FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

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THE EFFECT OF NON-HUMANOID SIZE CUES FOR THE PERCEPTION OF PHYSICS PLAUSIBILITY IN VIRTUAL REALITY

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ABSTRACT

This thesis studies the relationship between inhabited scale and the perception of physics in virtual reality. The work builds upon the findings of an earlier study on the perception of physics when a user is virtually scaled down. One of these studies involved having users evaluate the movement of soda tabs dropped and thrown by a doll-sized humanoid robot when the user was either scaled normally or scaled down. This thesis aimed to replicate the study with the alteration of using a cat as a more natural, non-humanoid actor to throw the soda tabs. Similarly to the previous study, it was hypothesized that participants would prefer realistic physics when at a normal scale and unrealistic physics when virtually scaled down. For this, a photo-realistic virtual environment and a realistic animated cat were created. The method of study involved participants observing the cat drop soda tabs from an elevated platform. Participants experienced the event with both realistic physics (dubbed true physics) and unrealistic physics (dubbed movie physics) and were asked to choose the one they perceived as most expected. This method was repeated for participants at a normal scale and when they were virtually scaled down. The study recruited 40 participants, and the results were unable to confirm either hypothesis and were unable to find a preference towards either physics preference. The result differs from Pouke's study which was able to find a preference for movie physics when participants were virtually scaled down. This thesis discusses the findings and also uses supplementary gathered data to offer potential rationalizations and insights into the received result.

Keywords: Virtual reality, perception, scaling, plausibility, human factors

Pouke S. (2022) Ei-humanoidin koko vihjeiden vaikutus fysiikan uskottavuuden havainnollistamiseen virtuaalitodellisuudessa. Oulun yliopisto, Tietotekniikan tutkinto-ohjelma, 60 s.

TIIVISTELMÄ

Tämä diplomityö tutkii käyttäjän koon ja fysiikan havainnollistamisen välistä suhdetta virtuaalitodellisuudessa. Tämä työ perustuu Pouken tekemiin löytöihin fysiikan havaitsemisessa kun käyttäjää virtuaalisesti kutistetaan virtuaalitodellisuudessa. Yhdessä näistä tutkimuksista käyttäjiä kysyttiin arvioimaan nukkekokoisen humanoidirobotin heittämien tölkinrenkaiden liikettä kun käyttäjä oli joko normaalin kokoinen tai virtuaalisesti kutistettu pieneksi.

Tämän työn tavoitteena oli toistaa kyseinen tutkimus, mutta vaihtaa humanoidirobotin tilalle kissa toimimaan luonnollisempana tekijänä. Kuten aiemassa tutkimuksessa, tämän työn hypoteesiksi oletetaan että käyttäjät suosivat todenmukaista fysiikkaa normaalissa mittakaavassa ja epärealistista fysiikkaa kutistettuna. Tämän selvittämistä varten luotiin fotorealistinen virtuaaliympäristö sekä realistisesti animoitu kissa. Tutkimuksen menetelmässä osallistujat tarkkailivat kissaa, joka pudotti tölkinrenkaita korotetulta alustalta. Osallistujat kokivat tapahtuman sekä realistisella fysiikalla että epärealistisella fysiikalla, ja heitä pyydettiin valitsemaan se, jonka he pitivät odotetuimpana. Tämä menetelmä toistettiin osallistujille normaalissa mittakaavassa ja kutistettuna. Tutkimukseen rekrytoitiin 40 osallistujaa, ja tulokset eivät pystyneet vahvistamaan kumpaakaan hypoteesia eivätkä löytäneet mieltymystä kumpaankaan fysiikkaan. Tulos eroaa edellisestä tutkimuksesta, joka löysi mieltymyksen epärealistiseen fysiikkaan, kun osallistujia oli kutistettuna. Tässä työssä keskustellaan tästä havainnosta sekä tarjotaan mahdollisia rationalisointeja ja muita löydöksiä saaduista täydentävistä tuloksista.

Avainsanat: Virtuaalitodellisuus, havainnollistaminen, skaalaus, uskottavuus

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FOREWORD

I would like to thank Prof. Timo Ojala and Dr. Evan Center for acting as my supervisors and guiding me with this thesis, and Dr. Matti Pouke for the idea for this thesis. I would also like to thank and express my gratitude to my brother, Eeli Pouke who helped in creating an immaculate model and pristine animations for the cat that was so vital for the success of this thesis.

Oulu, November 30th, 2022

Sakaria Pouke

LIST OF ABBREVIATIONS AND SYMBOLS

VR	Virtual Reality
IPD	Inter-pupillary distance
PI	Place Illusion
PSI	Plausibility Illusion
PBR	Physically Based Rendering
VE	Virtual Environment

1. INTRODUCTION

1.1. Inception of the Idea

In 2022 Pouke. et al. conducted studies [1][2]exploring the ability of users to deduce the reality of physics in a virtual environment when inhabiting a doll's or giant's body. Experimental evidence showed that when participants were tasked with dropping objects while scaled as either unusually big or small, the level of gravity that was felt as most realistic was respectively unrealistically large or small. User scaling in virtual environments is generally achieved by giving specific size cues. In these studies, the participant's height and their virtual inter-pupillary distance (IPD) were altered. IPD here refers to the distance between a user's pupils. In a further study, participants were placed in two scenarios; one where they were at a normal scale and one where they were virtually scaled down. This time, the size cue participants experienced was in the form of embodying a virtual doll-sized body. Participants then observed a humanoid doll-sized robot throwing soda tabs 2 distinctive times. Once with a realistic gravitational strength and once with a lower-than-normal strength (dubbed movie physics). Subjects were asked to choose which of these physics they preferred. Interestingly, this study found that most participants selected the movie physics as the more plausible physics for the scenario for both scenarios.

One potential shortcoming discussed in this study was that it used a doll-sized humanoid to showcase the physics. This means that participants may possibly receive mismatching size cues from the humanoid itself. Essentially, regardless of the other size cues, participants may be most heavily influenced by the cues of the humanoid, which they perceive to be of normal human size. This then influences their perception of the size of the soda tab being thrown, as well as the following rigid body physics. This led to an interesting avenue of research. Altering the study by using a different and more natural method to induce rigid body physics may cause a difference in the perceived true physics.

The aim of this study is to repeat the method of the aforementioned study, but omit using a humanoid in showcasing the physics. Instead, this study will attempt to use a more natural and plausible method for generating rigid body physics for the participant to observe. The study decided to use an adult-sized cat for dropping and throwing the soda tabs. We assume the cat to be a more familiar and natural actor than a small humanoid robot.

1.2. Applications

This study aims to add to the existing literature on the causes and effects of virtually altering the scale of humans. The research conducted here will provide additional understanding as to how scenarios, where physics has to be understood, should be crafted or taken into account.

With the rise of multiple commercial VR headsets and new industries for Virtual Reality Applications, the amount of virtual environments tailored for virtual reality has drastically risen [3]. Whether the environment is intended for industrial use or for entertainment, a subset of these environments will intend to scale the user. Examples of this are the already present multi-scale collaboration virtual environments (mCVE). In these, multiple users are placed at different levels of scale in order to better achieve a collaborative goal. For instance, Zhang and Furnas [4] presented an interactive environment that would have users inhabit two different scales. The environment placed two city planners in a city with one at street scale and the other as a giant who could see the whole city. This allowed for interesting cross-collaboration between the scales, such as the user inhabiting the giant being able to move the street-sized user to specific locations very precisely.

Another big industrial sector where VR could drastically alter common practices is Healthcare and Medicine. Healthcare professionals could use VR to train themselves in different tasks such as surgical operations. Using VR would allow the operator to change their own scale to better see and understand the operation they were conducting, though this would require them to understand the consequences of changing their scale.

Using VR in education is also becoming much more commonplace. In subjects such as physics where visualization is key for understanding, VR could prove to be an excellent tool. Being able to scale a student down and show them physical phenomena at small scales could hasten understanding and learning, but it would be paramount that the environment mimicked reality as well as possible, and that students understood at what scale they were operating.

Advances in imaging techniques and robotics also open up new concepts for small-scale operations. Systems such as teleoperated small-scale robots could become commonplace in commercial applications in the future. However, the intuitiveness of controlling these systems is still not understood. For example, The ability of the operators of these systems in reacting to unfamiliar situations is unclear. Time-sensitive tasks and physics in particular could provide a challenge to operators if the environment is not understood correctly.

1.3. Thesis Structure

The following section will introduce research that is related to this study. This will include previous studies conducted on the effect of scale on physics perception as well as studies focusing on the factors that are important for creating the illusion of feeling small.

Section 3 will explain the design of the study. This includes conceiving hypotheses for the study and explaining the implementation and proceedings of the study. A very large part of the implementation will also go in-depth about the methods used to create the 3D environments used in the study. Prototypes, tests, and contemplated methods will be explained in the appropriate sections to give extra insight into how the environment and its features were created. Some background information on the inner workings of those methods will also be given to allow for a better understanding of how they work and why those methods were chosen.

Section 4 will state the results and discuss the findings. All of the gathered data will be stated before any of the findings are contemplated. The limitations and future work will also be discussed.

Finally, section 5 will conclude the thesis with a summary of the findings.

2. RELATED WORK

2.1. Inducing the Sensation of Feeling Small

To be able to determine a participant's preference for physics while inhabiting a small scale, we first have to ensure that they feel small. There are several different elements that have to be taken into account to reach an adequate sensation of feeling small.

2.1.1. Perspective

Eye height has been shown to be an important factor for distinguishing apparent sizes in virtual environments. Sedgwick [5] first proposed the idea that the horizon line is a source of information for estimating the sizes of objects. This theory has been further tested by Wraga [6] by altering the effective eye height of participants using a false floor. The study found that height judgments of objects were affected by altering eye height, whereas width judgments were not. Similarly, Dixon et al. [7] tested the difference in eye height variation in non-immersive displays and immersive environments. The study concluded that eye height scaling was only evoked when within an immersive environment and not when using non-immersive displays.

Furthermore, height has been shown to affect egocentric distance perception (the distance from an observer to an object) as well. The study by Leyrer at al.[8] tested participants on their accuracy of verbal distance judgments, given a specific virtual eye height as well as a self-animated avatar. The findings suggest that eye height had a major influence on the estimates the participants gave, both in egocentric distances as well as the dimensions of the virtual room. However, the study also mentions that small differences in virtual eye height went unnoticed between participants. Interestingly, this phenomenon is not replicated in the study by Deng et al [9]. Here the participants were asked to gauge whether their feet would be above or below the ground when given a specific environment and virtual height. The paper hypothesizes that this may be due to the fact that participants in this study were primed to look for small differences in height.

The virtual inter-pupillary distance (IPD) has also been shown to be significant for the scale perception of objects. IPD refers to the distance between the pupils of a human. In virtual terms, this refers to the two cameras that are being used to render the image for each eye. By moving the distance between these cameras we can change the virtual IPD for a participant in a virtual environment. In their study, Pimusomboon et al [10], tasked participants with judging the size of spheres in a virtual environment with varying levels of IPD. The experimental results supported their hypothesis that IPD affected the participant's perception of a virtual object's size. Objects were perceived to be smaller with a bigger IPD and bigger with a small IDP.

It is important to note that the virtual height and IPD of a participant are potentially interlinked in creating the sensation of a different sense of scale. Pimusomboon also hypothesized that both a larger IPD and a larger eye height independent of each other would cause participants to feel like a giant. However, their experimental results suggest that it may take both the greater IPD and the greater height to induce the sensation of feeling like a giant in participants.

2.1.2. Body Cues

When gauging for scale, it can be theorized that humans use their own bodies as a reference. Virtual reality allows us to alter the appearance of the inhabited body, which can yield some interesting results. For instance, Ogawa et al [11], explored how the realism of an avatar affects perceived object sizes. In the study, a virtual hand was given various levels of realism and size, and subjects were asked to evaluate the size of a cube. The study found that the cube was perceived to be smaller when the hand was enlarged and not true to size. This effect was only measured in the case of the realistic hand model, which indicates a realistic avatar induces a stronger sense of body ownership, which in turn causes users to rely on scaling objects with their body as a metric.

Using the body as a reference for measuring distances is not limited to the hand. Van der Hoort et al.[12] conducted an experiment in which participants experienced ownership of a doll's or giant's body. To achieve this, users were shown an alternate body from the waist down in VR. This body was touched synchronously with the participant's own body with a small rod. This strongly induced the sensation that the artificial body was the participant's own body, as the brain attempts to reconcile the spatially and temporally correlated visual and somatic signals. For the control, participants were also given an asynchronous touch, to reduce the feeling of body ownership. The study found that when participants were in a tiny body, they perceived objects to be larger and further away. Conversely, when they were in a larger body, they perceived objects to be smaller and closer. Additionally, the effect was greater when the participant's and doll's bodies were correctly synchronized compared to when the body ownership illusion was disrupted.

2.1.3. Environmental Cues

Another arising factor for determining one's size is the environment and its contents. Humans will often use different objects as a reference to gauge the height of other things. This can also be used to gauge the height of one's self.

When testing for eye-height sensitivity, in addition to varying height, Deng et al. [9] also varied the environment the participant was in. The uncertainty intervals for eye height manipulations were found to be smaller for environments that contained strong familiar size cues, such as doors and items of furniture. Deng et al. also reference previous research by Epstein [13] which suggests that familiar objects with an assumed canonical size influence distance perception.

An abundance of environmental cues can also potentially lessen the impact of other cues such as height. In their study, Kim et al.[14] asked participants to estimate the sizes of cubes whilst placed in a virtual room. Participants were given different levels of height as well as IPD. The measured discrepancy in size estimates when eye height was altered was very low, which goes against previous literature in the field. Kim theorizes that this could be due to the large number of familiar size cues that were placed in the virtual environment, which may provide a stronger sense of size constancy for objects when at different eye heights.

2.2. Plausibility and Presence

For this study, it will be important to consider both the plausibility and presence of the environment. Presence or Place illusion (PI), as described by Slater [15] refers to the sense of being in that place, that a user has when inhabiting an environment. PI is often confused or assumed to be the same as immersion. Rather, immersion should be considered as the means or boundaries that allow PI to occur. For example. a virtual reality headset provides many immersive systems such as head tracking and surround sound, but two users can have different levels of PI based on their actions or thoughts. Though both users had the same level of immersion, they still felt different levels of place illusion. Plausibility or the plausibility illusion (PSI) in turn refers to the feeling that the things happening in the environment are real. For example, consider an environment where a bird is sitting on a rock in front of a user. When the user approaches the bird, it leaps into the air near the user and flies away. Though the bird is not actually there for real, the user may still be startled by it and try to avoid hitting it. The user has essentially considered the actions of the bird somewhat believable.

In short, while PI is concerned with how the world is perceived, PSI is concerned with what and how happenings are perceived. It should be noted that these components are qualia. This means that the strengths of the illusion are subjective and vary from person to person, and as such, they can not be directly measured but can be indirectly assessed using various questionnaires and physical or behavioral responses. In this study, we will want to measure the strength of these illusions, as they may correlate with how participants deem the physics should work.

2.3. Presence and Photo-Realism

An important factor to consider for achieving high levels of presence is the type of style the environment is created in. In particular, the level of photo-realism in a virtual environment has been studied for its effect on plausibility or presence.

Balakrishnan et al [16], demonstrated in their study that spatial presence, as well as spatial memory, were increased when users were placed in a photo-realistic environment over a simplistic line rendered environment. Likewise, increased place illusion has been correlated with photo-realistic characters acting in an environment. Zibrek et al.[17] studied participant reactions to an expressive human character represented either photo-realistically or with a simple, stylized look. The study noted that participants responded to the expressions of the photo-realistic character more than that of the stylized character. The study also found that participants preferred the environment that was rendered realistically.

However, the impact of photo-realism on increased presence is not so clear-cut. In their study [18], Zimmons investigated the impact of lighting and surface detail on presence, task performance, and object recall in a virtual environment. The study placed participants in a virtual room containing a six-meter-deep pit surrounded by a ledge and asked them to drop a ball at a specific target within the pit. This procedure was followed for multiple different levels of rendering fidelity. The study found no significant difference in physiological responses between the different levels, implying that the presence experienced was the same regardless of the level of photo-realism.

However, it is important to try to avoid the uncanny valley effect that can sometimes arise from character designs that attempt to be photo-realistic but fail in certain areas. This creates a dip in the correlation between perceived realism and how realistically the character is rendered. As was first shown by Mori [19], unnatural movements in particular can cause a feeling of eeriness in viewers. Mori was able to find this in the case of humanoids, but the phenomenon has also been found in zoomorphic robots by Löffler et al. [20].

2.4. Human Ability for Physics and Gravity Perception

The ability of humans to discern the correct strength of gravity should be considered in this study to evaluate it as a method for determining if deviations from the norm are able to be perceived.

McIntyre et al. [21] studied the ability of humans to adapt to different gravitational strengths with astronauts. The experiment had astronauts catch vertically moving balls, and found that they were less accurate in this task in lower gravity conditions than in earth's gravity.

Within Virtual Reality, testing of the humans' ability to adapt to different gravitational situations has been conducted. For example, Russo et al. [22] had participants intercept horizontally thrown balls with a racket at 1g and 0g gravity. The study found that participants used an internal understanding of gravity in both scenarios, despite knowing otherwise. Senot et al. [23] were able to find similar results in a study where balls were dropped vertically down with gravitationally consistent accelerating velocity versus a constant velocity. In this study participants were much more likely to anticipate and intercept the ball when in conditions most similar to those on earth.

To a similar effect, Moscatelli [24] conducted an experiment asking participants to judge the duration of motions when either the participant or the scene was tilted by 45 degrees and found that judgments for a downward motion were better than for an upward motion for both scenarios, though tilting reduced the effect. Moscatelli argues that implicit knowledge of gravity is used to calculate the time of downward trajectories of objects.

Jörges [25] shows in his paper the efficacy of gravity as a strong Bayesian prior and that it is perceived with multiple senses, such as the visual, and vestibular senses as well as body orientation. The reliability of this prior is very high, and as such, it can override any conflicting information. This effect is given as one of the reasons that performing tasks with an alternate gravity in VR is often performed poorly.

2.5. Physics at Different Scales

The study of physics at smaller scales has already been investigated in multiple ways. Pouke et al. [1] conducted a study on the perception and understanding of physics on both a smaller and a larger scale. In the first study, participants were scaled down to the size of a doll, and placed in a university campus virtual environment containing multiple accurate size cues such as tables, chairs, books, and soda cans. Participants were then given the task of dropping and throwing five pull tabs. The tabs were chosen due to their reasonable authenticity in the chosen environment as well as their consistent mass. This interaction was conducted with both "real" physics and "movie" physics. In the real physics scenario, the strength of gravity was set at a normal level whereas in movie physics gravity was set as lower than normal. The strength of the lower gravity was dialed such that the objects appeared as if dropped from a normal human height when observed from the scale of a doll. The participants were asked which of the two interactions felt correct. The study predicted that scaled-down users would find movie physics matched their expectations better than true physics and that it would also appear more realistic. Indeed, both hypotheses were supported as the study found that about 3 in every 4 participants felt the movie physics to be correct, and 9 out of 10 participants felt that the movie physics matched their initial expectations better.

The second study followed a similar procedure, but this time users were scaled up to be giants, 10 times larger than the average human. For this, a real-world outdoor marketplace was constructed as a 3D environment. While real physics was kept the same, movie physics was created by raising normal gravity levels by a factor of 10x to mimic the conditions that would match the normal human scale. Instead of soda tabs, participants were tasked with dropping wooden logs (3 meters long with a diameter of 27.7 cm). Participants were instructed to drop three logs into a sea visible in front of the subjects. Like the first study, it hypothesized that for a scaled-up user, movie physics was more likely to feel realistic and match the user's expectations. The experiment was able to confirm that movie physics felt more realistic but was unable to confirm that movie physics matched the expectation of the participants, as 70 percent of participants chose movie physics as more realistic but only 63 percent of users considered movie physics as matching their expectations better.

Pouke also studied the impact of the body ownership illusion for both the estimation of object sizes and the perception of physics [2]. Akin to the study by Van de Hoort [12], participants were subjected to visuotactile stimuli to elicit a body ownership illusion for an invisible doll-sized body. Participants were given both synchronous stimuli to reach the body ownership and asynchronous stimuli for preventing the onset of the illusion. After subjecting the participants to one set of stimuli they were asked to estimate the size of cubes. Additionally, the participants were shown a scaled-down robot handling soda tabs with both real and movie physics. Participants were asked to pick which version of physics they preferred. The study predicted that movie physics would be preferred when participants were given synchronous stimuli while true physics would be preferred with asynchronous stimuli. However, the study found that movie physics was selected by a majority in both of the conditions, which questions the impact of body scaling as the reason for a preference for movie physics. The study was also not able to replicate the findings by Van de Hoort in regard to size estimation. Participants found the objects to be smaller rather than bigger with synchronous stimuli compared to asynchronous stimuli.

Questionnaire data in the study showed that participants felt they had invisible legs with both stimuli which were then theorized to be the reason for a preference for movie physics in both conditions. The study also theorizes that the humanoid robot used for the physics task could also act as a strong size cue with the potential to override the cues given by the participant's virtual body. Moreover, the animation performed by the robot appeared very human-like, which could reinforce the illusion that the motions in the task were being performed at a human scale.

3. STUDY DESIGN

3.1. Hypotheses

This study will mimic the approach taken by Pouke et al. [2]. Therefore, hypotheses 3 and 4 from the study will be copied. These investigate whether the apparent naturalness of rigid body dynamics changes when the user is virtually scaled down. In our case, we also want to determine whether a non-humanoid entity performing the physics experiment will have different results from the previous study which used a humanoid entity.

Thus we get the following hypotheses:

1. When observing physics at a normal scale, subjects will consider true physics to appear more real.
2. When observing physics while standing and scaled with IPD scaling, the participants will consider movie physics to appear more real.

These hypotheses were preregistered [26] to be evaluated using an exact binomial test (one-tailed) with an alpha threshold of less than 0.05 to support each hypothesis separately.

3.2. Study Protocol

Participants are placed in two of four scenarios (A1, B1, A2, and B2). In these, they will observe a cat drop soda tabs. The behavior of the cat and the look of the environment will stay the same for each scenario, but the inhabited scale in VR will change, and the gravitational scale of the scene observed first will change. For legibility's sake, the differences in gravity have been dubbed "True" for a gravitational scale of 1 and "Movie" for a gravitational scale of 1/5.

Table 1. Different scenarios

VR scale / First gravitational scale	1	1/5
True	A1	B1
Movie	A2	B2

Each participant will observe from both perspectives (A and B), but the first gravitational scale may vary. To control for any potential ordering biases, the order of the scenarios will be altered based on a balancing sheet. Participants can be run with either of the views first, and either of the gravity's first. However, the following scenario will always keep the same viewing angle, until both gravitational scenarios have been observed. We end up having 8 different orders in which we can run participants. The order will cycle 5 times until 40 participants have been run. The complete order can be seen in figure 1.

ID (eg. 01M)	Males	ID (eg. 01F)	Females
	A1B1		A1B2
	A1B1		A1B2
	B1A1		B2A1
	B1A1		B2A1
	A1B2		A2B1
	A2B2		A2B1
	B2A2		B1A2
	B2A1		B1A2
	A2B1		A2B2
	A1B1		A2B2
	B1A1		B2A2
	B1A2		B2A2
	A2B2		A1B2
	A2B2		A1B2
	B2A2		B2A1
	B2A2		B2A1
	A1B1		A2B1
	A1B1		A2B1
	B1A1		B1A2
	B1A1		B1A2

Figure 1. Counterbalance sheet

After the participant is shown the scenarios from one perspective, they are asked to choose the scenario where the falling of the objects matched their expectations. The asked question is given as:

- Thinking back on how the pull tabs were behaving, which matched your expectations, the first or the second time?

3.3. Additional Data Collection

Participants are finally given a questionnaire of a modified Slater-Usoh-Steed (SUS) questionnaire [27]. This questionnaire aims to find out the level of presence and plausibility that the user experiences while in virtual reality. The full questionnaire can be found in the appendix 1. Participants are also asked for some background information about their age, gender, virtual reality, and video game experiences. The data gathered in this questionnaire will be used in further exploratory analyses.

3.4. Participant Selection

For this experiment, we are not interested in any specific age range or any specific vocation. Participants with any levels of experience with VR or any other virtual environments are admissible, though these aspects will be asked about in the final questionnaire. A balance between the sexes will be striven for but with leeway for a slight bias in either direction. Subjects that could not see clearly due to lens fog or subjects who self-report not having normal, or corrected normal vision or stereo vision will be excluded. The experiment will collect data from 40 participants. This sample size is based on the related previous studies [1] [2].

The target of 40 participants for this study was achieved with a balance of 21 males, and 19 females. The age of participants averaged to 27, with the youngest and oldest ages recorded as 21 and 40 respectively.

3.5. Virtual Environment

3.5.1. Chosen Game Engine

The following implementation was constructed using Unreal Engine 5 [28]. The game engine was chosen to be the same as the engine in the previous study. Unreal Engine creates the capability to produce excellent-looking photo-realistic environments and interactions with relative ease, while also keeping much of the complex optimizations necessary under the hood. Using Unreal Engine allows us to quickly iterate over and alter the scene we wish to create.

3.5.2. The Surroundings

As this study is based on the study by Pouke, we will want to minimize the number of changes done to any aspects of the experiment. This will allow us to get data that is much more comparable to the original study. As such, the environment will be constructed the same way with a few minor alterations.

As we will be using a cat to demonstrate the physics, we will also need a ledge from which to drop items. We want the trajectory and the time objects spend in the air to be as close to the original study as possible, so we also want the ledge to be at the same height as from where the original humanoid threw the objects. This is a relatively low height for which using a table would not seem plausible. Instead, a platform cart shown in figure 2 was modeled as a more plausible platform. The platform was given a blue rubber surface with metallic edges. The pattern on the rubber was left very simple so that the physical interactions would be seen as clearly as possible.

Figure 2. Platform cart

Additionally, a cat carrier (seen in figure 3) was added on top of the table from which the cat could appear and disappear. This allows for very a very distinctive start and stop to the scene since the cat always starts or ends up in the carrier. Since the carrier also hides the cat, it allows us to get away with a cruder reset for the animation of the cat, and resetting a level for different gravitational or viewing conditions won't show the cat as a rigid statue before the animation is initiated.

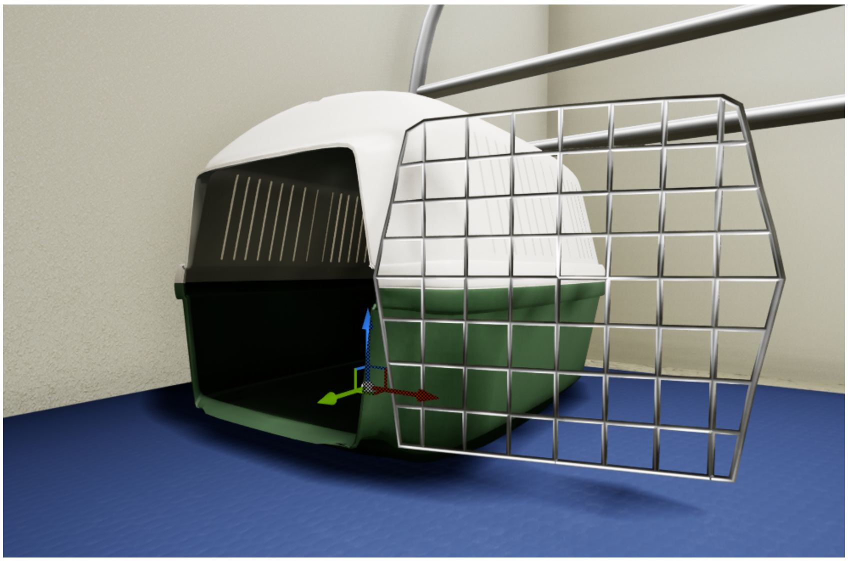

Figure 3. Cat carrier

The virtual environment will be created with a photo-realistic style to attempt to achieve higher levels of presence but also to keep in line with the same level of realism as in the scenario in the study by Pouke. A photo-realistic environment also has the possibility of providing more size cues due to its more complex nature. As a concrete example, the textures of floors and walls are generally more complex and full of patterns in a photo-realistic environment, while in a stylized environment these are often left simple and mono-colored. The extra detail could provide the participant with extra information from which they can deduce their size.

One important aspect that was kept note of during the production of the virtual environment was the size of objects. Since our study is concerned with an accurate sense of gravity and its perception, it is important that we measure the objects in the environment to be exactly the same size as they are in the real world. Measurements were conducted during the modeling of individual objects as well as when compositing the scene together as seen in fig 4.

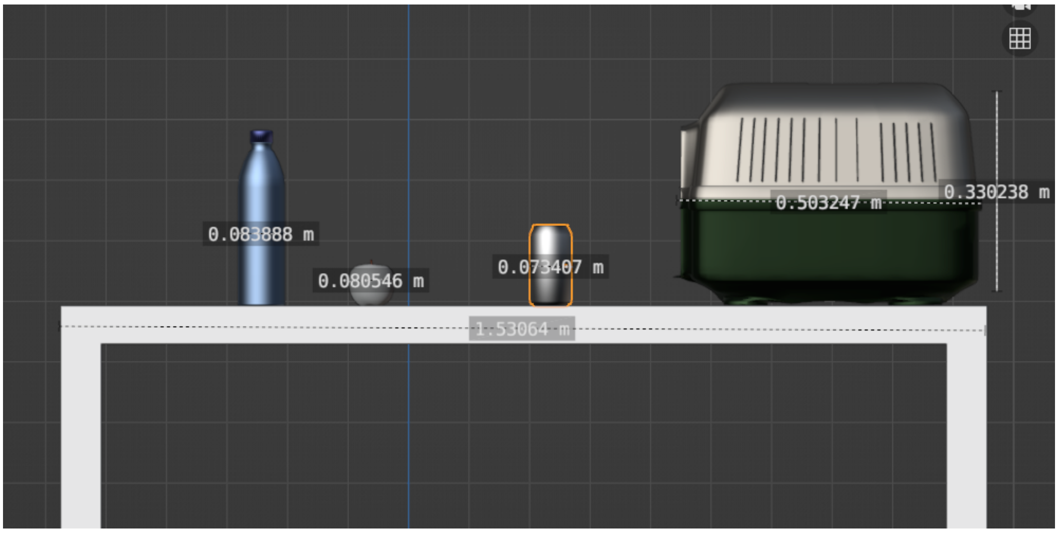

Figure 4. Object measurements

To achieve an adequate photo-realistic level, materials were chosen to use the Physically Based Rendering (PBR) approach for their shading. In practice, objects were given at the least a diffuse, roughness, metal, and normal texture (e.g in figure 5). These textures were used to approximate how lighting bounces off objects to give them photo-realistic features, such as specular highlights and detailed shadowing. Advanced methods such as vertex displacement and parallax mapping could be used to add minor detail to the environment, but their perceived effects would be relatively minute in our case, so they are not absolutely necessary.

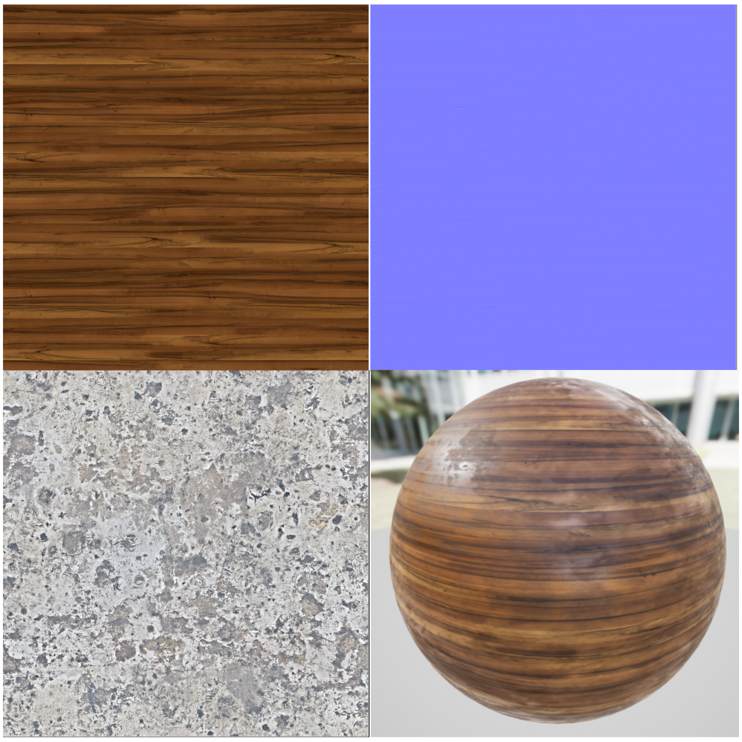

Figure 5. Diffuse, normal, and roughness textures for a wood material

Many of the objects in the environment are static, such as the carrier, the table, and the walls. As we know that they will not move during the proceedings, we can calculate additional static lighting effects on them. More specifically, we can simulate multiple bounces of light and calculate how they impact the shadowing of areas. This process takes some time to compute, but since we know the objects are static, this only needs to be done once, after which the objects can read that data from what is known as a shadow map. The resulting shadows can be seen in figure 6.

Figure 6. Shadowing of the environment

Figure 7. Back of the room

The objects that are dropped or thrown off the ledge stay the same as in the original study, as tabs from soda cans. These objects were shaded with the Physically based rendering approach to achieve a maximal photo-realistic look. As the objects are not static, they can not use any offline generated data for lighting. However, due to their metallic property, we can capture the reflection of the environment as a spherical texture, and then lay this texture onto the objects to mimic the reflection that would be present on the objects.

During the prototyping phase, other objects were theorized as potential candidates for being dropped. A coke can, apple, and water bottle (seen in figure 8) were created and used for their high plausibility of appearing in a scene such as this. However, for the sake of consistency with the previous study, this idea was discarded and the soda tabs seen in figure 9 were used instead.

Figure 8. Unused physics objects

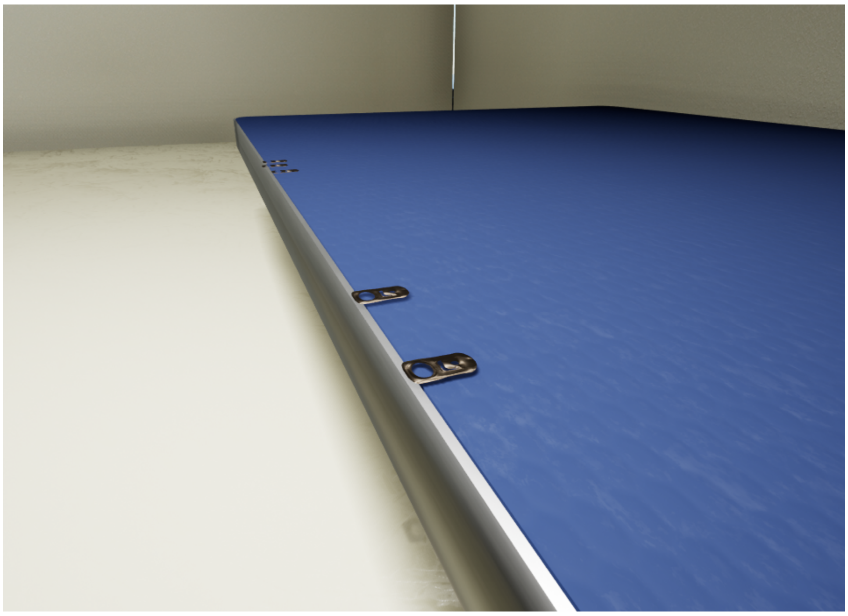

Figure 9. Soda tabs

3.5.3. The Cat

To maximize the place illusion, the cat was chosen to be created with a photo-realistic design so that it matches the surroundings. This means that extra attention was paid to both the model and the animations of the cat. The final rendition was completely custom-built so that it could be maximally catered to fit the environment and meet high standards for its visual fidelity.

The cat was 3D Modelled using Blender[29]. The shape of the cat was modeled as skinny and without the extra volume as this would be added later on as fur using a different method. The model for the cat went through two distinct iterations. The first iteration of the cat was modeled as a 10-week-old kitten, seen in figure 10. Unknowns about the performance of the fur implementation meant that a model that would require less fur was conceptualized. A 10-week-old kitten simply does not have the same size and surface area for fur that an adult cat would have, which would decrease the amount of needed fur. However, research into the methods of generating fur proved to be optimistic in terms of performance. Additionally, an adult cat was theorized to be of a more familiar size to the general population than a kitten, and therefore would provide a more reliable size cue for the participants to observe. With the performance of fur no longer being a major issue, the second iteration of the model was made to be a fully grown adult cat seen in figure 11.

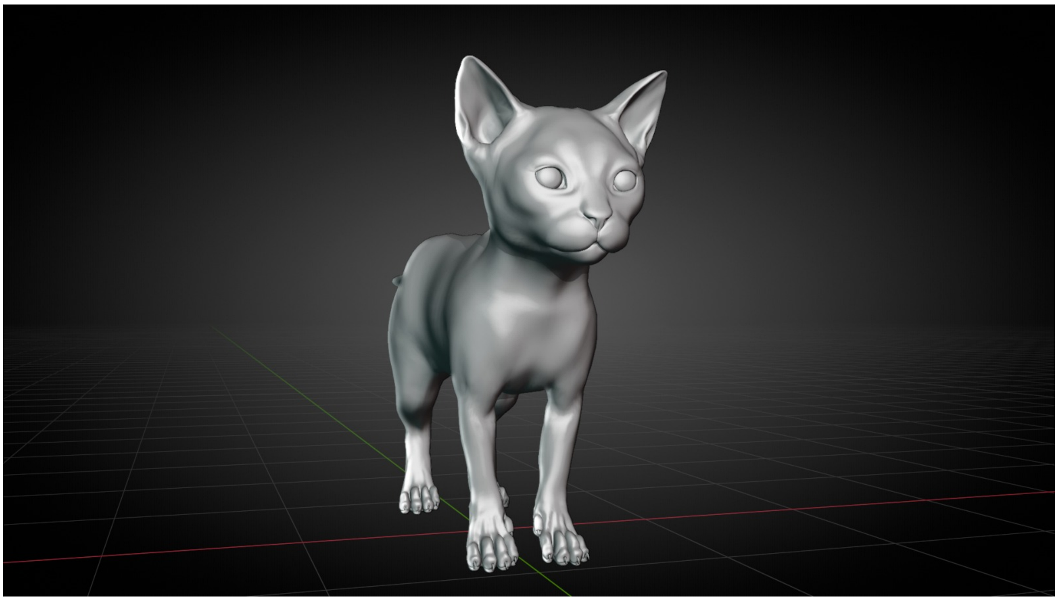

Figure 10. Kitten model without fur

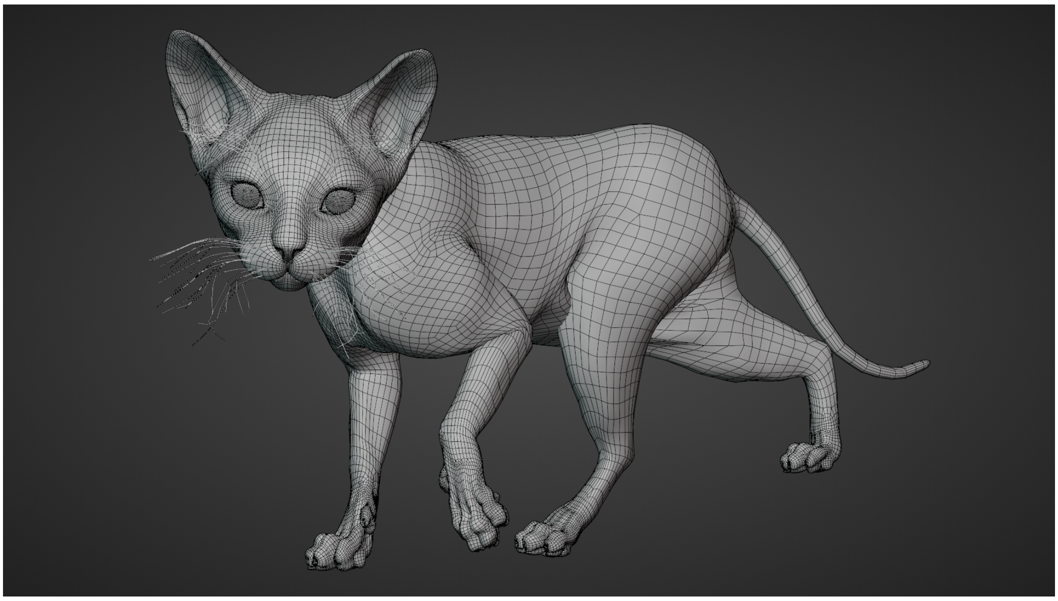

Figure 11. Cat model without fur

Fur

Multiple ways of creating the cat's fur were contemplated and evaluated based on their performance in VR and the final look. Initial prototyping for this took place before the final cat was modeled, and so a placeholder wolf model adapted from the model by Haupt [30] was used to evaluate the different possible techniques.

A traditional approach to rendering fur is to use hair cards. In this method, a texture of a fur clump is placed on a plane or card, and these cards are then scattered around the mesh to mimic the appearance of fur as can be seen in figures 13 and 12. This method offers good levels of performance since every fur strand does not need to be rendered individually. However, since the cards are two-dimensional, the cards may look wrong when viewed from certain angles, as can be seen in figure 14. This problem can be somewhat alleviated with careful placement of the cards.

An important aspect of hair cards found while testing was to avoid using translucent materials. It is possible to use this to mimic the effect of light shining through hair strands, but this lead to large amounts of overdraw. In short, we can not choose a single color value to be drawn onto the screen as it needs to be a combination of multiple layers of the translucent material. This means that pixels have to be drawn more than once which can cause a big performance hike. A simpler material that cuts out the hair card as one piece was used instead. The difference in overdraw can be seen in figures 15 and 16.

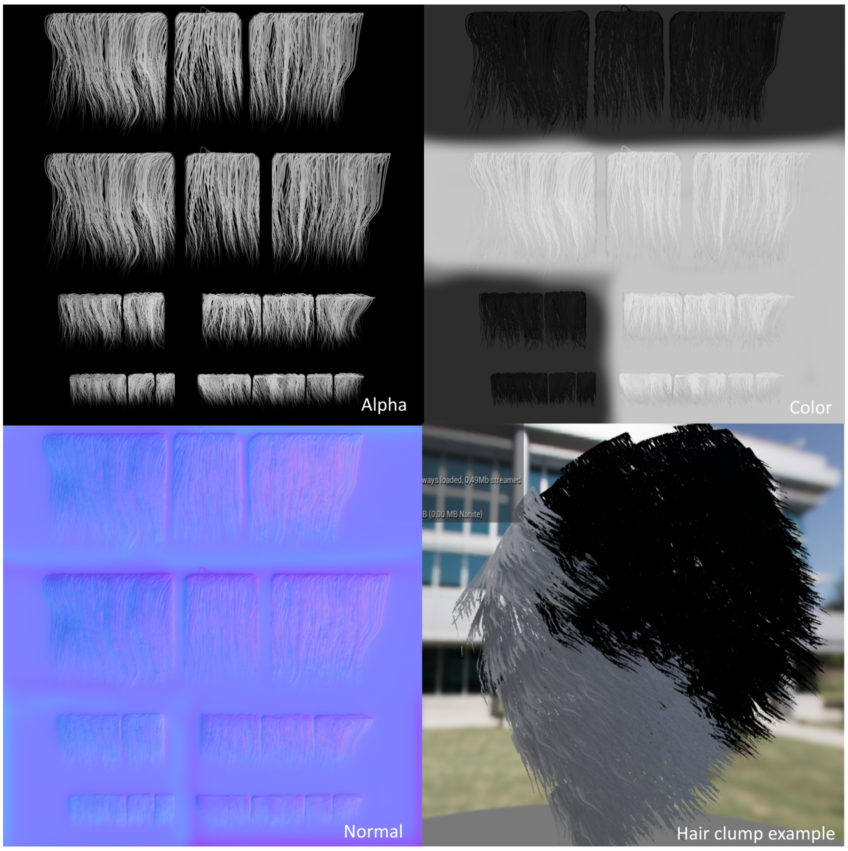

Figure 12. Card textures

Figure 13. Cat model with cards

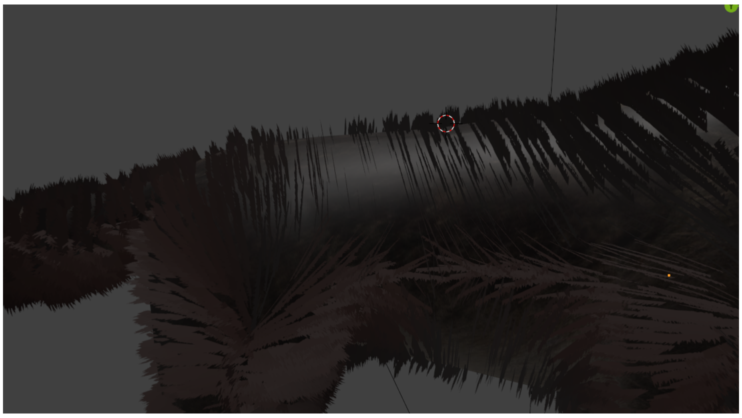

Figure 14. Cards from an unflattering angle

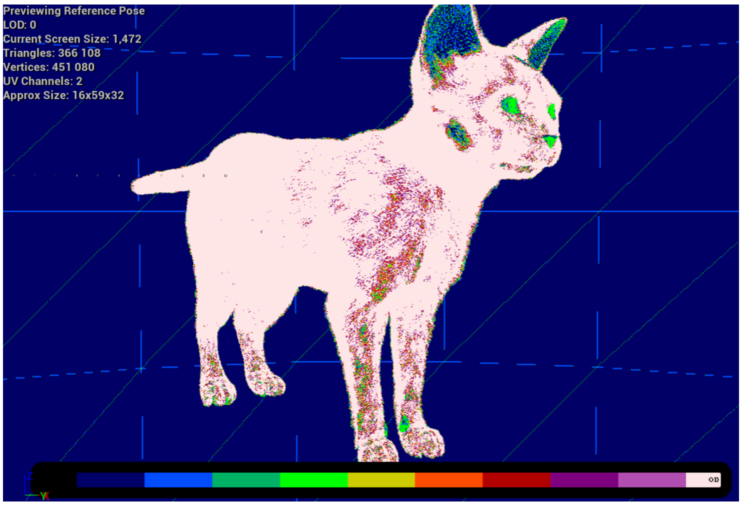

Figure 15. Overdraw with translucent hair cards

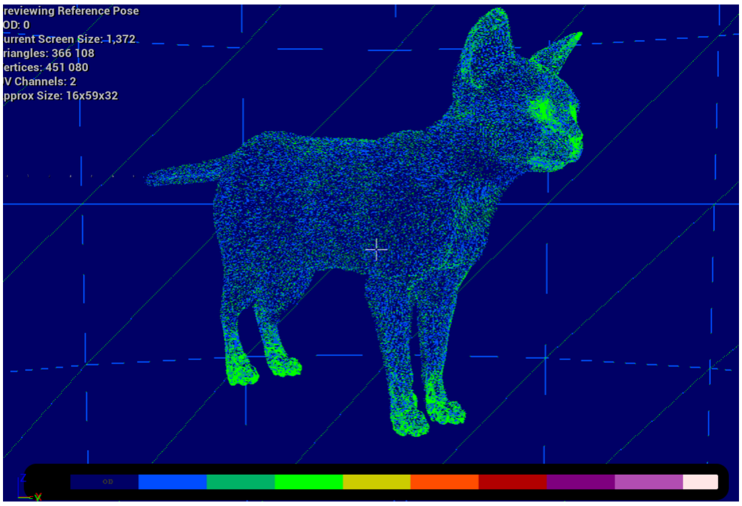

Figure 16. Overdraw with cutout hair cards

A different and more novel approach is to use individual hair strands. Unreal Engine offers a way to render out curve data as individual hair strands. The Groom plugin for UE4 and UE5 allows one to import curve data stored in the alembic format, and instance it as hair strands. This allows for very high customization of the hair. Elements such as hair length, width, and shape can be altered to be different on individual hairs. This method also does not suffer from looking bad at specific angles, as the hair strands render out as three-dimensional. The drawback to this method is its performance. To get adequate coverage of fur, we potentially need to render out millions of curves, which is very costly for performance, and when rendering for VR, every frame counts. An example of this can be seen in figure 17 and figure 18

Figure 17. Groom hair system with 31,000 strands

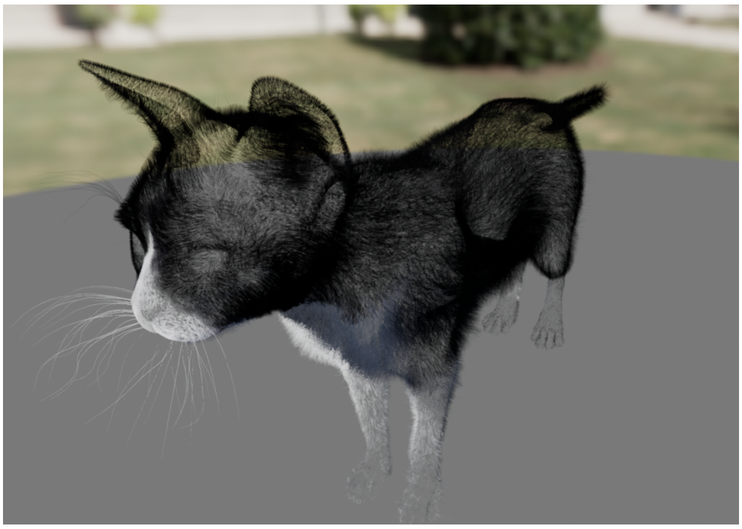

Figure 18. Cat hair strands

An additional method contemplated was to fake the appearance of fur using parallax-occlusion mapping. This method does not generate any extra curves or cards onto a mesh. Instead, this method takes a height map of a fur texture and uses this to alter the UV coordinates of a mesh based on the viewing angle and the height map value. When a fur texture is then set to use these altered UV coordinates, it will be distorted such that it gives the appearance of depth in the texture. Using normal maps and applying extra shadowing detail can then be used to sell further the illusion of depth. This method is relatively easy on performance and looks fairly good, though it does lack the customizability of the aforementioned techniques, meaning that the fur may look more homogeneous. Additionally and crucially, this method does not create a noisy silhouette on the animal which appears naturally in fur and would be present in the card and curves methods. The parallax fur was tested on the wolf model as is shown in figure 19 and implemented on the cat as seen in figure 20.

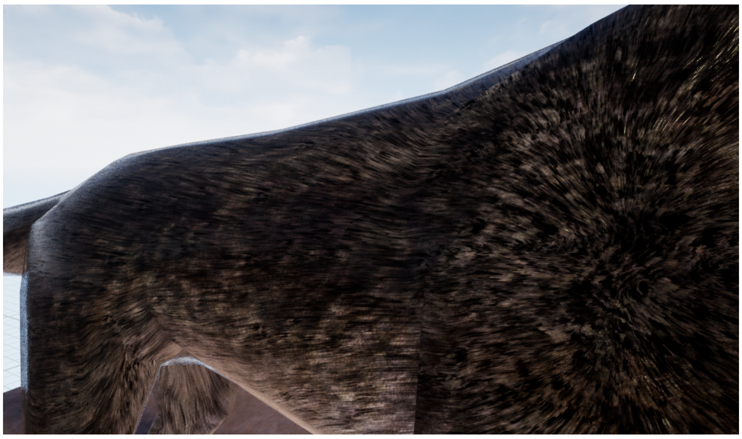

Figure 19. Tested Parallax Occlusion mapped fur

Figure 20. Cat Parallax-Occlusion mapped fur

The final method for creating the fur was chosen to be a combination of all the parallax occlusion mapping and the hair card method as seen in figure 21. The combination was chosen due to it having the best balance between looks and performance. In testing, it was noted that the parallax occlusion mapping method created an excellent undercoat for the animals. The undercoat of a furry animal consists of densely populated short fur. Creating this undercoat using hair strands or cards would be costly, as we would need a vast amount of extra geometry or curves to create the required density. Instead, the parallax occlusion mapping method provides an excellent and easy way to create this undercoat, while also remaining lighter on performance. For the longer and less uniform hairs, the cat model was covered with hair cards. These cards enhance the silhouette as well as give some extra volume to the model. The cards also give some variety and randomness to the fur so that it does not appear too uniform.

Using a combination that also included the hair strands was contemplated. Strands were added along the mesh, which did give the cat extra fluffiness, and also added a small extra layer to the silhouette, which can be seen in figure 22 However this method yielded some extra performance concerns. Specifically in VR, using strands would almost half the frame rate, regardless of how many strands were used.

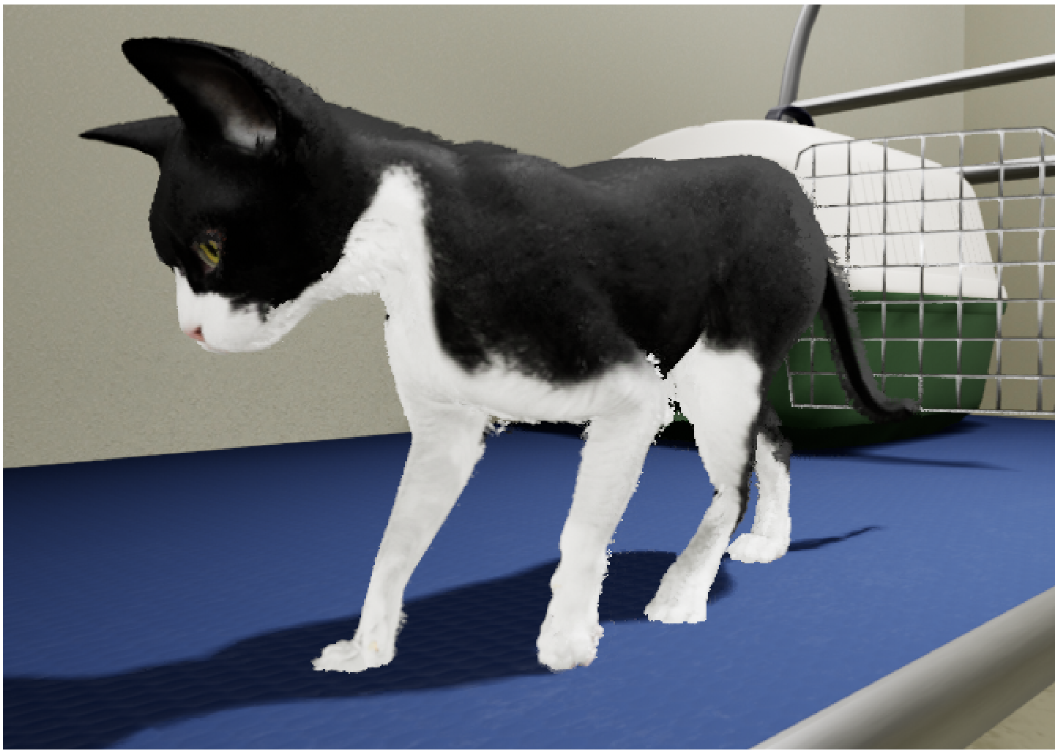

Figure 21. Parallax-Occlusion and hair cards

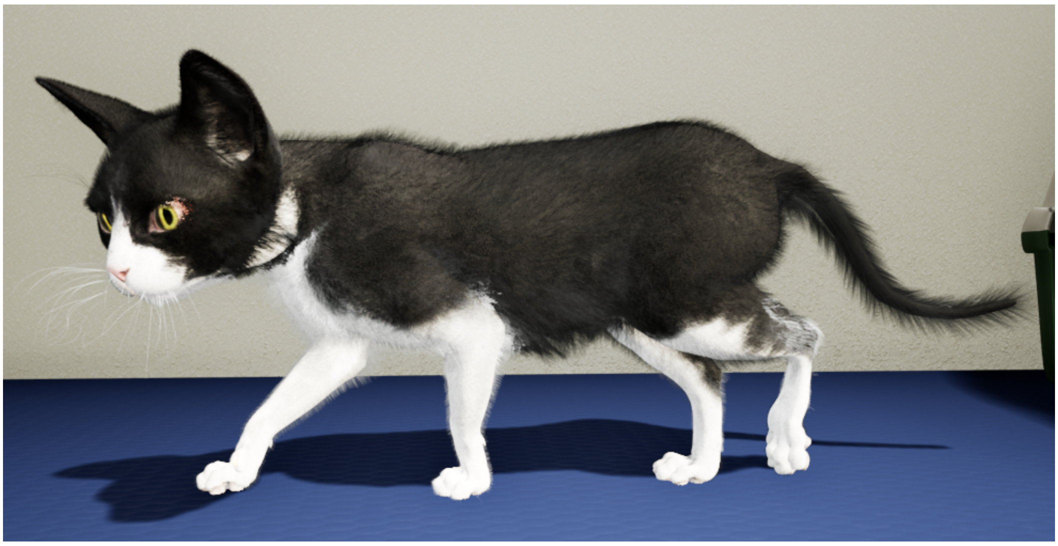

Figure 22. Parallax-Occlusion and hair strands

Cat eyes

An important aspect of creating a lifelike feeling in any creature is to make the eyes as realistic as possible. A simple approach to this is to use the standard PBR workflow, where the roughness and metal factors are adjusted for a proper reflective appearance. However, for the highest fidelity, a material with features such as varying levels of refraction and reflection for different parts of the eye would be optimal. Fortunately, Weta and Unreal produced an example product of a Meerkat [31] that had a sophisticated eye shading model that could be adapted to work with a cat. This shading model was tailored to use a custom-made eye texture with some tweaks to key parameters. Using this material instantly gave the cat an extra level of plausibility as can be seen in the figures 23 and 24.

Figure 23. Old cat eyes

Figure 24. New cat eyes

Animations

A key part of harboring the plausibility illusion in the cat is to have believable animations. Extra detail and consideration were given to make sure that the cat behaved realistically, and that the way it dropped objects happened plausibly.

To this end, a scenario was created where the cat would drop five soda tabs. The cat would initially be hidden in a carrier placed on a table, from which it will hop out and move towards objects set near the edge of the table. The cat would then drop the objects one at a time, with ample time in between drops to make sure the whole path of the object to the ground could be followed by the observer. Three of the thrown soda tabs would be thrown weakly, to mimic the original experiment's dropping of the tabs and the last two would be thrown with more force akin to the humanoid throwing the tabs. After dropping the objects the cat would walk back into the carrier. For a more sophisticated behavior, it was theorized that the cat could jump onto the table and then drop back down. This could provide an even clearer distinction for when the scenario starts and stops and would also hide the cat from sight very well. However, this lead to concerns about participants getting extra gravity cues based on the time and the weight of the jump, which could bias the results.

The animation for the cat was created using Blender software by creating key-framed poses and graphically editing the resulting interpolations as seen in figure 25. It was decided that the animation for the cat was to be created as one whole event, rather than joining multiple animations together to create a collage of animations. Generally, behaviors for complex animated objects in game engines are achieved by creating sets of different animations, such as walk cycles and object interaction animations. This allows for these to be mixed and matched together by applying animation blending, which blurs the seams between the starts and ends of these animations. This approach is very effective for creating behavior where the next action taken is not necessarily known, but it can leave some minor imperfections or unnatural behaviors in the space between two animations, as blending is not always perfect.

Our scenario consists of well-defined actions, that will always play out in the same way. As such, we do not need the modularity that is provided by animation sets. Instead, we can afford to create one complete animation, starting all the way from the cat hopping out of the carrier, to hopping back in. This allows having complete control over every aspect of the event, as well as allowing us to pay attention to details that may go unnoticed or be too difficult to achieve when constructing the animation from animation sets.

The animation was first blocked out into its key poses after which the movements between these poses were refined to appear natural. Features such as slight muscle movements or weight shifts were given extra attention, as these are often the aspects that truly make movement feel alive and real.

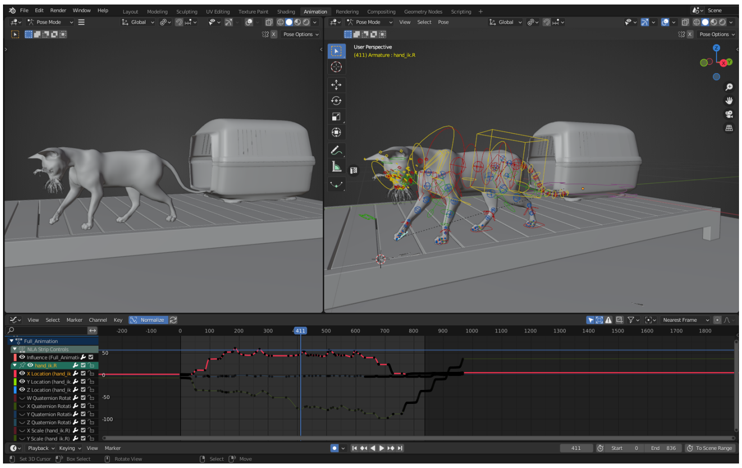

Figure 25. Cat animation creation in Blender

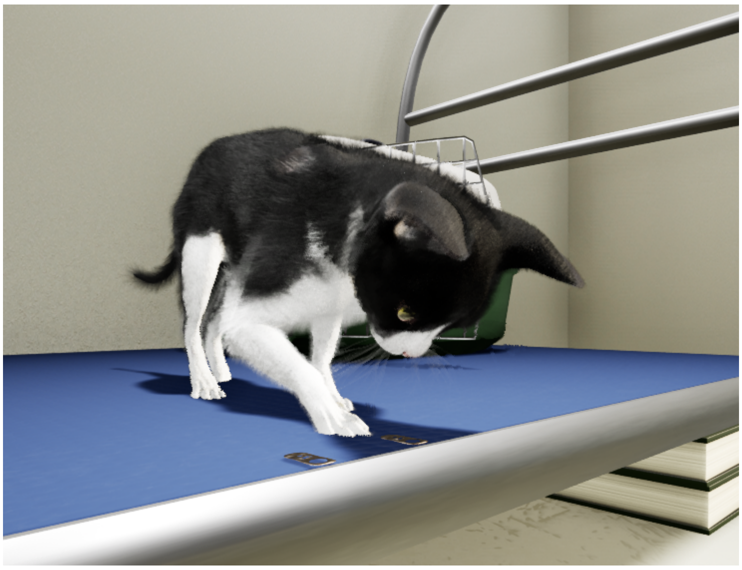

Figure 26. Cat in action

3.5.4. Physics Implementation

An optimal solution for this study to create the intended physics for this study would be to set up the kinematic and simulated objects and simply let Unreal Engine's physics calculations determine the paths that objects take. The engine does however create small variances for collisions between objects, and at the small scale that our interactions happen, it could drastically alter the way the physics is seen by different participants. Therefore it was decided that a single simulation for each gravity level would be recorded into an animation. In practice, we create the physics simulation in the engine with the correct levels of gravity and masses, and this simulation is then recorded so that it can be played back to users rather than having to calculate a new physics simulation each time. Using animations instead of a simulation also has the added benefit of being much easier on performance, though the physics calculations in this scenario are not very complex.

For the simulation itself, a physics collider is added to the soda tabs as well as to the paw of the cat. As the shapes of the falling objects are quite simple, using a primitive collider sufficed to approximate the physics, though it was not too costly to use a complex collider in this case either. The used collider can be seen in figure 27.

The recording of the simulation was made possible by the Take Recorder plugin that Unreal Engine offers. During simulation, each soda tab's position and rotation were recorded with a resolution of 30 frames per second (seen in figure 28). The physics simulation for the tabs was then disabled and replaced with the recorded transformations. This animation was finally synced up to play at the same time as the cat animation.

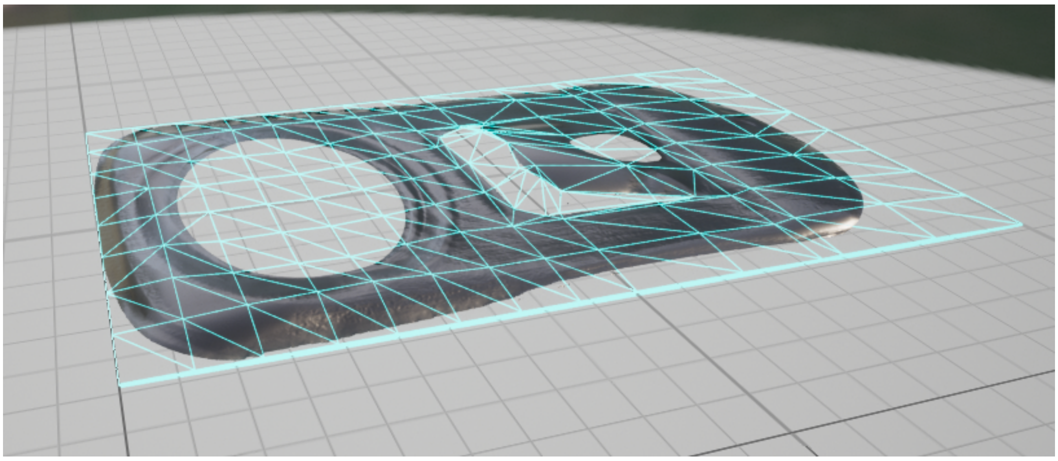

Figure 27. Soda tab collision mesh

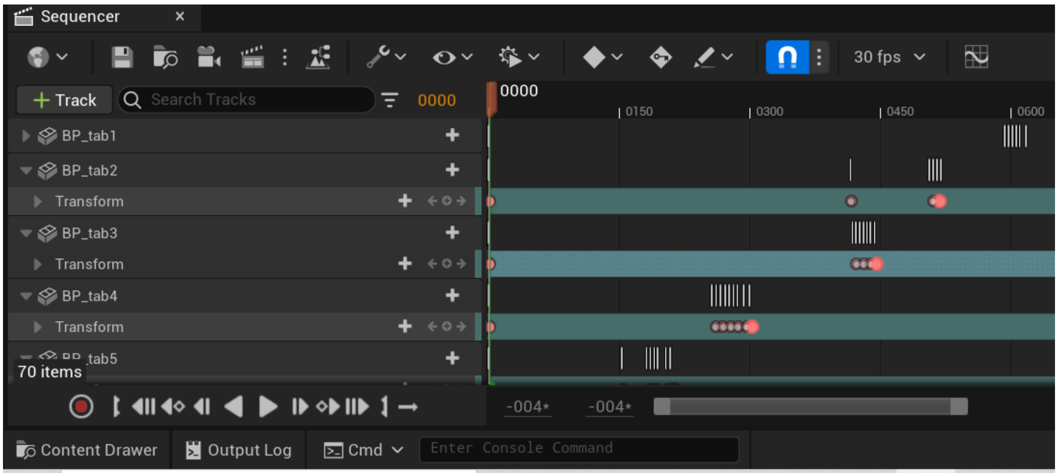

Figure 28. Soda tab recording

3.6. Perspective Shifts

The perspectives as seen in VR for scenarios A and B are depicted in figures 29 and 30 respectively. It is important to note that the IPD-scale changes for the scenarios are only visible when viewing the image as stereo and can not be seen in the figures. The IPD scale has a considerable impact on the apparent scale of objects as was shown by Pimusomboon et al. [10]. The changing of height and IPD scale cues needed to make participants feel small was implemented by altering Unreal Engine's "World to Meters" parameter available for VR builds. This is set to a value of 100 as the default, representing 100 centimeters. To make the participant feel 5 times smaller, we can set this parameter to a value of 20.

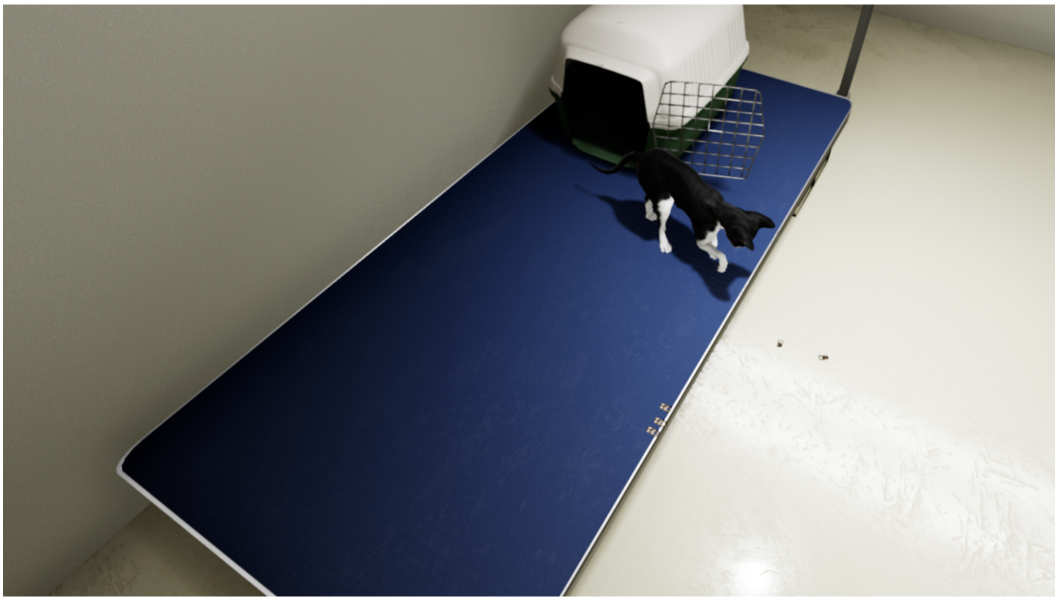

Figure 29. Normal size perspective as seen in VR

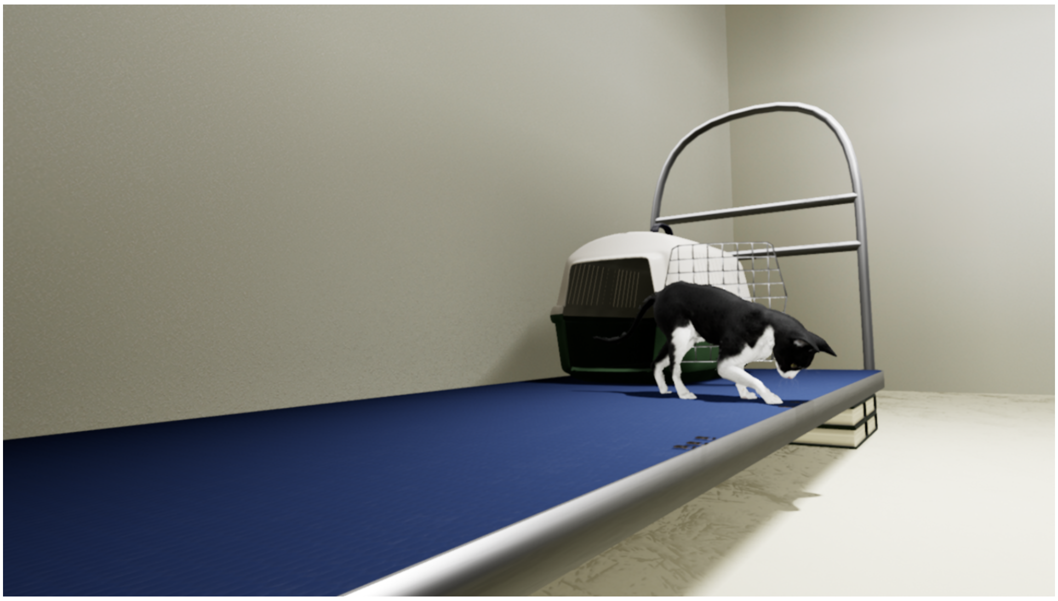

Figure 30. Small size perspective as seen in VR

3.6.1. Other Optimizations and Tweaks

The created environment and cat were given a few optimizations so that it would run properly, with at least 90 FPS with the Valve Index headset.

The Unreal Engine project settings were tweaked to tailor to the needs of VR. By default Unreal Engine works with deferred rendering, which, while optimal for rendering multiple lights effectively, is not as optimal for VR [32]. Using forward rendering alleviates some performance issues, though this effectively limits us to one real-time light, as having multiple lights using forward rendering can become costly very quickly. Fortunately, most of our environment consists of static objects, and therefore we can use completely baked lighting for most of the scene, and only have one real-time light for the dynamic objects.

Fixed foveated rendering was also used to add some extra performance overhead. In this, the resolution of the edges of the screen is rendered with a lower resolution than that of the center. This effect can is potentially visible to viewers, but when the effect is slight enough it often goes unnoticed, as most users tend to keep their attention towards the center of the screen.

3.6.2. Builds

The created environment was finalized by packaging it into a standalone executable. Four executable files were built which varied the scale of the user in VR and the strength of the gravity presented first to the participant.

4. RESULTS

The devised experiment consisted of both confirmatory and exploratory sections. The confirmatory will evaluate the presented hypotheses while the exploratory will consider other gathered data (i.e.the post-experiment questionnaire) and relate them to the gathered results. This allows us to confirm or reject the hypotheses while also giving potential reasons or extra insights into the result.

4.1. Confirmatory Results

The preference for the behavior of the pull tabs in both scenarios was marked down as "True" or "Movie for each participant. The full data on this can be found in appendix 2. To evaluate the hypotheses we can use an exact binomial test. A one-tailed test will be used for both scenarios. Scenario A (normal scale) will be tested for having a preference toward true physics while Scenario B (scaled down) will be tested for a preference toward movie physics.

From a total of 40 answers, scenario A recorded 23 true answers and 17 movie answers. For our hypothesis, the binomial test gives us $p = 0.215$. This result is above the 0.05 threshold which means we fail to reject the null hypothesis. This result matches the result found in the original study by Pouke.

From 40 answers, scenario B recorded an even split of 20 true answers and 20 movie answers. For our hypothesis, the binomial test gives $p = 0.563$. This result is over the 0.05 threshold meaning we fail to reject the null hypothesis. This result differs from the original study by Pouke. This finding suggests that using a more natural actor does have an effect on the perception of physics when at a small scale.

4.2. Exploratory Results

The following sections will present the data gathered from the post-experiment questionnaire as well as compare them to the confirmatory results.

4.2.1. Comparison between the Scenarios

While we failed to reject the null hypotheses in both of our scenarios, we can still investigate the difference between the preferred physics. For this, we use a logistic mixed-effect model to estimate the effects of each scenario on the physics preference. "True" and "Movie" physics as well as scenarios A and B were codified as 1 and 0 respectively to serve as a response variable. The strength of the predictor is reported as the estimate for the odds ratio, with a 95% confidence interval. This model reported an odds ratio of 1.365, with a confidence interval of [0.559, 3.45], which estimates that the scenario had a small effect on the chosen physics preference. However, the confidence interval is quite large and includes 1, which means that it is possible that there is no difference between the scenes.

4.2.2. SUS Questionnaire

The post-experiment questionnaire presented six questions from the SUS questionnaire. These questions are used to evaluate the level of place illusion that users felt in the virtual environment. The questions are answered on a scale of 1-7, and scoring for this study was achieved by dividing the number of questions given an answer of 6 or 7 by the total amount of questions[27].

The mean and median scores for presence were calculated to be 0.33 and 0.25 respectively. The variance was recorded as about 0.1. The SUS scores of individual users can be seen in figure 31. These statistics place the SUS scores on the lower end of the presence spectrum, but with a good amount of variance.

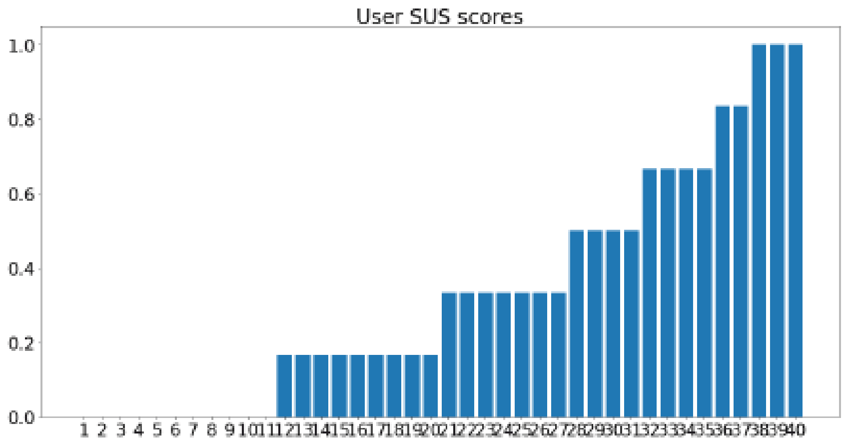

Figure 31. Individual SUS scores

For further analysis, participants were categorized according to their SUS scores, and their answers to the confirmatory results were evaluated according to these groups. In this, the ratio of preferences for true physics over the total amount of answers in that group was calculated for both scenarios A and B. This can be seen in figure 32. The graph also shows the number of participants who fall in each threshold of PI as the green bars. A mixed-effect model was calculated on the data to estimate the effects of PI and the scenarios simultaneously on the chosen physics model. It should be noted that while the model is able to also calculate the strength of only the main effect, in this and future cases we are only interested in the interaction effect between two demographic variables.

The model yielded an odds ratio of 0.194 with a confidence interval of [0.083, 3.61]. This suggests a substantial interaction between the preference for physics when combined with the scenarios and PI score, but the large confidence interval which includes 1, means that the effect can not be conclusively confirmed.

For easier visualization, participants were also grouped split into low and high-presence groups and similarly tested for the ratio of true physics. Participants with a low PI score preferred real physics 60 and 50 percent of the time in scenarios A and B respectively, while participants with a high PI score preferred real physics 55 and 50 percent in scenarios A and B respectively. The results are visualized in figure 33. A two-tailed Fisher exact test was performed individually for both scenarios for these groups yielding a p-value approaching 1 on both scenarios A and B, indicating a near similar set of results regardless of the PI score.

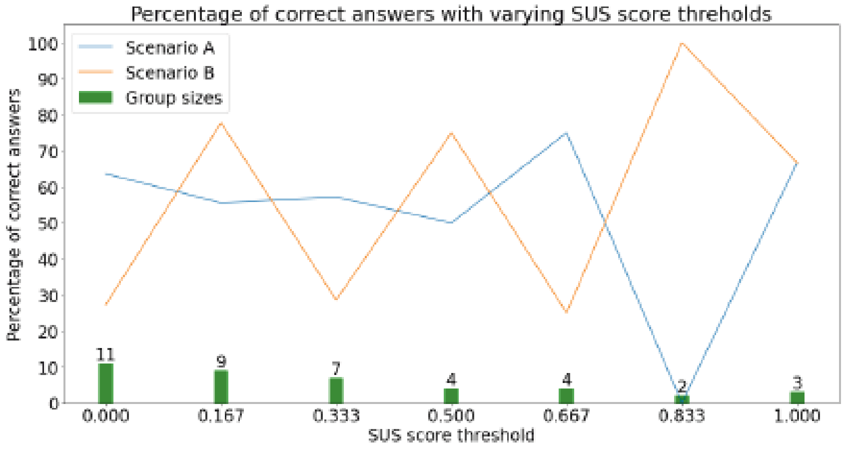

Figure 32. Percentage of true physics preferences at different SUS groups.

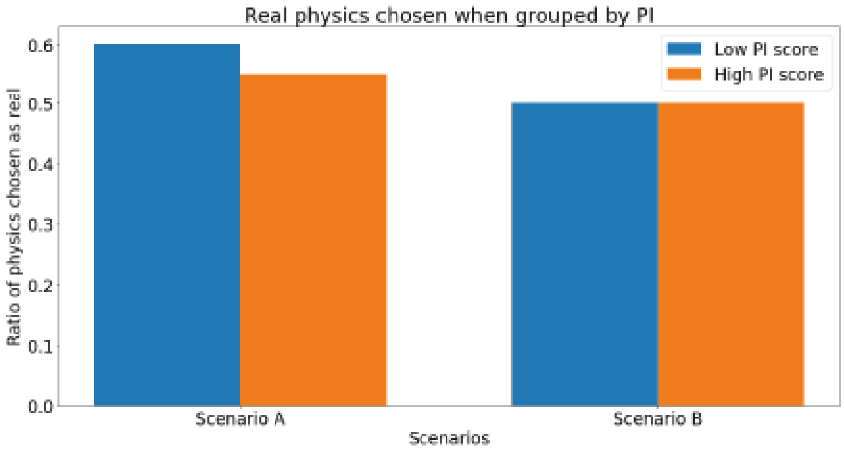

Figure 33. Percentage of true physics preference when grouped as low and high presence.

4.2.3. VR Use Frequency Comparisons

The post-experiment questionnaire inquired participants about how much they use VR systems. Participants were given a scale from 1-7 ranging from never having used VR systems, to using one every day. All Participants only reported frequency in 3 categories. 20 participants reported using VR once or twice, 11 reported using VR once or twice a year, and 9 reported using VR once or twice a month. This can be seen in table 2. Logistic mixed-effect regression was calculated on the effect of both the frequency of use of VR and the scenario against the preference for physics. This gave an odds ratio of 1.030 with confidence intervals of [0.334, 3.17], suggesting no significant effect, but leaving a possibility for an effect due to the large confidence intervals.

Table 2. Frequency of gaming

Frequency	n	Percent
Once or twice	20	50%
Once or twice a year	11	27.5%
Once or twice a month	9	22.5%

Similarly to the SUS scores, we can group users by their frequency of VR use and evaluate their preference for true physics for scenarios A and B. This is seen in figure 34

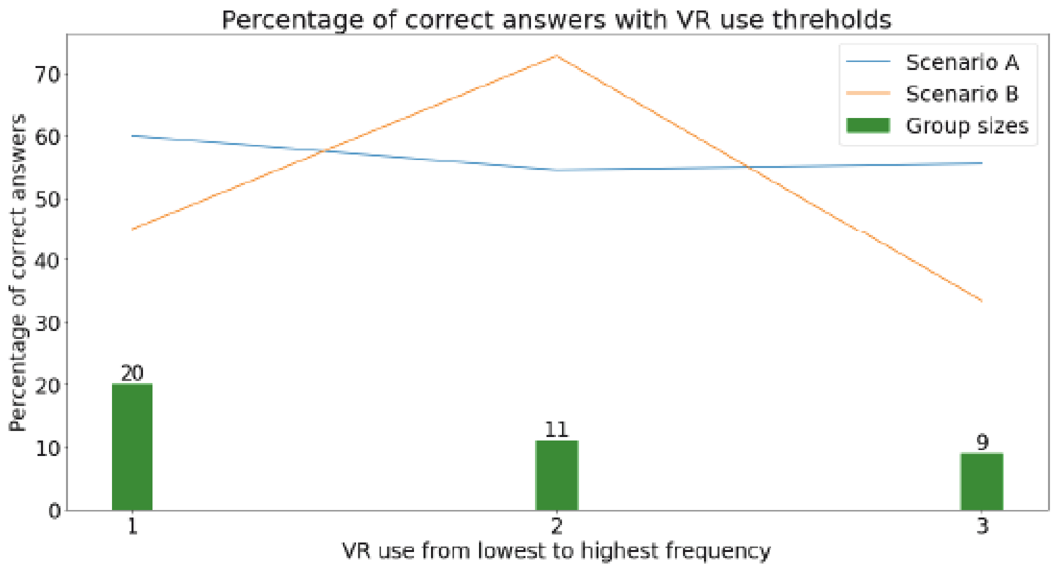

Figure 34. Percentage of true physics preferences at different frequencies of VR use

4.2.4. Gaming Frequency Comparisons

In addition to VR use, participants were also asked a question about their frequency of gaming. Participants were given the same scale from 1-7. The frequencies can be seen in table 3.

Participants were grouped according to their gaming frequencies and the groups were evaluated for their preference for true physics for scenarios A and B. This is seen in figure 35. Mixed-effect modeling on the scenario and the gaming frequency yielded an odds ratio of 1.112 with confidence intervals of [0.648, 1.94], estimating a minuscule effect of both gaming frequency and the scenario on the physics preference.

Table 3. Frequency of gaming

Frequency	n	Percent
Never	7	17.5%
Once or twice	3	7.5%
Once or twice a year	11	27.5%
Once or twice a month	6	15.0%
Once or twice a week	6	15.0%
Several times a week	6	15.0%
Every day	1	2.5%

Gaming frequency was also investigated by splitting the participants into either a low or high gaming frequency group and testing for their ratio of preferred real physics. Participants who reported a low amount of gaming preferred real physics 50 and 45 percent of the time in scenarios A and B respectively, while participants who reported high amounts of gaming preferred real physics 65 and 60 percent of the time in scenarios A and B. This is visualized in figure 36. A two-tailed Fisher exact test was performed on these groups yielding a p-value of 0.52 and 0.34 in scenarios A and B respectively. This result suggests a correlation but does not show any statistical significance which is often considered for p-values of less than 0.05

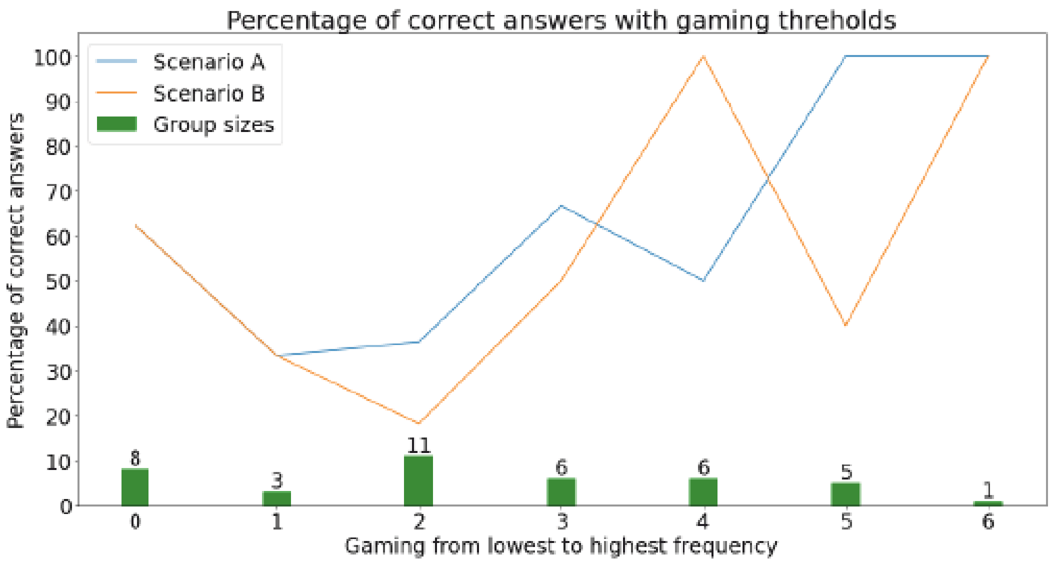

Figure 35. Percentage of true physics preferences at different frequencies of gaming

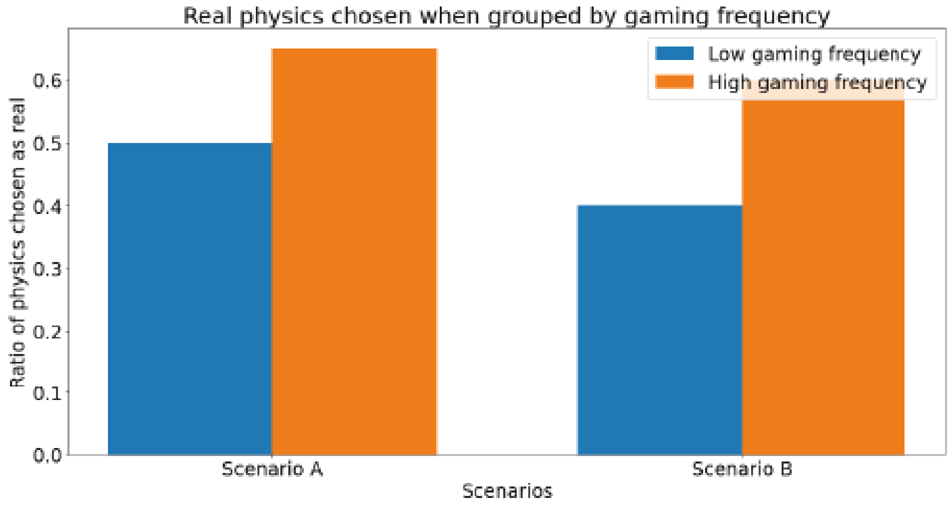

Figure 36. Percentage of true physics preferences when grouped by low and high gaming frequency.

4.2.5. Comparisons between Reported Gender

A difference between the reported gender of the participant and chosen preferences were investigated. It is important to note that the gender counts are not exactly the same, as 21 males and 19 females participated. Male participants preferred real physics 13 and 8 times out of 21 in scenarios A and B, while female participants preferred real physics 10 and 12 times out of 19. The results of this can be seen in figure 37. The mixed-effect model combining scenario and gender (coded as male = 0, female = 1) found an odds ratio of 4.363 with a confidence interval of [0.699,33.17] suggesting a substantial effect of the combined predictors on physics preference. However, the confidence interval leaves the possibility of no effect, though it also leaves the possibility of an even bigger effect.

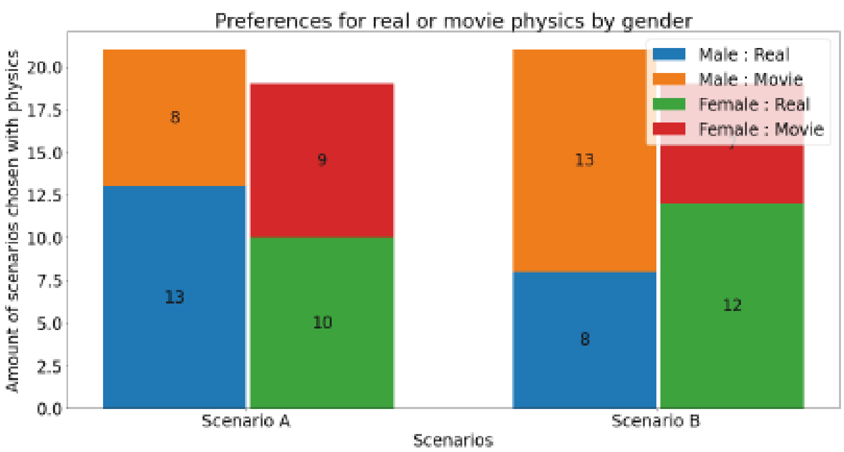

Figure 37. Preferences for true or movie physics by reported gender

4.2.6. Ordering Comparisons

An investigation was made on the order in which participants experienced the scenarios and physics. Firstly, participants were grouped according to whether they experienced scenario A or scenario B first. When scenario A was the first scene that was experienced, real physics was chosen 13 and 11 times out of 20 in scenarios A and B respectively. When scenario B was the first scene that was experienced, real physics was chosen 10 and 9 out of 20 times in scenarios A and B respectively. The results are seen in figure 38, which presents both the amount preference for real and movie physics. Performing logistical regression on physics preference with both scenarios and the first scenario experienced shows an odds ratio of 1.248 with a confidence interval of [0.205, 7.79], suggesting a small effect but leaving the possibility for a big effect.

The number of participants with the same or different preferences for both scenarios was also added to complement the ordering analysis. Participants opted for the same preference of physics in both scenarios 21 times, and a different preference 19 times.

Participants were also grouped by whether they experienced true or movie physics first in each scenario. In scenario A, when real physics was seen first real physics was preferred 14 out of 20 times, and when movie physics was seen first, movie physics was chosen 11 out of 20 times. In scenario B, when real physics and movie physics was seen first, real physics and movie physics were preferred 10 out of 20 times. These can be seen in figure 39. Here, the mixed-effect model gives an odds ratio of 4.711 with a confidence interval of [0.128, 4.89], estimating a large effect between the preference and the scenario when combined with the first physics model seen in a scenario, but with the possibility of no effect.

Finally, participants were grouped by the very first physics model they saw regardless of the scenario experienced and evaluated for their answers for both scenarios. While the results seen in figure 39 consider each scenario individually, This analysis only cares about the very first physics model experienced. However, the results are still categorized into scenarios A and B. When real physics was seen first, real physics was preferred 12 and 9 times out of 20 in scenarios A and B respectively. When movie physics was seen first, movie physics was preferred 9 out of 20 times in both scenarios A and B. The results are seen in figure 40. The mixed-effect model for this gives an odds ratio of 1.869 with a confidence interval of [0.331, 13.43], suggesting a moderate effect between the preference and the scenario when combined with the very first physics model seen. However once again, the confidence interval leaves the possibility of no effect or an even greater effect. Here, the fisher exact test gives us p values of 1 and 0.75 for A and B respectively, indicating high levels of similarity between the preference in both groups for both scenarios.

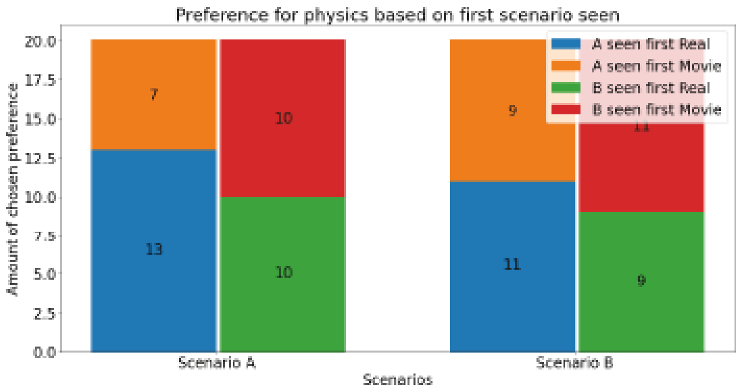

Figure 38. Preference for physics based on the first scenario seen

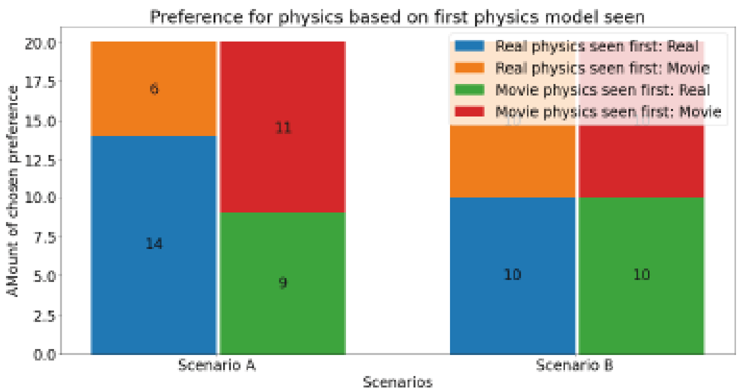

Figure 39. Preference for physics based on first physics model seen

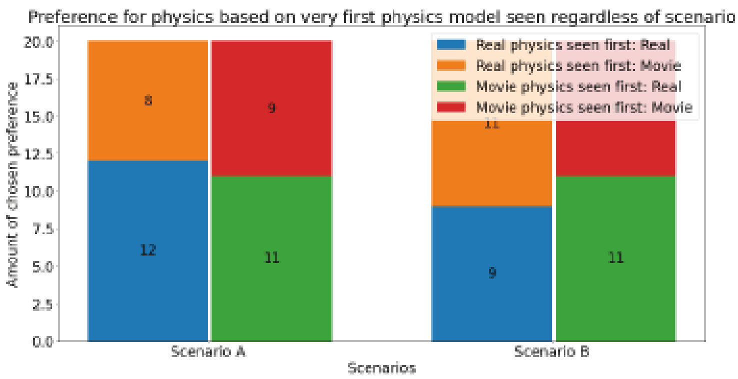

Figure 40. Preference for physics based on very first physics model seen regardless of scenario

5. DISCUSSION

The following discussion will first focus on the confirmatory results yielded by the study. The exploratory results will then be contemplated and will be used to hypothesize reasons for the received confirmatory result as well as to gauge other potential factors that may impact the perception of physics when one is shrunk to one-fifth of their original size in Virtual Reality.

5.1. Hypotheses

The received answers for the exact binomial test for both scenarios A and B lie over a p-value of 0.05, which means that we fail to reject both null hypotheses.

The previous study by Pouke et al. was not able to find evidence for the corresponding first hypothesis which expected subjects to consider true physics as more real when standing and at a normal scale. This finding aligns with ours, though the result is still somewhat surprising. It would be reasonable to expect that participants would be able to clearly discern between realistic and unrealistic physics when presented at a normal scale as was shown by Jörges [25]. This discrepancy seems to point toward other factors within virtual reality or the study that could cause participants to get either confused about the correct physics or unintentionally convinced of the wrong physics.

Our study differs from the Body scaling study in regards to the second hypothesis which expected subjects to consider movie physics more real when standing and scaled down using IPD scaling and height cues. While Pouke was able to reject the null hypothesis in his earlier study, we fail to reject it. The reasons for this rejection may be partially explained by the intended difference of having a non-humanoid. Though not present in the hypothesis, using a more natural method for showcasing rigid body physics was thought to cause less preference for movie physics.

The change in the ratio of chosen real physics to movie physics should not be disregarded. It is possible that using a more natural way to showcase physics is needed for participants to prefer real physics, but other, currently unknown factors are also needed for participants to consider real physics to be correct. These factors could be the same ones that are needed to make real physics preferred when viewed from the normally scaled perspective. This result could also suggest that there may be an inherent bias for choosing movie physics when scaled down in VR, and only by tipping the scales by creating a very specific virtual environment targeted to make one type of physics look more plausible, can one escape this bias.

5.2. Impact of the Cat and the Plausibility Illusion

This study showed that using a different, natural actor plays a difference in how physics is perceived while inhabiting a small scale. However, the reason for this difference is still somewhat unclear. One theory that could explain the result is that the cat provides a very potent size cue when compared to the humanoid robot that was used in the original study. This cue may allow participants to better gauge their size, and consequentially estimate physics more properly. This theory would be given ground by asking participants to estimate their own size when scaled down in a virtual environment.

Alternatively, given the effort taken to create a natural and realistic look and behavior for the cat, it is reasonably safe to assume that the cat acted as a more plausible actor for dropping the tabs than a humanoid robot. As the cat was the only effective difference when comparing the original study and this study, it can be theorized that the strength of the plausibility illusion correlates with the perception of gravitational physics at small scales. To reach more conclusive data on this, the participant's levels of presence should be separated into the Place illusion (PI) component and the Plausibility Illusion (PSI) component as shown by Slater [33]. These could then be measured separately and compared with the participant's preference for physics.

5.3. SUS Scores and Implications

The SUS scores reported in this study spread across many different values. Nevertheless, the mean and median scores do end up on the slightly lower end. The reasons for this are unclear, but factors such as the short time spent in VR and the instructions given from outside the virtual environment could influence this score.

Grouping participants according to their felt plausibility illusion does not seem to show any correlation with the participants' preference for physics in either of the scenarios. The largest dichotomy between the scenarios is seen at the second-highest SUS score of 0.833, where movie physics was preferred at a normal scale, while real physics was preferred at a small scale. However, this group only consists of 2 participants, and the pattern is not seen in the group with the highest SUS score of 1.0, meaning this result is likely an incidental finding.

Grouping participants into low and high groups gives us similar findings. Scenario A shows a very slight difference in the ratio of preferred real physics between the high and low plausibility illusion levels, while scenario B shows an even split. The mixed-effect model suggests that participants with higher PI would be less likely to choose real physics at a small scale. This is, however, a very unreliable estimate due to the amount of data. The fisher test for the individual scenarios does confirm that both groups were very similar in their preferences for physics.

These results seem to indicate that the place illusion does not have a major influence on the way that humans perceive gravitational physics in virtual environments.

5.4. Reaching a Higher Place Illusion

Although not the most precise of metrics, the low mean score of 0.33 calculated in the SUS questionnaire shows us that further improvements to the environment could have been made. Although the SUS scores did not correlate with the chosen physics, it is possible that a certain threshold for place illusion that was not reached in this study may allow for a better perception of physics. Especially when considering scenario A, one could reasonably assume that if a maximal place illusion and realism were reached, real physics would always be preferred as this would exactly match the real world.

Improvements to the rendering within the environment could help reach higher levels of the plausibility illusion such as increased texture detail and higher quality lighting and reflections. Using a more natural and plausible environment may also play a factor. The environment used in this study may appear somewhat sterile to users, with only a few furniture pieces and other objects placed around the room. Using a room that appears more natural scenario may help with increasing the sense that a person feels like they are in a real existing place.

Future improvements to hardware could also help with increasing presence. Factors such as field of view and resolution undoubtedly play an impact on the presence the participants feel, and increasing the fidelity of these factors would help to reach higher levels of it.

5.5. Effect of VR and Game Experience on Physics Perception

The usage of VR technologies only fell onto the lower frequencies that were presented. Participants only reported using VR once or twice, or once or twice a month or year. Interestingly, however, no one reported never using VR before. The relative novelty of VR in commercial use may explain the reason for this result.

Grouping participants according to their VR usage shows no distinct differences in preference in either scenario. Participants seem to hover at the same levels in both physics types regardless of how much VR usage they have. The linear regression performed on this data also suggests no effect. This finding would indicate no correlation between physics preference and VR usage, but it is important to note that the data in this category is quite incomplete, as we do not have any participants who used VR technologies very frequently.

The frequency distribution of gaming falls on a wider spectrum, though the participants are weighted more toward the lower frequencies. Grouping participants by their gaming frequency and physics preference does give an interesting result. At a glance, the graph seems to indicate a positive correlation between gaming frequency and the preference for real physics in both scenarios. Most strikingly, all participants who reported gaming at least several times a week preferred real physics in scenario A, while only about 40 percent of participants who reported gaming once or twice a year preferred real physics. An interesting quirk in this result is that participants who reported never having played video games preferred real physics over 60 percent of the time.

Splitting the participants into two groups also shows that participants at high levels of gaming frequency were more likely to choose real physics than those who had low levels of gaming frequency. Though we do not reach statistical certainty, the fisher test for this also suggests a link between chosen physics and gaming experience in both scenarios.

The mixed-effect model also shows that participants were consistent in their physics preference when considering the different scenarios at different levels of gaming frequency. A participant was no more likely to choose real physics in scenario B than A with any PI score.

These results may be indicative of video game experience influencing physics perception in Virtual Reality. It is possible that the more experience participants have had with physics in other virtual environments, the better they are able to discern between differences in these physics models. It can also be hypothesized that participants with no experience in video games relied purely on real-world experiences to evaluate the physics, while participants with some but little gaming experience tried to rely on their lesser understanding of the physics in virtual environments, which could cause them to err in their preference.

5.6. Differences in Perception by Gender

The participants of the study were recorded as 21 males and 19 females. This balance allows for a good investigation into any potential differences in physics preferences. The data shows a small tendency for males to prefer real physics more in scenario A and movie physics in Scenario B, while females slightly preferred real physics over movie physics in both scenarios. The mixed-effect model here suggests a very large effect of gender on the chosen preference when also considering the scenario. The analysis suggests that women are more likely than men to choose real physics when placed at a small scale versus at a normal scale, though the confidence intervals do leave room for other possibilities, such as no effect, or an even bigger effect.

5.7. The Effect of Ordering

Although balancing the order in which participants experience the scenarios and physics effectively rids us of bias towards a physics preference, it is still possible that some particular order does lead to a particular preference. In particular, the scenario which was run first, or the physics model that was seen first could lead to a potential bias in either of the scenarios.

Grouping participants by the scenario they saw first gives us a small difference in answers. When scenario A was seen first, real physics was preferred 13 and 11 times in scenarios A and B respectively. When scenario B was seen first, real physics was preferred 10 and 9 times for scenarios A and B. This as well as the mixed-effect model suggests a slightly higher preference for real physics when scenario A is seen first.

The difference is very small so any concrete conclusions cannot be made, but it is possible that participants base their true preference of physics on the first scenario they see, and try to stay consistent with that preference in the second scene. However, the participant preference similarity between scenarios shows that about half the people kept the same preference for both scenarios while the other half changed their preference. Thus it is unlikely that participants worried about answer consistency to a great extent. This is also evident when users are grouped by the very first physics simulation they saw, as the fisher test and mixed-effect model present no confirmed bias towards either physics in either scenario.

The first physics model participants see could also cause certain biases towards a physics preference. Grouping in this way gives us an interesting result. When in scenario A, participants who saw real physics first were more likely to prefer real physics, and participants that saw movie physics first were slightly more likely to prefer movie physics. Scenario B instead, consists of an even split between both physics preferences when both physics models were seen first. This result provokes interesting hypotheses. While the data did not reach statistical significance, it is possible that the first physics model seen does cause a bias towards that model, and that this is the most strong when participants first see the model that they are most familiar with. In practice, when participants saw the correct physics model at a normal scale and perspective, they accepted it as the ground truth and based the rest of their physics preferences on this.

5.8. Limitations

This study is not without its limitations. Firstly, this study only considered a total of 40 participants. Conducting this study with higher participant counts would provide more data for studying both the confirmatory and the exploratory results. The higher participant count would be especially interesting for reaching statistical significance in the exploratory analyses for both the fisher tests and the mixed-effect models, which now only hint at possible correlations.

In the work considering presence, it is important to note that the questionnaire used gives us ordinal data where the distances between different levels are subjective. Using this metric to search for correlations is therefore somewhat imprecise. Other methods such as a participant's behavioral attitudes towards the environment or an event could be used to provide stronger data for reaching a specific level of presence, though this is mostly only possible with experiments that are able to provide an event that plausibly elicits a behavioral response.

An additional piece of data that was not gathered but would have provided interesting results was the impression that the cat left on the participant. Whether the participant found the cat to behave realistically may or may not have shown a correlation to the physics chosen. This would have given more ground to studying the relation between the plausibility illusion and the preference for physics.

Asking participants questions on how small they actually felt in both scenarios could have also helped distinguish whether one of the reasons for inaccurate physics preferences was that participants simply did not experience the intended small scale. In particular, participants that felt a mismatch between different size cues could misunderstand their size and therefore evaluate the size of the soda tabs and their interaction with gravity inaccurately.

5.9. Future Work

This work has provided new insight into the subject of perceived physics when users are virtually subjected to a smaller scale. It also raises multiple new directions for study in this field.

One avenue of continuing this study is to change some notable factors in the study. For instance, altering the study to contain different types of physics items such as bottles and apples, and elevating the dropping platform for a longer period of time to see the physics at work could cause differences in the perception of the correct physics model.

Another notable factor to study is the impact of presence. Though presence was not considered very correlational with the chosen physics, creating a test with a higher presence score could provide interesting results. A similar study that first confirmed high levels of presence could be used for this effect.

Similarly, dividing presence into PI and PSI and studying these components independently in relation to perceived physics would provide a better understanding of how presence impact this perception. The plausibility illusion would be especially interesting to study. In its essence, this study is trying to determine whether an implausible physics scenario is seen as plausible when participants are subjected to a different scale. Therefore, other plausible or implausible events happening in the environment could bear a big importance in the perception of the studied event.

Work on the impact of order could also provide interesting results. The magnitude of this impact if any is still unclear but there is a possibility that this factor largely affects the received result. Getting rid of potential bias from this would be difficult, but if it can be factored into the calculation it could provide clearer results.

The impact of gaming experience also provides an interesting hypothesis. Studies where participants are first introduced to the correct physics and gravity in unbiassing ways to ensure their familiarity with physics in virtual environments or screening participants for a set level of experience with physics in virtual environments could cause real physics to be chosen more consistently. Finding the required amount of experience needed to appreciate physics correctly could have valuable benefits in both studies and in commercial use.

Finally, exploratory studies on finding possible unknown factors influencing the perception of physics would be useful for creating even better tests. Research into any possible factors influencing physics perception in virtual reality at any scale would be beneficial for clearing up any uncertainties related to this study.

6. CONCLUSIONS

The work in this study was conceived as a branch of the Body Scaling study by Pouke et al. [2]. The study aimed to use the same approach for studying how well humans can perceive physics when they are virtually scaled down. In particular, this study wanted to determine whether humans prefer real physics or unreal (dubbed "movie") physics when objects are dropped or thrown with different levels of gravity. Participants' answers were investigated for both when they were placed in the environment with a normal scale as well as one-fifth of the normal scale.

In this work, we have attempted to create a virtual environment compatible with virtual reality to test a user's ability to perceive rigid-body physics from a normal and small scale. In accordance with the original study and to maximize presence, the environment was designed to be photo-realistic to mimic reality as well as possible. To achieve this, industry-standard methods and novel techniques were used for creating static and dynamic actors in the environment as well as accurate physics. Specific attention was given to the cat actor in the environment which was prototyped with multiple models and techniques to ensure that it was as plausible and immersive in the environment as possible. The environment was finally optimized to work at an adequate level of performance to be used with the Valve Index VR headset.

The procedures of the study mirrored the procedures in the Body scaling study. Participants were briefed that they would be placed in an environment where they were to observe soda tabs being dropped or thrown. Participants were then placed in the two scaled scenarios, shown both physics models, and asked for their preference for the correct physics. Finally, participants were given a post-experiment questionnaire.

The study set out to test two hypotheses. Firstly, we expected that participants would choose normal physics over movie physics when placed in the environment at a normal scale. Secondly, we expected that participants would choose movie physics when placed in the environment at a small scale. This study also included an exploratory section where reasons and insights into the received results could be contemplated.

The results of the experiment were analyzed with an exact binomial test and found that neither of the hypotheses could be confirmed. This result deviated from the Body Scaling study with respect to the second hypothesis, where it was able to confirm that participants preferred movie physics when scaled down. The intended difference of having a non-humanoid as the actor was hypothesized to cause enough of a difference for movie physics to no longer be a clear preference, whereas other unknown factors could tip the scale towards a clearer preference for true physics.

Other factors and collected data in the study were analyzed for their potential impact on the results. These analyses are exploratory in nature and do not provide any conclusive evidence, but may point towards possible correlations. Firstly, the gathered SUS scores averaged out at the slightly lower end of the spectrum showing that presence could have been improved for this study. Grouping participants by their SUS scores did not indicate any major correlation with the preference for physics in either scenario. Similarly, grouping by reported gender showed small differences, but not in magnitudes that would indicate any clear pattern.

Participants reported very similar frequencies for the usage of VR and grouping by this did not yield any correlations which are to be somewhat expected due to the small differences in frequencies. In contrast, participants reported a wide range of answers for the frequency of gaming. When grouped by this, a possible positive correlation could be made. Experience with physics in virtual environments was hypothesized to cause better ability in discerning differences between physics models.

Finally, participants' preferences for physics were analyzed based on the order that they saw the scenarios, and in the order that they saw the physics models. Grouping participants by the first scenario they saw did not lead to any major differences in physics preference. However, when participants saw the real physics models first in scenario A, they were more likely to prefer real physics. It is possible that participants based their answers on the first physics model they saw, in particular when this was the real physics model seen from a normal scale which would appear the most natural.

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8. APPENDICES

1. Post Experiment Questionnaires

Post experiment questionnaire

1. ID (researcher fills)

____
____
____
____
____

Please rate your sense of being in the virtual environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place.

2. I had a sense of “being there” in the virtual environment...

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much

To what extent were there times during the experience when the virtual environment was the reality for you?

3. There were times during the experience when the virtual environment was the reality for me...

	1	2	3	4	5	6	7	
At no time	○	○	○	○	○	○	○	Almost all the time

When you think back to the experience, do you think of the virtual environment more as images that you saw or more as somewhere that you visited?

4. The virtual environment seems to me to be more like...

	1	2	3	4	5	6	7	
Images I saw	○	○	○	○	○	○	○	A place that I visited

During the time of the experience, which was strongest on the whole, your sense of being in the virtual environment, or of being elsewhere (in the VR laboratory)?

5. I had a stronger sense of...

	1	2	3	4	5	6	7	
Being elsewhere (in the laboratory)	○	○	○	○	○	○	○	Being in the virtual environment

Consider your memory of being in the virtual environment. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By ‘structure of the memory’ consider things like the extent to which you have a visual memory of the virtual environment, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.

6. I think of the virtual environment as a place in a way similar to other places that I've been today...

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

During the time of the experience, did you often think to yourself that you were actually in the virtual environment?

7. During the experience I often thought that I was really standing in the virtual environment...

	1	2	3	4	5	6	7	
Not very often	○	○	○	○	○	○	○	Very much so

8. Age

9. Gender

10.
Corrected vision (eyeglasses, contact lenses)?

11. Have you used any VR systems previously and how many times (for example Google Cardboard, GearVR, Oculus Go, Oculus Rift, HTC Vive, Valve Index, Playstation VR)?

- ◯ Never
- ◯ Once or twice
- ◯ Once or twice a year
- ◯ Once or twice a month
- ◯ Once or twice a week
- ◯ Several times a week
- ◯ Every day

12. How often do you play or used to play video games?

- ◯ Never
- ◯ Once or twice
- ◯ Once or twice a year
- ◯ Once or twice a month
- ◯ Once or twice a week
- ◯ Several times a week
- ◯ Every day

2. Participant Answers

Participant answers - Sheet1

User ID	A	B
pilot	Real	Movie
01F	Real	Real
02M	Real	Movie
03F	Real	Real
04M	Real	Movie
05F	Movie	Movie
06F	Real	Real
07M	Real	Movie
08M	Movie	Movie
09M	Real	Movie
10F	Real	Real
11F	Movie	Real
12F	Real	Real
13M	Movie	Real
14F	Movie	Real
15M	Real	Real
16F	Movie	Movie
17M	Real	Movie
18F	Movie	Real
19F	Real	Real
20M	Real	Real
21M	Real	Real
22M	Movie	Movie
23M	Movie	Real
24M	Real	Real
25M	Real	Movie
26M	Movie	Movie
27M	Movie	Real
28F	Movie	Movie
29F	Movie	Real
30F	Real	Movie
31M	Real	Movie
32M	Movie	Movie
33M	Real	Movie
34M	Movie	Movie
35F	Real	Movie
36F	Real	Movie
37M	Real	Real
38F	Movie	Movie
39F	Movie	Real
40F	Real	Real

Codes:
A1 = Large Real first
A2 = Large Movie first
B1 = Small Real first
B2 = Small Movie first