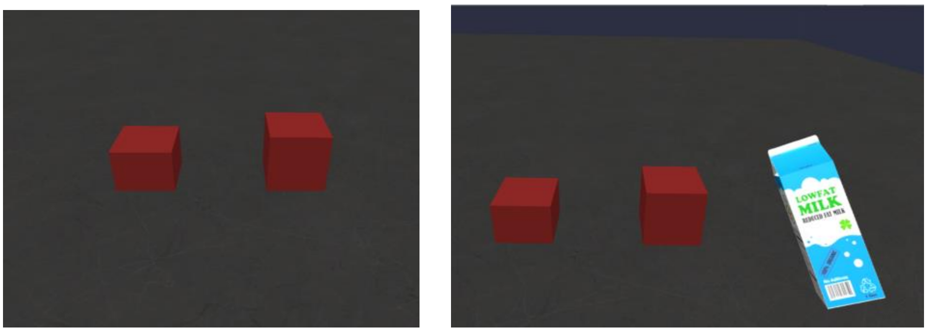

Figure 22. Third experiment, without milk carton and milk carton in hand.

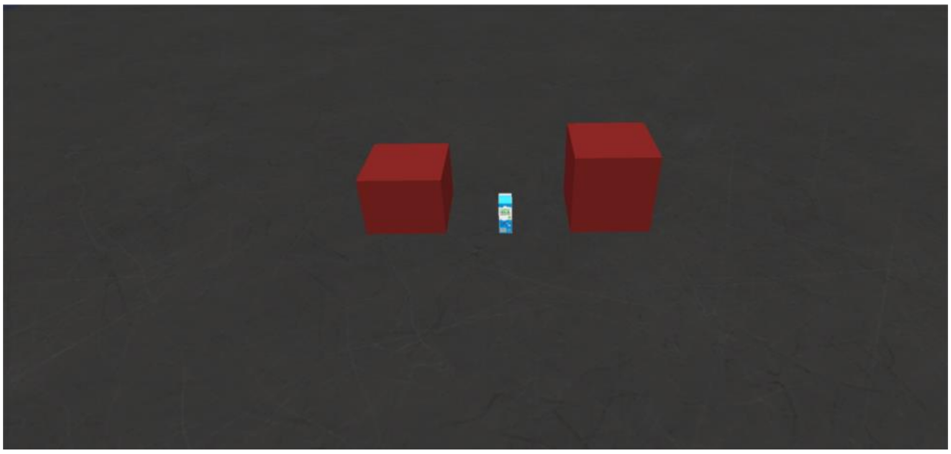

Figure 23. Third experiment, milk carton between boxes.

4.6. After-experiment open questions

After the three experiments, when the participant had given their answers, they were told to take the headset off and was asked following open questions:

> Have you used VR before this experiment, if so, how often or how many times?”
>
> “How did you feel about your own height in the VR environment?”
>
> “How did you estimate the distances? What about heights?”
>
> “Was estimating the sizes and distances different from real life, if so how?”
>
> “If the same test was done in real life, would your answers be the same or different?”

Summary of the answers to these questions can be found in the section 4.8. Test participants.

4.7. Results

People tended to underestimate distances between themselves and an unfamiliar object in a VE. This result is similar to what has been found in previous research, as mentioned before [24, 25, 22, 23]. At a known distance on average people underestimated the height of unfamiliar objects slightly. Having a known object in hand gave a small improvement in accuracy. When the known object was next to the unfamiliar object, the improvement was more noticeable.

4.8. Test participants

The participants had varying amounts of experience of VR before these tests (0...200+ hours). One had never used VR before, two of the participants had used VR previously for under two hours, 14 for two to 20 hours and six for over 20 hours.

Of the 44 participants 32 reported not feeling anything odd about their own height, five reported feeling too tall, six reported feeling too short and one reported feeling something odd about their height but could not specify how it felt weird. With the data, we got we cannot say if this had any effect on the participants' answers, because there was underestimations and overestimations also among people that felt that their height was correct or did not feel anything odd about it.

When evaluating the distance in the first experiment, the test participants reported imagining a one-meter step or their own height on the floor. Some reported trying to estimate the distance based on how big the object would be. Some used intuition or previous knowledge about a certain distance. Also, calculating the distance by knowing own height and the angle of head and trying to relate the distance to the room height were mentioned.

For the heights, the participants mostly used to relate the object to their own height and to the known distance between the participant and the object. Some participants reported that they estimated heights by trying to visualize the milk carton, which they were shown in the beginning, next to the objects. And when the milk carton was presented in the virtual environment (VE) to the participant, they compared directly to it.

Answers to the last two open questions were mixed. Some participants answered that evaluating distances and sizes was similar in VR than it is in real life and that they would give similar answers, while others reported that evaluating in VR differs a lot from the real life and that their answers would answer significantly differ from the answers they gave now.

4.9. Pictures of tests

Figures 24-26. Thesis group testing the environment.

5. CONCLUSION

When studying how humans perceive height and distance in VR with an HMD, many variables need to be considered when planning the experiments. Since how humans perceive objects is such a complex topic, for our experiments we made an environment that was as bare as possible. This included using an empty room with no furniture and nothing on the walls and choosing a monotonic floor texture. The virtual room's height matched the test rooms real height. This allowed us to collect data in a controlled environment with minimal possibilities for individuals to use any tricks to improve their results.

Based on the experiments with 44 participants, we can conclude that in VR people underestimate unknown distances and underestimate unknown heights when the distance is known. Having a familiar size objects in the virtual environment helps people to more accurately perceive height of objects. When the FSO is closer to the object that is being estimated, the estimate gets more accurate (FSO in hand vs FSO between boxes).

In future studies, we believe that things such as the effect of shadows, the objects being evaluated not only on the ground but also off the ground, and the effect of different FSO's and different cues could be considered as valuable subjects.

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Appendices

Appendix 1: Pilot test questions

Experiment 1: “In front of you is a bird. How far is the bird?”

Experiment 2.1: “The two birds in front of you are two and four meters away, tell their heights from the beginning of the leg to the top of their heads.”

Experiment 2.1: “The two birds in front of you are one and three meters away, tell the height of the smaller from the beginning of the leg to the top of its head and the bigger from the floor to the top of its head.”

Experiment 3: “There are six birds around you, they are three meters away from you. Tell their heights from floor to top of the head / beginning of the leg to the top of the head / from the stick to the top of the head and sort them from smallest to biggest.”

Experiment 4: “The two birds in front of you are two meters away. Tell the heights of the birds from the beginning of the legs to the top of the bird’s head. There is a milk carton in your hand, do you want to change your answers? The milk carton is now between the birds, do you want to change your answers? What is the height of the milk carton? What is the height of the real milk carton?”

Appendix 2. Pilot test data

EXP1												
Actual size	Experiment 1 - Distance	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean	
12	Bird 1 12m - Distance	10	10	10	15	15	12	17	8	10	11.9	
6	Bird 2 6m - Distance	5	5	5	4	7	6	5	5	5	5.2	
3	Bird 3 3m - Distance	2.5	2.5	2	2	2	2.5	2	3	3	2.4	
m	Error in percents (%)	p1	p2	p3	p4	p5	p6	p7	p8	p9		
	Bird 1 12m - Distance	-16.7	-16.7	-16.7	25	25	0	41.7	-33.3	-16.7	-0.9	
	Bird 2 6m - Distance	-16.7	-16.7	-16.7	-33.3	16.7	0	-16.7	-16.7	-16.7	-13.0	
	Bird 3 3m - Distance	-16.7	-16.7	-33.3	-33.3	-33.3	-16.7	-33.3	0	0	-20.4	
	Deviation from actual distance	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean of deviation	Mean of absolute deviations
	Bird 1 12m - Distance	-2	-2	-2	3	3	0	5	-4	-2	-0.111	2.556
	Bird 2 6m - Distance	-1	-1	-1	-2	1	0	-1	-1	-1	-0.778	1
	Bird 3 3m - Distance	-0.5	-0.5	-1	-1	-1	-0.5	-1	0	0	-0.611	0.611

EXP2												
Actual size	Experiment 2 - Relative Size	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean	
43.1	Room 1 - Bird 1 - 2m	40	30	40	40	30	35	40	60	30	38.3	
68.6	Room 1 - Bird 2 - 4m	80	60	70	90	50	50	100	100	70	74.4	
19.1	Room 2 - Bird 1 - 1m	15	15	10	15	13	20	20	40	15	18.1	
68.6	Room 2 - Bird 2 - 3m		40	50	80	35	60	70	100	40	59.4	
cm	Error in percents	p1	p2	p3	p4	p5	p6	p7	p8	p9		
	Room 1 - Bird 1 - 2m	-7.3	-30.4	-7.3	-7.3	-30.4	-18.8	-7.3	39.1	-30.4	-11.1	
	Room 1 - Bird 2 - 4m	16.6	-12.6	2.0	31.2	-27.1	-27.1	45.7	45.7	2.0	8.5	
	Room 2 - Bird 1 - 1m	-21.5	-21.5	-47.7	-21.5	-32.0	4.6	4.6	109.2	-21.5	-5.3	
	Room 2 - Bird 2 - 3m		-41.7	-27.1	16.6	-49.0	-12.6	2.0	45.7	-41.7	-13.5	
	Deviation from actual size	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean of deviation	Mean of absolute deviations
	Room 1 - Bird 1	-3.1	-13.1	-3.1	-3.1	-13.1	-8.1	-3.1	16.9	-13.1	-4.8	8.546
	Room 1 - Bird 2	11.4	-8.6	1.4	21.4	-18.6	-18.6	31.4	31.4	1.4	5.8	16.016
	Room 2 - Bird 1	-4.1	-4.1	-9.1	-4.1	-6.1	0.9	0.9	20.9	-4.1	-1.0	6.04
	Room 2 - Bird 2		-28.6	-18.6	11.4	-33.6	-8.6	1.4	31.4	-28.6	-9.2	20.28

EXP3												
Actual size	Experiment 3 - Relative Size 2	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean	
32.4	Bird 1	30	25	20	30	20	25	35	40	30	28.3	
63.7	Bird 2	60	40	45	75	40	50	66	100	70	60.7	
19.1	Bird 3	20	15	10	15	10	15	20	20	10	15	
28.4	Bird 4	30	20	15	25	20	25	30	40	35	26.7	
27.9	Bird 5	30	25	25	30	20	25	32	40	35	29.1	
68.6	Bird 6	70	45	50	80	40	50	70	130	60	66.1	
cm	Error in percents (%)	p1	p2	p3	p4	p5	p6	p7	p8	p9		
	Bird 1	-7.3	-22.7	-38.2	-7.3	-38.2	-22.7	8.2	23.6	-7.3	-12.4	
	Bird 2	-5.9	-37.2	-29.4	17.7	-37.2	-21.5	3.6	56.9	9.8	-4.8	
	Bird 3	4.6	-21.5	-47.7	-21.5	-47.7	-21.5	4.6	4.6	-47.7	-21.5	
	Bird 4	5.5	-29.7	-47.2	-12.1	-29.7	-12.1	5.5	40.7	23.1	-6.2	
	Bird 5	7.4	-10.5	-10.5	7.4	-28.4	-10.5	14.5	43.2	25.3	4.2	
	Bird 6	2	-34.4	-27.1	16.6	-41.7	-27.1	2	89.4	-12.6	-3.7	
	Deviation from actual size	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean of deviation	Mean of absolute deviations
	Bird 1	-2.4	-7.4	-12.4	-2.4	-12.4	-7.4	2.7	7.7	-2.4	-4.0	6.306
	Bird 2	-3.7	-23.7	-18.7	11.3	-23.7	-13.7	2.3	36.3	6.3	-3.1	15.526
	Bird 3	0.9	-4.1	-9.1	-4.1	-9.1	-4.1	0.9	0.9	-9.1	-4.1	4.707
	Bird 4	1.6	-8.4	-13.4	-3.4	-8.4	-3.4	1.6	11.6	6.6	-1.8	6.492
	Bird 5	2.1	-2.9	-2.9	2.1	-7.9	-2.9	4.1	12.1	7.1	1.2	4.896
	Bird 6	1.4	-23.6	-18.6	11.4	-28.6	-18.6	1.4	61.4	-8.6	-2.5	19.291
	Orders	p1	p2	p3	p4	p5	p6	p7	p8	p9	Correct	
	Bird 1	2	4	3	3	3	3	4	2	2	4	
	Bird 2	5	5	5	5	5	6	5	5	6	5	
	Bird 3	1	1	1	1	1	1	1	1	1	1	
	Bird 4	3	2	2	2	4	2	2	3	3	3	
	Bird 5	4	3	4	4	2	4	3	4	4	2	
	Bird 6	6	6	6	6	6	5	6	6	5	6	

EXP 4												
Actual size	Experiment 4 - height - 2m	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean	
25.5	Bird 1	25	15	10	20	15	20	23	20	15	18.1	
36.3	Bird 2	40	25	20	35	25	30	35	70	30	34.4	
25.5	Bird 1.2 - fso in hand	20	15	15	20	15	18	23	15	30	19.0	
36.3	Bird 2.2 - fso in hand	40	25	25	35	25	27	35	50	60	35.8	
25.5	Bird 1.2 - fso next to	20	15	20	20	20	18	23	15	40	21.2	
36.3	Bird 2.2 - fso next to	40	25	30	30	30	27	35	50	60	36.3	
22.3	milk carton in VR (hand)	25	17	20	25	20	22	37	40	40	27.3	
23.4	milk carton IRL	30	20	20	25	20	20	20	30	45	25.6	
cm	Error in percents	p1	p2	p3	p4	p5	p6	p7	p8	p9		
	Bird 1	-1.9	-41.2	-60.8	-21.5	-41.2	-21.5	-9.8	-21.5	-41.2		
	Bird 2	10.3	-31.1	-44.9	-3.5	-31.1	-17.3	-3.5	92.9	-17.3		
	Bird 1.2 - fso in hand	-21.5	-41.2	-41.2	-21.5	-41.2	-29.4	-9.8	-41.2	17.7		
	Bird 2.2 - fso in hand	10.3	-31.1	-31.1	-3.5	-31.1	-25.6	-3.5	37.8	65.4		
	Bird 1.2 - fso next to	-21.5	-41.2	-21.5	-21.5	-21.5	-29.4	-9.8	-41.2	56.9		
	Bird 2.2 - fso next to	10.3	-31.1	-17.3	-17.3	-17.3	-25.6	-3.5	37.8	65.4		
	milk carton in VR (hand)	12.0	-23.9	-10.4	12.0	-10.4	-1.5	65.7	79.1	79.1		
	milk carton IRL	28.2	-14.5	-14.5	6.8	-14.5	-14.5	-14.5	28.2	92.3		
	Deviation from actual size	p1	p2	p3	p4	p5	p6	p7	p8	p9	Mean of deviation	Mean of absolute deviations
	Bird 1	-0.5	-10.5	-15.5	-5.5	-10.5	-5.5	-2.5	-5.5	-10.5	-7.4	7.379
	Bird 2	3.7	-11.3	-16.3	-1.3	-11.3	-6.3	-1.3	33.7	-6.3	-1.8	10.156
	Bird 1.2 - fso in hand	-5.5	-10.5	-10.5	-5.5	-10.5	-7.5	-2.5	-10.5	4.5	-6.5	7.492
	Bird 2.2 - fso in hand	3.7	-11.3	-11.3	-1.3	-11.3	-9.3	-1.3	13.7	23.7	-0.5	9.649
	Bird 1.2 - fso next to	-5.5	-10.5	-5.5	-5.5	-5.5	-7.5	-2.5	-10.5	14.5	-4.3	7.492
	Bird 2.2 - fso next to	3.7	-11.3	-6.3	-6.3	-6.3	-9.3	-1.3	13.7	23.7	0.1	9.093
	milk carton in VR (hand)	2.7	-5.3	-2.3	2.7	-2.3	-0.3	14.7	17.7	17.7	5.0	7.297
	milk carton IRL	6.6	-3.4	-3.4	1.6	-3.4	-3.4	-3.4	6.6	21.6	2.2	5.933

Appendix 3. Main tests questions

Before starting experiments

We'll be asking the height of things in VR and at what distance things are in VR. Just to calibrate your estimations, here's a milk carton that is 23.4 centimeters tall. If you see a milk carton inside VR, you can assume that it is the same size. You can assume that your height is about the same in VR than it is in IRL and that the height of the room the about the same in VR than it is in IRL. Please stand still during the experiment.

Experiment 1

You now see a box in front of you. Please estimate the distance between you and the box. Please give the answer in meters and centimeters.

Experiment 2

There are six boxes around you. The distance between you and each of the boxes is three meters. Please put them in order from shortest to tallest.

Now estimate the height of each box in centimeters.

<u>Experiment 3</u>

There are two boxes in front of you. The distance between you and the boxes is two meters. Please estimate their height.

Now with milk carton in your hand, do you want to change your estimate or leave your answer the same?

Now the milk carton is in between the boxes, do you again want to change your estimate or leave your answer the same?

<u>After-experiment thoughts</u>

Have you used VR before this experiment, if so, how often or how many times?

How did you feel about your own height in the VR environment?

A lot of things that help you to estimate distances and heights have been removed from the environment. How did you estimate the distances? What about heights?

Was estimating the sizes and distances different from real life, if so, how?

Appendix 4. Main tests data

EXP1 - Distance

Box Height 65cm	s1	p2	p3	p4	p5	p6	p7	p8	p9	s10
Box 1 - 11m	7	7	8	7	5.5	10	8	12	6.5	15.0
Box 2 - 7m	4.5	4.5	5	4.5	4	5	6	5	3	7.0
Box 3 - 3m	3	2	2	2.5	2	2.5	2.5	2.5	2	3.0

Box Height 65cm	s11	s12	s13	s14	s15	s16	s17	s18	s19	s20
Box 1 - 11m	6	5	3	10	8.5	6	13	15	8	10.0
Box 2 - 7m	5	4.3	2	4.5	4.75	4	8	10	5	5.0
Box 3 - 3m	2.5	2	1.5	2.35	3.25	2.2	3.5	4	2	2.0

Box Height 65cm	s21	s22	s23	s24	s25	s26	s27	s28	s29	s30
Box 1 - 11m	6.5	10	15	6	4.5	10	6	7.5	4.5	8.0
Box 2 - 7m	4	4	8	3.5	3.5	4	3	6	2	6.0
Box 3 - 3m	2	2	3	1.25	1.75	2.5	2	3.5	1	3.5

Box Height 65cm	s31	s32	s33	s34	s35	s36	s37	s38	s39	s40
Box 1 - 11m	12	8	5	3	20	10	5	15	12	8.5
Box 2 - 7m	6	5	3	2.1	7	6	3	12	8	5.0
Box 3 - 3m	2	2	2	1.5	2	2	1	4	2.5	2.0

Box Height 65cm	s41	s42	s43	s44
Box 1 - 11m	7.5	6.2	7	10
Box 2 - 7m	4	3.9	4	5
Box 3 - 3m	2.25	2.3	2	2.5

Real dist, m	AVERAGE	min	max
11	8.58	3	20
7	4.98	2	12
3	2.31	1	4

Experiment 1 – Error in percents

EXP1 - Distance										
Box Height 65cm	s1	p2	p3	p4	p5	p6	p7	p8	p9	s10
Box 1 - 11m	-36.4	-36.4	-27.3	-36.4	-50.0	-9.1	-27.3	9.1	-40.9	36.4
Box 2 - 7m	-35.7	-35.7	-28.6	-35.7	-42.9	-28.6	-14.3	-28.6	-57.1	0.0
Box 3 - 3m	0.0	-33.3	-33.3	-16.7	-33.3	-16.7	-16.7	-16.7	-33.3	0.0
Box Height 65cm	s11	s12	s13	s14	s15	s16	s17	s18	s19	s20
Box 1 - 11m	-45.5	-54.5	-72.7	-9.1	-22.7	-45.5	18.2	36.4	-27.3	-9.1
Box 2 - 7m	-28.6	-38.6	-71.4	-35.7	-32.1	-42.9	14.3	42.9	-28.6	-28.6
Box 3 - 3m	-16.7	-33.3	-50.0	-21.7	8.3	-26.7	16.7	33.3	-33.3	-33.3
Box Height 65cm	s21	s22	s23	s24	s25	s26	s27	s28	s29	s30
Box 1 - 11m	-40.9	-9.1	36.4	-45.5	-59.1	-9.1	-45.5	-31.8	-59.1	-27.3
Box 2 - 7m	-42.9	-42.9	14.3	-50.0	-50.0	-42.9	-57.1	-14.3	-71.4	-14.3
Box 3 - 3m	-33.3	-33.3	0.0	-58.3	-41.7	-16.7	-33.3	16.7	-66.7	16.7
Box Height 65cm	s31	s32	s33	s34	s35	s36	s37	s38	s39	s40
Box 1 - 11m	9.1	-27.3	-54.5	-72.7	81.8	-9.1	-54.5	36.4	9.1	-22.7
Box 2 - 7m	-14.3	-28.6	-57.1	-70.0	0.0	-14.3	-57.1	71.4	14.3	-28.6
Box 3 - 3m	-33.3	-33.3	-33.3	-50.0	-33.3	-33.3	-66.7	33.3	-16.7	-33.3
Box Height 65cm	s41	s42	s43	s44						
Box 1 - 11m	-31.8	-43.6	-36.4	-9.1						
Box 2 - 7m	-42.9	-44.3	-42.9	-28.6						
Box 3 - 3m	-25.0	-23.3	-33.3	-16.7						

AVERAGE ERROR - %		abs avg error %	min	max
Box 1 - 11m	-21.96	34.36	-72.73	81.82
Box 2 - 7m	-28.88	36.02	-71.43	71.43
Box 3 - 3m	-22.84	28.52	-66.67	33.33

Experiment 2

Actual size - cm		s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
17.0	Box 1	16	20	15	20	18	15	13	25	13	20
58.0	Box 2	50	50	45	45	50	50	34	50	50	110
30.0	Box 3	23	35	25	25	34	25	18	35	23	40
100.0	Box 4	100	95	80	90	80	100	60	110	120	150
13.0	Box 5	13	15	10	15	10	10	7	15	10	12
74.0	Box 6	60	60	55	60	65	60	40	70	70	100
Actual size - cm		s11	[redacted]	s13	s14	s15	s16	s17	s18	s19	s20
17.0	Box 1	14		8	20	20	20	16	18	70	15
58.0	Box 2	55		23.4	70	57	60	45	50	200	50
30.0	Box 3	30		15	35	37	35	30	30	100	20
100.0	Box 4	100		47	115	100	105	98	95	200	80
13.0	Box 5	10		5	12	13.5	14	12	13	50	10
74.0	Box 6	60		25	75	60	70	52	60	120	60
Actual size - cm		s21	s22	s23	s24	s25	s26	s27	s28	s29	s30
17.0	Box 1	20	15	30	13.5	27	25	12	15	12.7	15
58.0	Box 2	60	50	100	40	75	40	15	40	38.1	40
30.0	Box 3	40	30	50	23.4	40	30	10	20	20.32	25
100.0	Box 4	100	100	150	70	100	100	55	70	93.98	80
13.0	Box 5	15	12	20	9	20	10	10	10	6.35	10
74.0	Box 6	70	65	120	46.8	80	60	26	50	50.8	50
Actual size - cm		s31	s32	s33	s34	s35	s36	s37	s38	s39	s40
17.0	Box 1	14	10	10	70	15	30	20	20	15	15
58.0	Box 2	60	50	25	190	50	60	60	45	35	60
30.0	Box 3	25	25	15	120	30	45	25	23	20	25
100.0	Box 4	100	100	50	230	80	120	100	100	60	100
13.0	Box 5	10	5	5	50	10	25	15	14	10	10
74.0	Box 6	70	60	30	180	60	90	70	60	35	65
Actual size - cm		s41	s42	s43	s44						
17.0	Box 1	20	14	15	15						
58.0	Box 2	45	42	60	50						
30.0	Box 3	30	20	30	30						
100.0	Box 4	130	76	100	130						
13.0	Box 5	15	10	10	10						
74.0	Box 6	50	48	60	80						

Actual - cm	Mean	ABS deviation	Mean's deviation from actual size - (%)
17.0	17.175610	0.1756	1.03
58.0	50.841463	-7.1585	-12.34
30.0	27.968780	-2.0312	-6.77
100.0	94.877561	-5.1224	-5.12
13.0	11.654878	-1.3451	-10.35
74.0	60.941463	-13.0585	-17.65

Experiment 2 – Error in percents

Actual size - cm		s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
17.0	Box 1	-5.88	17.65	-11.76	17.65	5.88	-11.76	-23.53	47.06	-23.53	17.65
58.0	Box 2	-13.79	-13.79	-22.41	-22.41	-13.79	-13.79	-41.38	-13.79	-13.79	89.66
30.0	Box 3	-23.33	16.67	-16.67	-16.67	13.33	-16.67	-40.00	16.67	-23.33	33.33
100.0	Box 4	0.00	-5.00	-20.00	-10.00	-20.00	0.00	-40.00	10.00	20.00	50.00
13.0	Box 5	0.00	15.38	-23.08	15.38	-23.08	-23.08	-46.15	15.38	-23.08	-7.69
74.0	Box 6	-18.92	-18.92	-25.68	-18.92	-12.16	-18.92	-45.95	-5.41	-5.41	35.14

Actual size - cm		s11	~~s12~~	s13	s14	s15	s16	s17	s18	~~s19~~	s20
17.0	Box 1	-17.6	~~-11.8~~	-52.9	17.6	17.6	17.6	-5.9	5.9	~~311.8~~	-11.8
58.0	Box 2	-5.2	~~-31.0~~	-59.7	20.7	-1.7	3.4	-22.4	-13.8	~~244.8~~	-13.8
30.0	Box 3	0.0	~~-23.3~~	-50.0	16.7	23.3	16.7	0.0	0.0	~~233.3~~	-33.3
100.0	Box 4	0.0	~~-30.0~~	-53.0	15.0	0.0	5.0	-2.0	-5.0	~~100.0~~	-20.0
13.0	Box 5	-23.1	~~-7.7~~	-61.5	-7.7	3.8	7.7	-7.7	0.0	~~284.6~~	-23.1
74.0	Box 6	-18.9	~~-39.2~~	-66.2	1.4	-18.9	-5.4	-29.7	-18.9	~~62.2~~	-18.9

Actual size - cm		s21	s22	s23	s24	s25	s26	s27	s28	s29	s30
17.0	Box 1	17.6	-11.8	76.5	-20.6	58.8	47.1	-29.4	-11.8	-25.3	-11.8
58.0	Box 2	3.4	-13.8	72.4	-31.0	29.3	-31.0	-74.1	-31.0	-34.3	-31.0
30.0	Box 3	33.3	0.0	66.7	-22.0	33.3	0.0	-66.7	-33.3	-32.3	-16.7
100.0	Box 4	0.0	0.0	50.0	-30.0	0.0	0.0	-45.0	-30.0	-6.0	-20.0
13.0	Box 5	15.4	-7.7	53.8	-30.8	53.8	-23.1	-23.1	-23.1	-51.2	-23.1
74.0	Box 6	-5.4	-12.2	62.2	-36.8	8.1	-18.9	-64.9	-32.4	-31.4	-32.4

Actual size - cm		s31	s32	s33	~~s34~~	s35	s36	s37	s38	s39	s40
17.0	Box 1	-17.6	-41.2	-41.2	~~311.8~~	-11.8	76.5	17.6	17.6	-11.8	-11.8
58.0	Box 2	3.4	-13.8	-56.9	~~227.6~~	-13.8	3.4	3.4	-22.4	-39.7	3.4
30.0	Box 3	-16.7	-16.7	-50.0	~~300.0~~	0.0	50.0	-16.7	-23.3	-33.3	-16.7
100.0	Box 4	0.0	0.0	-50.0	~~130.0~~	-20.0	20.0	0.0	0.0	-40.0	0.0
13.0	Box 5	-23.1	-61.5	-61.5	~~284.6~~	-23.1	92.3	15.4	7.7	-23.1	-23.1
74.0	Box 6	-5.4	-18.9	-59.5	~~143.2~~	-18.9	21.6	-5.4	-18.9	-52.7	-12.2

Actual size - cm		s41	s42	s43	s44
17.0	Box 1	17.6	-17.6	-11.8	-11.8
58.0	Box 2	-22.4	-27.6	3.4	-13.8
30.0	Box 3	0.0	-33.3	0.0	0.0
100.0	Box 4	30.0	-24.0	0.0	30.0
13.0	Box 5	15.4	-23.1	-23.1	-23.1
74.0	Box 6	-32.4	-35.1	-18.9	8.1

Actual - cm	Avg of errors - %	ABS error of
17.0	1.032999	0.1756097561
58.0	-12.342304	-7.158536585
30.0	-6.770732	-2.031219512
100.0	-5.122439	-5.122439024
13.0	-10.347092	-1.345121951
74.0	-17.646671	-13.05853659

Experiment 3

Actual size -cm	Experiment 3 - height - 2m	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
34.0	Box 1	30	40	30	40	30	30	15	35	23	30
46.0	Box 2	40	50	40	60	40	40	20	45	30	40
34.0	Box 1 - fso in hand	30	35	30	40	30	30	23.4	30	27	30
46.0	Box 2 - fso in hand	40	45	40	60	40	40	32	45	40	40
34.0	Box 1 - fso next to	35	35	30	40	30	30	28	30	25	30
46.0	Box 2 - fso next to	50	45	40	60	40	40	46.8	45	40	40

Actual size -cm	Experiment 3 - height - 2m	s11	s12	s13	s14	s15	s16	s17	s18	s19	s20
34.0	Box 1	60	30	15	30	40	35	28	30	50	20
46.0	Box 2	80	40	25	50	50	50	35	40	70	30
34.0	Box 1 - fso in hand	60	30	30	35	40	35	28	30	50	30
46.0	Box 2 - fso in hand	80	40	50	55	50	50	35	40	70	50
34.0	Box 1 - fso next to	48	35	30	30	27	32	28	35	50	30
46.0	Box 2 - fso next to	60	50	47	50	37	46	40	50	70	50

Actual size -cm	Experiment 3 - height - 2m	s21	s22	s23	s24	s25	s26	s27	s28	s29	s30
34.0	Box 1	30	25	30	26	45	30	23	22	25.4	25
46.0	Box 2	50	35	45	32	55	40	30	28	35.56	35
34.0	Box 1 - fso in hand	30	25	30	26	28	30	23	22	25.4	25
46.0	Box 2 - fso in hand	50	35	45	32	37	40	30	28	35.56	35
34.0	Box 1 - fso next to	30	35	30	28	28	30	46	28	25.4	25
46.0	Box 2 - fso next to	50	45	45	41	37	40	52	46	35.56	35

Actual size -cm	Experiment 3 - height - 2m	s31	s32	s33	~~s34~~	s35	s36	s37	s38	s39	s40
34.0	Box 1	30	30	20	~~100~~	30	40	45	30	20	30
46.0	Box 2	40	40	25	~~125~~	50	50	60	40	25	40
34.0	Box 1 - fso in hand	30	40	25	~~150~~	15	40	45	30	20	30
46.0	Box 2 - fso in hand	40	50	35	~~175~~	40	50	60	40	25	40
34.0	Box 1 - fso next to	30	30	45	~~50~~	30	35	35	30	30	30
46.0	Box 2 - fso next to	40	40	60	~~80~~	50	45	50	40	40	45

Actual size -cm	Experiment 3 - height - 2m	s41	s42	s43	s44
34.0	Box 1	25	30	30	30
46.0	Box 2	35	40	50	40
34.0	Box 1 - fso in hand	25	27	30	30
46.0	Box 2 - fso in hand	32	36	50	40
34.0	Box 1 - fso next to	25	32	30	30
46.0	Box 2 - fso next to	32	48	50	40

Actual size -cm	Mean	ABS deviation	Mean's deviation from actual size - (
34.0	30.52	-3.48	-10.24
46.0	41.76	-4.24	-9.22
34.0	30.81	-3.19	-9.38
46.0	42.97	-3.03	-6.59
34.0	31.99	-2.01	-5.91
46.0	45.43	-0.57	-1.24

Experiment 3 – Error in percents

EXP 3 - error %

Actual size -cm	Experiment 3 - height - 2m	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
34.00	Box 1	-11.76	17.65	-11.76	17.65	-11.76	-11.76	-55.88	2.94	-32.35	-11.76
46.00	Box 2	-13.04	8.70	-13.04	30.43	-13.04	-13.04	-56.52	-2.17	-34.78	-13.04
34.00	Box 1 - fso in hand	-11.76	2.94	-11.76	17.65	-11.76	-11.76	-31.18	-11.76	-20.59	-11.76
46.00	Box 2 - fso in hand	-13.04	-2.17	-13.04	30.43	-13.04	-13.04	-30.43	-2.17	-13.04	-13.04
34.00	Box 1 - fso next to	2.94	2.94	-11.76	17.65	-11.76	-11.76	-17.65	-11.76	-26.47	-11.76
46.00	Box 2 - fso next to	8.70	-2.17	-13.04	30.43	-13.04	-13.04	1.74	-2.17	-13.04	-13.04

Actual size -cm	Experiment 3 - height - 2m	s11	s12	s13	s14	s15	s16	s17	s18	s19	s20
34.00	Box 1	76.47	-11.76	-55.88	-11.76	17.65	2.94	-17.65	-11.76	47.06	-41.18
46.00	Box 2	73.91	-13.04	-45.65	8.70	8.70	8.70	-23.91	-13.04	52.17	-34.78
34.00	Box 1 - fso in hand	76.47	-11.76	-11.76	2.94	17.65	2.94	-17.65	-11.76	47.06	-11.76
46.00	Box 2 - fso in hand	73.91	-13.04	8.70	19.57	8.70	8.70	-23.91	-13.04	52.17	8.70
34.00	Box 1 - fso next to	41.18	2.94	-11.76	-11.76	-20.59	-5.88	-17.65	2.94	47.06	-11.76
46.00	Box 2 - fso next to	30.43	8.70	2.17	8.70	-19.57	0.00	-13.04	8.70	52.17	8.70

Actual size -cm	Experiment 3 - height - 2m	s21	s22	s23	s24	s25	s26	s27	s28	s29	s30
34.00	Box 1	-11.76	-26.47	-11.76	-23.53	32.35	-11.76	-32.35	-35.29	-25.29	-26.47
46.00	Box 2	8.70	-23.91	-2.17	-30.43	19.57	-13.04	-34.78	-39.13	-22.70	-23.91
34.00	Box 1 - fso in hand	-11.76	-26.47	-11.76	-23.53	-17.65	-11.76	-32.35	-35.29	-25.29	-26.47
46.00	Box 2 - fso in hand	8.70	-23.91	-2.17	-30.43	-19.57	-13.04	-34.78	-39.13	-22.70	-23.91
34.00	Box 1 - fso next to	-11.76	2.94	-11.76	-17.65	-17.65	-11.76	35.29	-17.65	-25.29	-26.47
46.00	Box 2 - fso next to	8.70	-2.17	-2.17	-10.87	-19.57	-13.04	13.04	0.00	-22.70	-23.91

Actual size -cm	Experiment 3 - height - 2m	s31	s32	s33	~~s34~~	s35	s36	s37	s38	s39	s40
34.00	Box 1	-11.76	-11.76	-41.18	~~194.12~~	-11.76	17.65	32.35	-11.76	-41.18	-11.76
46.00	Box 2	-13.04	-13.04	-45.65	~~171.74~~	8.70	8.70	30.43	-13.04	-45.65	-13.04
34.00	Box 1 - fso in hand	-11.76	17.65	-26.47	~~341.18~~	-55.88	17.65	32.35	-11.76	-41.18	-11.76
46.00	Box 2 - fso in hand	-13.04	8.70	-23.91	~~280.43~~	-13.04	8.70	30.43	-13.04	-45.65	-13.04
34.00	Box 1 - fso next to	-11.76	-11.76	32.35	~~47.06~~	-11.76	2.94	2.94	-11.76	-11.76	-11.76
46.00	Box 2 - fso next to	-13.04	-13.04	30.43	~~73.91~~	8.70	-2.17	8.70	-13.04	-13.04	-2.17

Actual size -cm	Experiment 3 - height - 2m	s41	s42	s43	s44
34.00	Box 1	-26.47	-11.76	-11.76	-11.76
46.00	Box 2	-23.91	-13.04	8.70	-13.04
34.00	Box 1 - fso in hand	-26.47	-20.59	-11.76	-11.76
46.00	Box 2 - fso in hand	-30.43	-21.74	8.70	-13.04
34.00	Box 1 - fso next to	-26.47	-5.88	-11.76	-11.76
46.00	Box 2 - fso next to	-30.43	4.35	8.70	-13.04

Actual size -cm	Exp3 - height - 2m	avg error cms	abs avg error cms	Average error (%)	avg error abs %
34.00	Box 1	-3.48	7.67	-10.23	22.54
46.00	Box 2	-4.24	10.15	-9.22	22.06
34.00	Box 1 - fso in hand	-3.19	6.91	-9.38	20.33
46.00	Box 2 - fso in hand	-3.03	8.94	-6.59	19.44
34.00	Box 1 - fso next to	-2.01	5.08	-5.92	14.95
46.00	Box 2 - fso next to	-0.57	5.77	-1.25	12.55

Experiment 3 – Relative improvements

RELATIVE IMPROVEMENTS % - ALL PARTICIPANTS

BOX 1 - FSO HAND	0.00	14.71	0.00	0.00	0.00	0.00	24.71	-8.82	11.76	0.00	no change	31
	0.00	0.00	44.12	8.82	0.00	0.00	0.00	0.00	0.00	29.41	improved	8
	0.00	0.00	0.00	0.00	14.71	0.00	0.00	0.00	0.00	0.00	got worse	5
	0.00	-5.88	14.71	~~-147.06~~	-44.12	0.00	0.00	0.00	0.00	0.00		
	0.00	-8.82	0.00	0.00								
BOX 2 - FSO HAND	0.00	6.52	0.00	0.00	0.00	0.00	26.09	0.00	21.74	0.00	no change	32
	0.00	0.00	36.96	-10.87	0.00	0.00	0.00	0.00	0.00	26.09	improved	7
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	got worse	5
	0.00	4.35	21.74	~~-108.70~~	-4.35	0.00	0.00	0.00	0.00	0.00		
	-6.52	-8.70	0.00	0.00								
BOX 1 - FSO GROUND	8.82	14.71	0.00	0.00	0.00	0.00	38.24	-8.82	5.88	0.00	no change	21
	35.29	8.82	44.12	0.00	-2.94	-2.94	0.00	8.82	0.00	29.41	improved	19
	0.00	23.53	0.00	5.88	14.71	0.00	-2.94	17.65	0.00	0.00	got worse	4
	0.00	0.00	8.82	~~147.06~~	0.00	14.71	29.41	0.00	29.41	0.00		
	0.00	5.88	0.00	0.00								
BOX 2 - FSO GROUND	4.35	6.52	0.00	0.00	0.00	0.00	54.78	0.00	21.74	0.00	no change	20
	43.48	4.35	43.48	0.00	-10.87	8.70	10.87	4.35	0.00	26.09	improved	22
	0.00	21.74	0.00	19.57	0.00	0.00	21.74	39.13	0.00	0.00	got worse	2
	0.00	0.00	15.22	~~97.83~~	0.00	6.52	21.74	0.00	32.61	10.87		
	-6.52	8.70	0.00	0.00								

RELATIVE AVERAGE IMPROVEMENTS % - ALL PARTICIPANTS	
BOX 1 - FSO HAND	-1.18
BOX 2 - FSO HAND	0.10
BOX 1 - FSO GROUND	10.76
BOX 2 - FSO GROUND	11.52
RELATIVE AVERAGE IMPROVEMENTS % - OUTLIER EXCLUDED	
BOX 1 - FSO HAND	2.22
BOX 2 - FSO HAND	2.63
BOX 1 - FSO GROUND	7.59
BOX 2 - FSO GROUND	9.51