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The Induction and Objective Measurement of Illusory Roll-Axis Vection in Virtual Reality

Bachelor's Thesis (9 ECTS)

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Vektsiooni tekitamine ning objektiivne mõõtmine virtuaalreaalsuses

Lühikokkuvõte:

Vektsioon on defineeritud kui enese liikumise illusioon või enese liikumise subjektiivne tunnetus. Ajalooliselt on vektsiooni uuritud subjektiivse hinnangu meetoditega. Selles töös valmistati Unity programm eesmärgiga valideerida kaubanduslikult kättesaadavaid virtuaalreaalsusprille kui tööriistu, mille abil tekitada inimestes vektsiooni ning selle objektiivset mõju mõõta. Bakalaureusetöö raames viidi läbi katsed, et valideerida sellise lähenemise kasulikkust ning uurida, kas leiduvad mõõdetavad vahed vektsiooni tunnetuses, kui võrrelda erinevaid uudseid keskkonna pööramise viise ning erinevaid keskkondi. Katsetest saadud mõõtmistest oli võimalik välja lugeda vektsiooni mõjusid, kuid katsete alusel ei olnud võimalik teha järeldusi, et keskkonnad või keskkonna pööramise viisid oleksid oluliselt mõjutanud vektsiooni tunnetust. Tulemustest oli võimalik näha, et pööramise viis, millel oli kõige intuitiivsem seos katsealuse enda liikumisega, andis tulemuseks kõige väiksema mõõdetava efekti kontrolltingimusega võrreldes. Töö tulemusena on demonstreeritud uus viis, kuidas moodsate virtuaalreaalsusprillidega vektsiooni uurida.

Võtmesõnad:

Inimese ja arvuti interaktsioon, Vektsioon, Virtuaalreaalsus, HTC Vive, Unity, Ennustav kodeerimine

CERCS: P170 Arvutiteadus, arvanalüüs, süsteemid, kontroll

The Induction and Objective Measurement of Illusory Roll-Axis Vection in Virtual Reality

Abstract:

Vection is defined as the illusion of self-movement or the subjective experience of self-motion. Historically vection has been studied using subjective reporting methods. In this paper a Unity program is made to validate commercially available virtual reality headsets as an avenue for generation and objective measurement of vection. Experiments were conducted to validate the effectiveness of such an approach and to see if any differences could be measured when comparing different environments and novel ways of rotating the environment. The measurements detected the effects of vection but the differences in environment and ways of rotating the environment remained mostly inconclusive. It was observed that the rotation model which had the most intuitive connection to the subject's own movements resulted in less deviation from the baseline. Summarily, the results of this paper suggest new ways of studying vection with modern virtual reality headsets.

Keywords:

Human-Computer Interaction, Vection, Virtual Reality, HTC Vive, Unity, Predictive Coding

CERCS: P170 Computer science, numerical analysis, systems, control

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1. Introduction

Vection is a phenomenon defined as either the illusion of self-motion in the absence of actual movement (Dichgans & Brandt, 1978) (Fischer & Kornmüller, 1930) or as the conscious subjective experience of self-motion (Ash et al., 2013). To clear up any discrepancies, this paper will refer to it as illusory vection.

Vection has been usually measured by subjective self-reports and currently has need for objective measurement (Palmisano et al., 2015). While there have been hundreds of research papers published on this topic in nearly a century, and in the past years few have featured Virtual Reality (Bodenheimer et al., 2016). This paper finds that there is an opportunity in more objectively researching the effects of vection with commercially available head mounted displays. These devices provide a full range of motion freedom and “room scale” tracking.

The aim of this paper is a) to create an environment in which the generation of illusory roll-axis vection is possible through commercially available head mounted displays and b) to validate how objective measurements obtained through the head mounted displays can be used for measurement of the effects of perceived vection and c) see if different environments and ways of rotating the environment solicit different intensities of perceived vection.

The researchers believe that is an important study to two different groups: the psychologists investigating vection and the designers of walkable virtual environments, who will have more information on how people are adversely affected by motion in their environments. The researchers posit that this study might give environment designers better leverage over their audience’s sense of balance and location, which would allow them to make safer interactive environments, and give psychologists new insights about the computations in the brain.

The first chapter of the thesis gives a general overview of the theories this paper uses to predict possible behavior and discusses measurement in virtual reality. The second chapter of the thesis deals with the details on the tools used to create the environment, how the environment behaves in relation to the subject and the reasoning behind decisions made concerning the nature of the experiment. The final chapter gives an overview of the results of the conducted experiments and provides commentary and analysis concerning these results.

2. Background

2.1 The Predictive Mind

Per the theory of predictive coding the human perceptual system operates in a fashion, which attenuates expected stimuli and places more attention on stimuli, which act counter to the subject's mental model of the situation. (Hohwy, 2013) The brain continually attempts to correct the predictive model. When the predictive model fails, prediction errors are generated, which lead to updating and adjusting the mental model applied to the world. This is the mechanic through which the occurrence of prediction errors is decreased.

This theory, known as predictive coding theory would implicate, that environments and behaviors which the subjects have more experience with should generate more of a negative response, if the environments acts counter to subject's expectations of the environment.

2.2 Virtual Environment and Measurement of Vection

A previous study has already shown that "both linear and circular vection can be readily induced with head-mounted displays, with both patterns of optic flow and with more customary VR environments" (Bodenheimer et al., 2016) based on which it can be implied that illusory vection can indeed be generated in virtual environments

It has been shown that given appropriate visuals and a high level of interaction a subject will behave similarly in Virtual Reality to how he behaves in real life (Slater, 2009). Hence the observations made in VR environments should be directly transferable to the overall understanding of the experiential mechanics of the illusion of self-movement.

In this paper the researchers chose to set up an environment which generates circular vection on the roll-axis, as preliminary studies and the literature seems to point to the roll axis as generating the greatest subjective experience of vection (Tanahashi et al., 2012). An upright position also seems preferable to sitting or lying down, as these have been shown to lessen the effects of vection (Tanahashi et al., 2012). This summarily seems to point to a "vortex tunnel" simulation, like many amusement park attractions, to have the greatest yield of effects on a subject's sense of balance.

Previous attempts at objectively measuring the intensity of vection have been made on stationary subjects. The main candidates for this have been tracking eye movements, electroencephalography (EEG) or the postural responses of the standing subjects. (Palmisano et al., 2015) The latter seems to intuitively correlate with physical adjustments made to counteract the rotational forces of the exterior environment, which should, in turn result in clearly measurable differences in walking patterns for people experiencing roll-axis vection.

The head mounted display system used in this thesis provides an avenue to effectively measure the deviation from the expected walking path, as well as changes in walking style, speed and acceleration in 3-dimensional space. The researchers argue that these behavioral measures are ecologically more relevant than simply observing eye movements, brain waves or standing body posture. The researchers propose that it should be possible to detect the severity of the vection caused by the environment based on previously mentioned advantages in collection measurements.

3. Method

3.1 Tools and Physical Environment

For this thesis, the researchers opted to use an HTC Vive, which is a virtual reality headset developed by HTC and Valve Corporation. (HTC, n.d.) The HTC Vive accomplishes head tracking by using a “Lighthouse laser tracking system”, accelerometer and a gyroscope. Thanks to this combination of various sensors, the HTC offers a ‘room scale’ virtual reality experience to its users, meaning the users can walk around in a limited area with 6 degrees of freedom. The maximum area that the HTC Vive can operate in is up to is approximately 4.5m x 4.5m. (Digital Trends, 2016) For screens the headset uses an OLED 1080x1200 pixel display for each eye with a 90Hz refresh rate, this also means that positional data can be recorded 90 times per second, as new frames must be calculated.



Figure 1: Picture of virtual reality lab with person going through the experiment.

The experiments were carried out in a Virtual Reality Lab at the University of Tartu. The experiments used an HTC Vive that was set up in a space with the width and length of 3.5 meters and 4 meters respectively (see Figure 1). The walls in this room were somewhat padded due to the sound-dampening foam on the walls, but this did not cover all the walls. To avoid any accidental collisions with the walls, the experiments were conducted in a way, which had the subjects walk in the middle of the room and stop in a timely manner before accidentally walking into a wall. The experiment had the person stop approximately 0.2 meters before reaching the wall.

It has been shown that auditory stimuli can either help or hinder the illusion ofvection (Riecke et al., 2009) As the researchers decided to study the effects of visual stimulus in this

paper, over-the-ear headphones playing noise were used to filter out external auditory signals, which might reduce the effects ofvection due to providing a mental anchor to the exterior environment.

The noise played from the headphones was Brownian generated by Audacity, which is a free open source platform for editing audio. (Audacity, n.d.) Communication with the subject was maintained using a microphone connected to the headphones. Talking to the subject did not interrupt or lower the volume the noise, but was overlaid on top of it.

3.2 Unity and SteamVR

The virtual environment used in this thesis was developed using Unity version 5.5.2f1, which is an industry leading, free and fully featured game engine (Unity, n.d.). Unity provides an educational license which also covers research. Unity has programming language support for three languages: C#, Boo and Unity Script. For the purposes of this thesis, the script which conducts the experiment was written in C#.

It is possible to develop games for the HTC Vive in Unity thanks to a middle-layer, the SteamVR SDK (software development kit), which connects the hardware to the software. The SteamVR SDK adds some features like positional tracking of the headset, red lines denoting the edges of the area known as chaperone bounds, and allows scripts to access positional information. The SDK is interfaced with inside Unity through the Steam VR plugin (Valve Corporation, n.d.) added to the project though the asset store.

3.3 Virtual Environment Setting

The researchers opted to have a few static elements which remained the same over both environments. This has two main purposes: to maintain the same general “usability” of the environment by not introducing additional variables along the walking path and to make sure that the measurements would remain the same over all experiments.

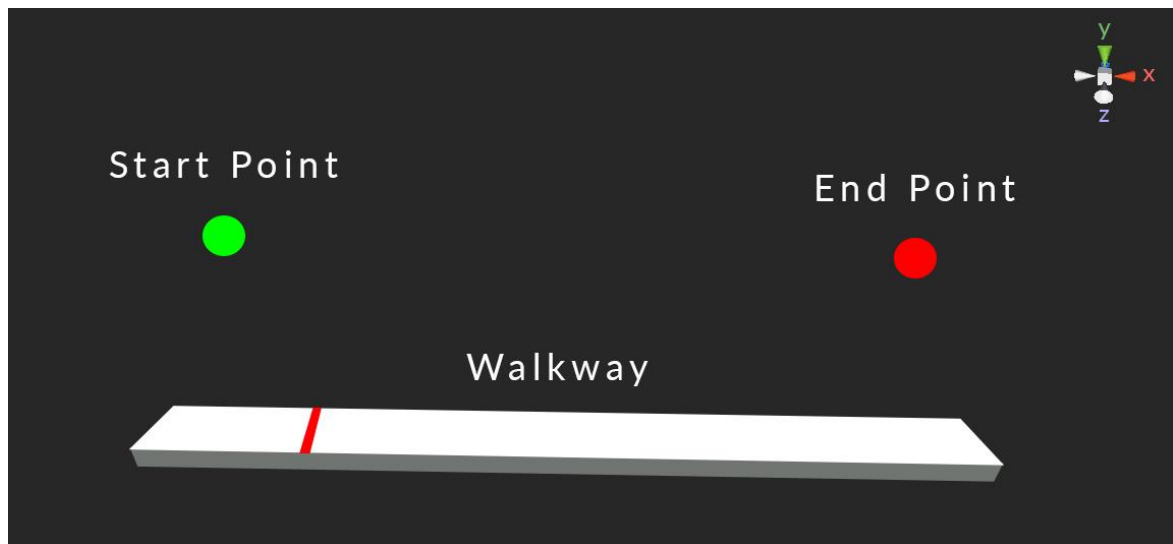


Figure 2: Stationary elements of the experiment.

There are 3 static elements (see Figure 2) in the environment. First, there is the walkway, on which the person walks during the experiment. The researchers assume not having a walkway would negatively impact the suspension of disbelief in the virtual environment. A walkway assures the subjects that there is a surface on which they are walking. This also serves to keep the subjects on track and walking a straight line to the best of their ability. There is a line on the walkway, which is used to indicate how far back the subject must stand

when waiting for the trial to start. The other two elements are the start and end points, which are spheres that are situationally colored indicate where the user should be walking to at any point (see Figure 2). The start and end points are adjusted to be at eye-level when the experiment is started.

Two different “rotatable” environments were used in these experiments. This was done to confirm whether different environments have a different impact on the severity of the illusory roll-axis vection generated, as might be suggested by predictive coding theory. Both environments had their own light sources, which rotated along with the rest of the environment.

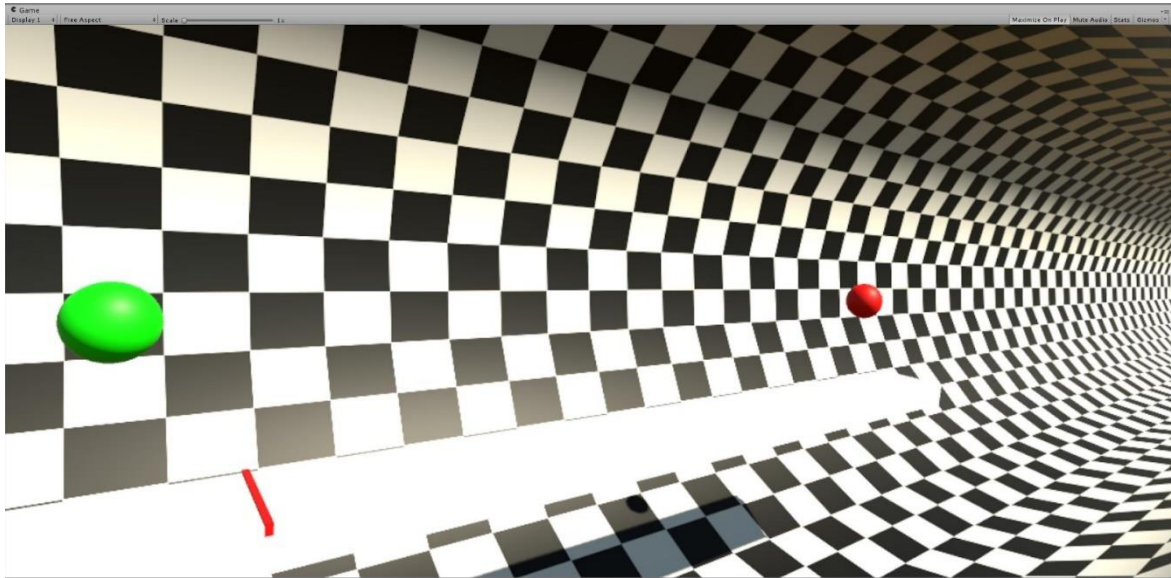


Figure 3: Side view of vortex tunnel with stationary objects

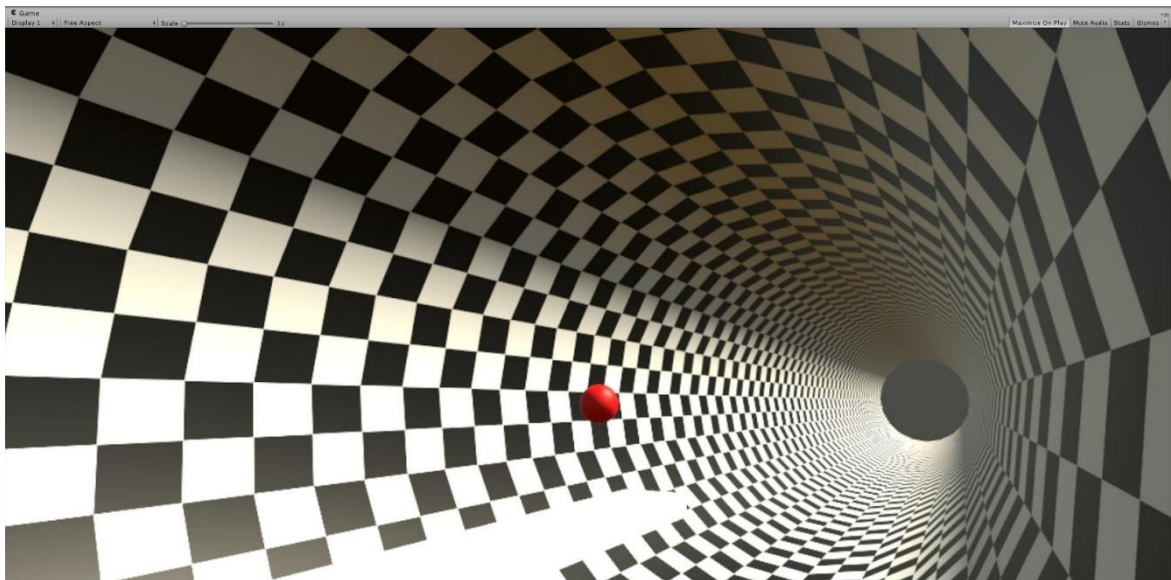


Figure 4: View when looking along the vortex tunnel.

The first environment (see Figure 3 and Figure 4) was inspired by real-life vortex tunnels used as attractions. The researchers knew such a model would certainly have some sort of effect on a walking person as the researchers had prior experience in the real-life versions of these and as mentioned previously, illusory vection can readily be generated by virtual environments. The environment models a very abstract environment to which people should

have no long-term day-to-day exposure. This paper posits that based on predictive coding this should have a noticeably smaller effect on vection as the mind should assign a slightly higher probability to the surrounding environment spinning than the subject themselves.

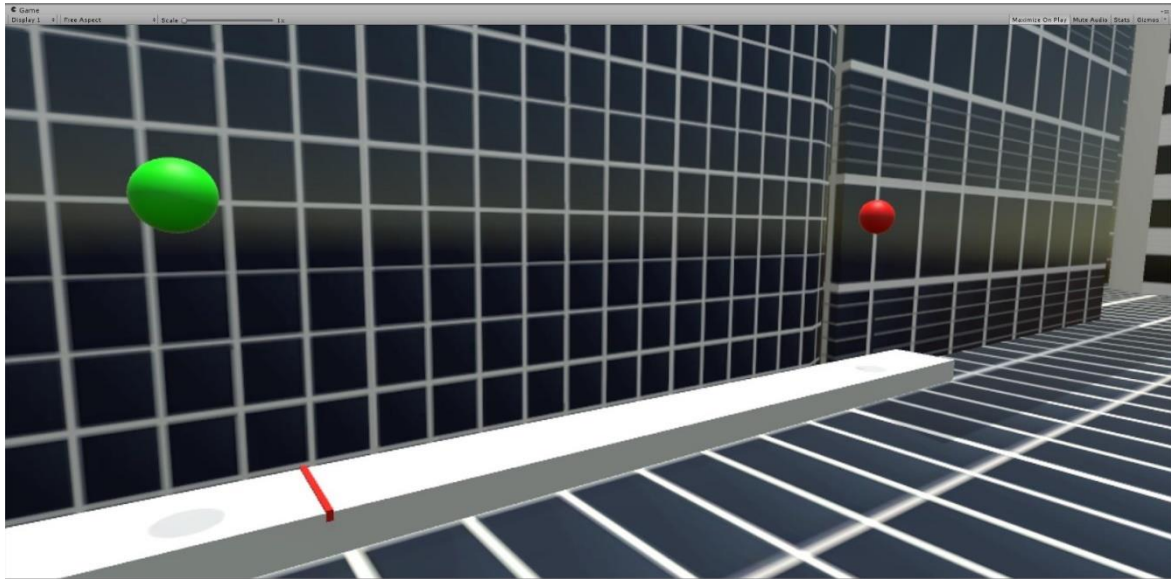


Figure 5: Side view of city with stationary objects

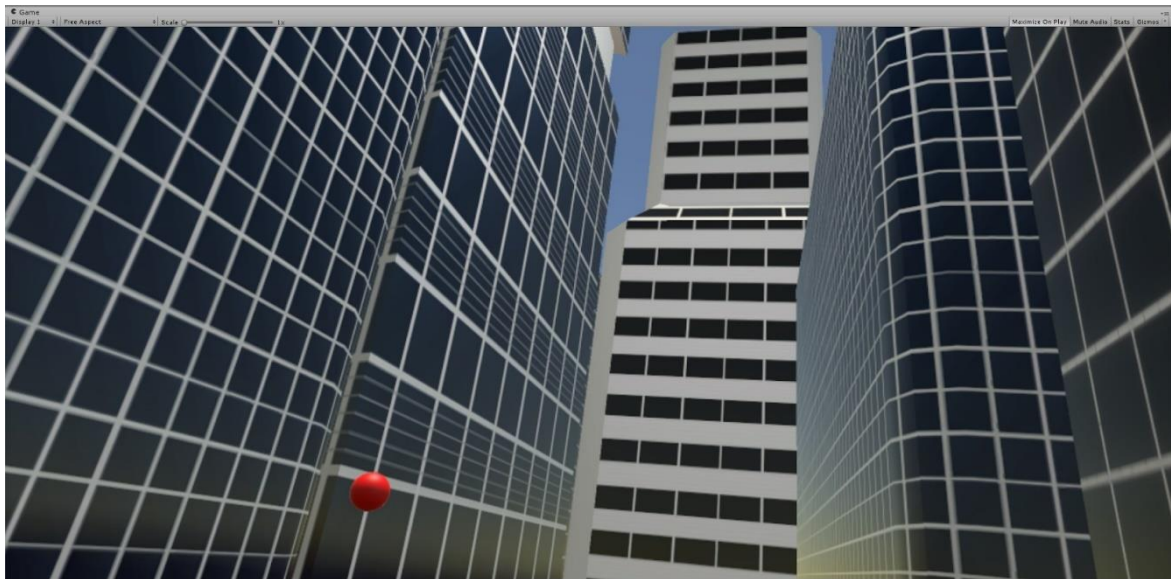


Figure 6: View when looking up in the city. Endpoint visible in bottom left corner.

The second environment which was used is a low-detail representation of a city environment. Based on predictive coding theory it could be inferred that situations more similar to real-life experiences should create a larger illusion of vection. This is backed up by earlier experimental findings. (Riecke, Schulte-Pelkum, Avraamides, & Von Der Heyde, 2006)

The assets used in this simulation are houses from the “White City” asset pack created by Ali Zanjiran available for free commercial use at the Unity Asset Store. (Zanjiran, n.d.)

3.4 Rotation Models

In the experiments an attempt was made to solicit behavioral responses from walking subjects by applying a rotational model to the environment. In this thesis, rotational model or RM for short is defined as a certain way in which the environment will rotate. Explanations about the characteristics of individual rotational models can be found on Table 1.

Table 1: Rotation Models

Rotational model	Description	Speed of rotation (deg/s)
RM0	No roll-axis rotation. Used to establish baseline pattern and timing of movement.	0
RM1	Constant rotational velocity. Most common model used in visual flow patterns and commercial vortex tunnels.	60
RM2	Constant rotational velocity alternating in direction every 2 seconds	60 or -60 alternating every 2 seconds
RM3	Rotational velocity dependent on the x-axis location of the subject. When at the starting point, spins counterclockwise at 120 deg/s, at the center of the area change in rotation reaches 0 and starts increasing clockwise rotation until reaching end point while spinning at around -100 deg/s.	60* head.location.x
RM4	Rotational velocity dependant on the speed at which the subject is traveling. Since location is being sampled 90 frames per second, the change from the last frame for a person walking at 0.75 m/s would be 0.75/90. This speed would therefore result in a rotational speed of 65 deg/s.	[change in location since last frame]*7800
RM5	Rotational model which mimics the rocking of a boat. The speed of the rotation is sinusoidal in nature. The x value for the cosine function used to rotate the environment is a multiple of the time elapsed since the start of the experiment, so each experiment will first start with the environment rotating clockwise.	cos(t)*60 - [current angle of rotatable]

Each of the rotational models is defined through the angular momentum and direction of the roll axis rotation. Negative rotation means turning counterclockwise. The angle of the rotatable object is recalculated every frame (see Appendix 1).

3.5 Environmental Interactions

The environment in which the experiment is conducted implements multiple environmental cues which are intended to cause the following behavior:

1. The start point turns green and the endpoint turns red. The subject is expected to move to the start point.
2. Once the subject reaches the start point, both the start and end point turn yellow and the subject is expected to stay near the start point for 10 seconds. If the subject leaves the area around the start point during this time, the start point will turn green and the end point will turn red, prompting the subject to return to the start point.
3. Once the subject has been near the start point for 5 seconds, the environment starts rotating. If the subject leaves the area around the start point during this time, the start point will turn green and the end point will turn red, prompting the subject to return to the start point.
4. Once the subject has been near the start point for 10 seconds, the end point turns green and the start point turns red. This prompts the subject to start moving towards the end point.
5. The start point continues to be red and the end point continues to be green while the subject moves towards the end point while a rotational model is applied to the environment.
6. Once the subject reaches the end point, the process is either repeated with the next trial, going back to 1., or both points start alternating between green and yellow to denote the end of the experiment.

A video of this interaction and the experiment in general was recorded and uploaded to Google Drive for demonstrative purposes. (Vasser & Tammsaar, 2017)

The delay between the start of the rotation model and the prompt to start walking is based on the research done on illusory vection showing that vection generally seems to have some onset time (Bodenheimer et al., 2016) (Tanahashi et al., 2012). As this thesis intended to measure the intensity of vection, it was decided that it would be in the interest of the experiment to have some sort of delay before walking, so the subject would start to experience vection before the start of the trial. Based on the researchers' empirical observations, it was decided that the 10 and 20 seconds cited in the research papers seemed to be too long in this context, so a 5 second delay was implemented instead.

The C# script (see Appendix 2) is written in a way, that data is only collected during stage 5 (see Appendix 1 switch case 4) while the subject is walking towards the end point. During this stage, data is collected 90 times a second (every frame) about the following values: the order number of the trial, point in time within the trial the data is collected, the time from the last frame, rotation model applied to environment, the change in X, Y and Z coordinates since the last frame and the change in roll spin and yaw of the head mounted display. At the end of each trial, this information is appended to a CSV file created at the start of the experiment. At the end of the experiment, a row of metadata is written into a separate metadata CSV file, containing the name of the experiment data CSV, start time of the experiment, end time of the experiment, the subjects age and gender and whether the subject had to remove their glasses to wear the headset.

3.6 Pilot Experiment

The experiment was piloted with 6 people to understand how to better formalize the experiment and understand what parts of the procedure needed to be improved or simplified. Data was collected based on the specified model above, but 4 out of 6 of the test subject's data

was rendered useless by an oversight in the code which caused the rotation model for each trial to not be recoded. This was later fixed for the main round of data collection.

Additionally, it was learned that the interaction model that this experiment uses to solicit certain behavior from the subject took about 3 trials to master. Knowing this the script was modified to run 3 trials with no environmental rotation (RM0) before trials which featured rotating environments start. The researchers think this should increase the accuracy of the collected data.

Out of the 6 subjects none reported feeling uncomfortable, sick or dizzy after the end of the experiment. It was decided to still verbally inquire how the subjects were feeling about one third of the experiment through just in case. One subject reported feeling dizzy much later in the day, which might mean the environment might cause late-onset simulation sickness in some people. The total time from the subject entering the lab to the subject exiting the lab was an average of 22 minutes.

3.7 Experiment Procedure

When the subjects enter the VR Lab they were presented with a informed consent document (see Appendix 3) describing the contents of the experiments as “experiments about balance and consciousness in virtual reality”, the basics of virtual reality and the overall procedure of the experiment and data collection. This document also clearly states that they can abandon the experiment at any time.

The subjects are given a cover story that that the researchers are studying their natural walking pattern within virtual environments. The subjects are not directly told that the headset is recording positional data.

The subjects are told to that they would have to walk across the room multiple times and should try to maintain as straight and stable of a walking pace as they could, without closing their eyes or somehow cheating the experiment, as this would make the data unusable.

The subjects are then asked to walk to the center of the 4x3 meter testing environment and helped with putting on the head-mounted display and noise-generating headphones. After this point, the conductor of the experiment moves to the computer and puts on a set of headphones with the microphone being connected in a way, which enables communication to the subject’s headphones.

The virtual environment is then started with either the ‘city’ or ‘vortex’ being the first environment. The subject is asked to look around the virtual environment and find the green sphere (the start point) and the red sphere (the end point). Then the subject is asked to walk over to the green sphere and make sure they are behind the red line on the ground. Then the subject is asked to face the other (now yellow) sphere and wait until it turned green. The subject is then asked to move in an even and natural walking pace straight to the green sphere. After the subject reaches the green sphere, it turns red and the subject is asked to return to the initial location. Then the process is repeated. The subject continues to receive instruction on walking pattern and interaction model for the first 3 trials.

All subjects are then subjected to a randomized order of rotational models consisting of 3 instances of RM0 and 2 instances of RM1-5 each.

After the subject has done 10 consecutive trials the subject is verbally asked if they feel dizzy or motion sick, as this would be a factor which would require either giving the subject some time to recover or ending the experiment entirely.

After all rotation models have been exhausted half-way through the experiment, the exterior environment changes from either “city” to “vortex” or “vortex” to “city”, depending on the current environment. The subject is then verbally informed, that everything else about the experiment is the same, but the environment has changed. Then the subject is again subjected to a randomized order of rotational models consisting of three instances of RM0 and 2 instances of RM1-5 each.

After the rotation models have been exhausted for this environment as well, the two spheres will blink green and yellow and the subject is informed that the experiment is over. The subject is then informed on how and what kind of data was collected and how it would be used.

4. Experiment Results

The experiment was conducted on 18 people, out of whom 3 were not included in the final data set. 2 subjects abandoned the experiment due to the environment affecting them to such a degree, that they were incapable of continuing. 1 subject was not included in the final dataset due to visibly not being affected by the environment at all. When the subject was asked what strategy they used to negate the effects of the environment, they responded with stating that they “counted steps” and found a way to ignore the environment fully. As this was not the aim of the experiment, this subject was not included in the data set.

Out of the 15 people whose data was analyzed, 4 were women and 11 were men, with the youngest participant being 21 and the oldest being 33. The average age of the participants was 25.4 with a standard deviation of 4.0.

This thesis used the free statistical programming language R (The R Foundation, n.d.) to analyze the data and the plotting system ggplot2 (Hadley, n.d.) to visualize the data. The program written to analyze the data and the data itself is in the “Results” folder of the ZIP file accompanying this thesis.

4.1 Measurement Anomalies

While analyzing the data, the researchers came across strange measurement outliers when looking at the speed for every frame in each trial. It was noticed that there were points where the speed changed from, for instance, 2.2 m/s to 10.0 m/s (see Figure 7). As this kind of a jump in speed between frames would mean the person would have had to accelerate at approximately 700 m/s^2 , this was found to be an unacceptable feature of measurement and the researchers sought to discern the reason of the error.

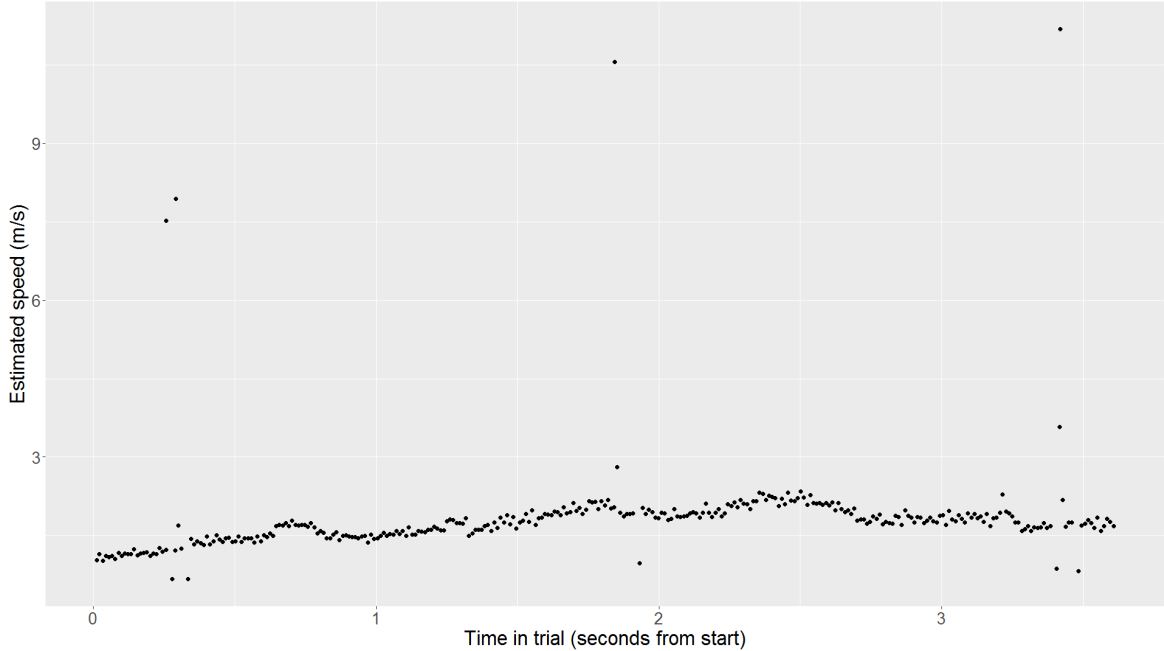


Figure 7: Spikes in estimated speed when observing a trial with 90Hz location sampling.

Based on these anomalies occurring mainly with either RM3 or RM5 as the environment's rotational model and the anomalies' distributions differing between the models (see Figure 8) the researchers hypothesized that the change in direction of rotation was causing subjects to turn their heads rapidly. This in turn would cause either a performance related mismeasurement, due to increased workload on the rendering engine, or a mismeasurement from the

hardware due to sensor accuracy diminishing while measuring high speeds. After analyzing the data further, the researchers found that these mismeasurements seemed to occur at the same time fluctuations occurred in the frame rate (see Figure 9), which hinted at this being a performance related issue rather than a measurement device related issue.

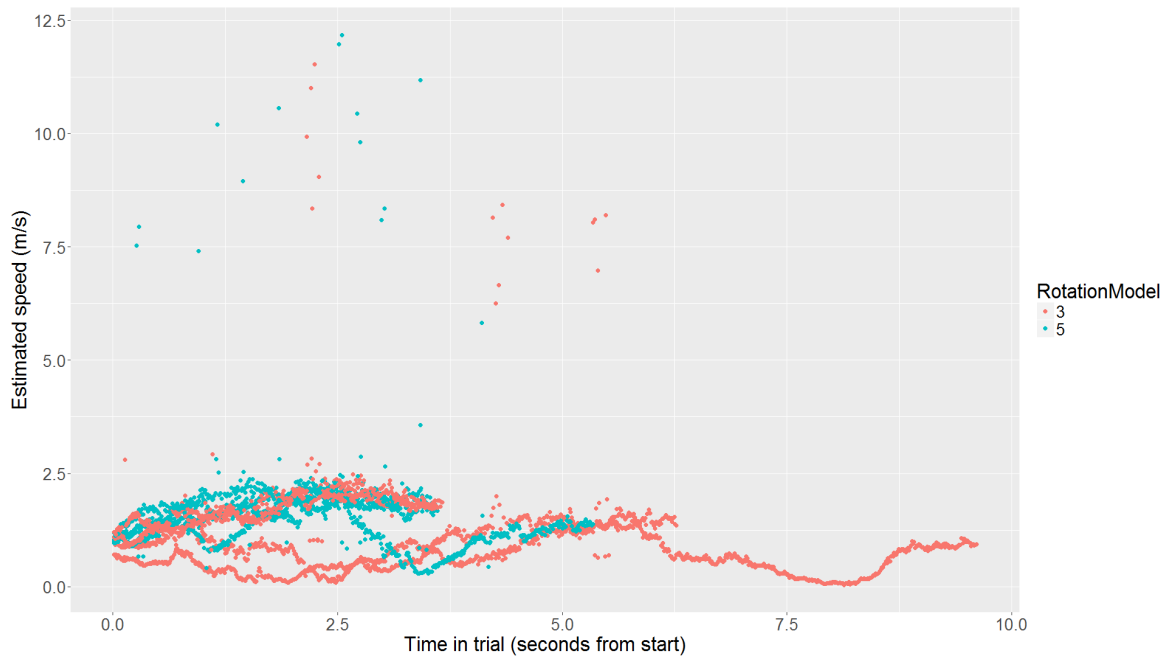


Figure 8: Distribution of speed over trial time in trials of RM3 and RM5

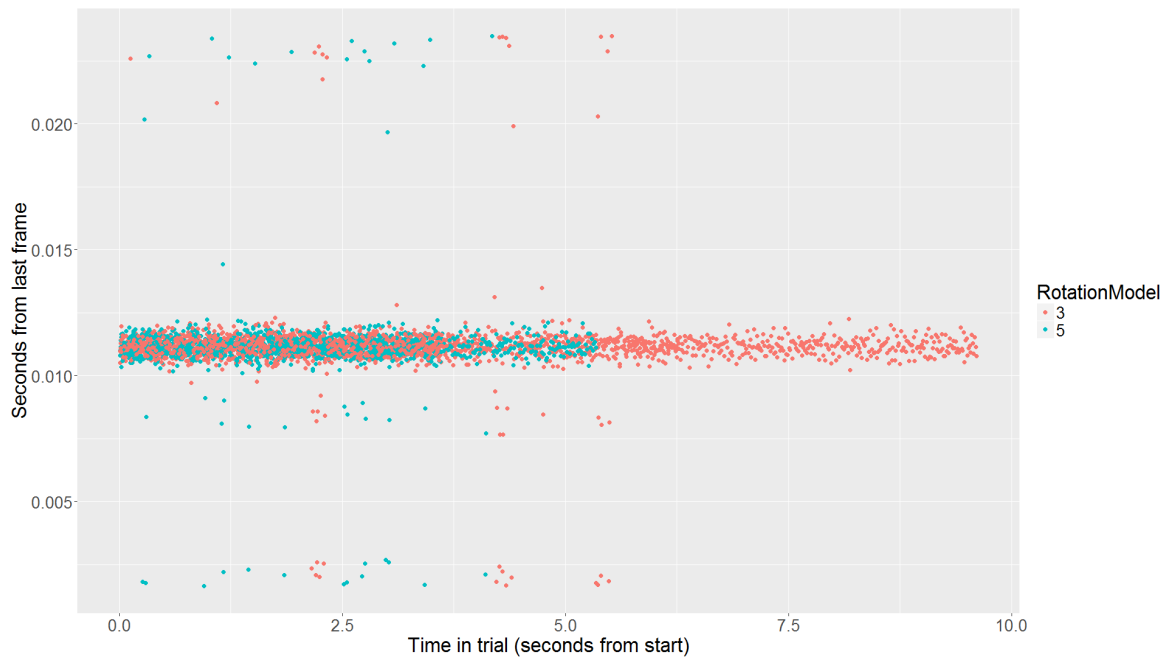


Figure 9: Distribution of frame rates over trial time in trials of RM3 and RM5

Two experiments were initially conducted in an attempt to recreate the drop in framerate. In the first experiment a researcher attempted to move through the environment as straight and even as possible. In the second one the same researcher did rapid side-to-side movements and head turns on many of the trials, which were not RM3 or RM5. This did not seem to generate an observable difference in anomalous frame rates (see Figure 10 and Figure 11), which invalidated the rapid head movement hypothesis entirely.

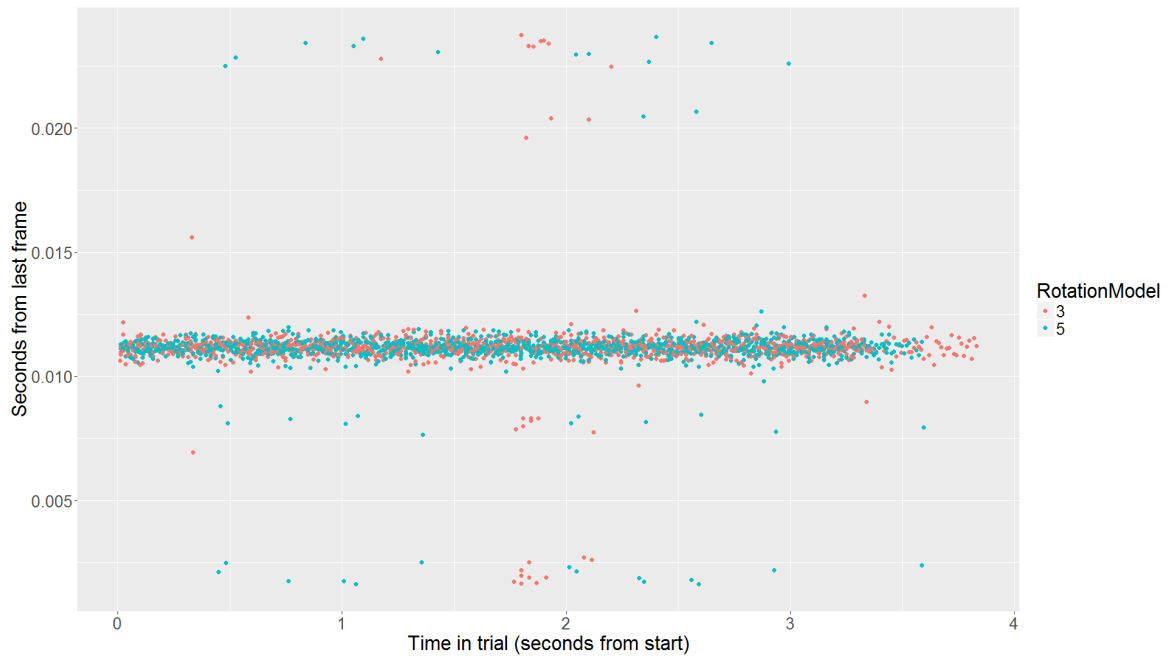


Figure 10: Distribution of frame rates over trial time when moving in a stable manner.

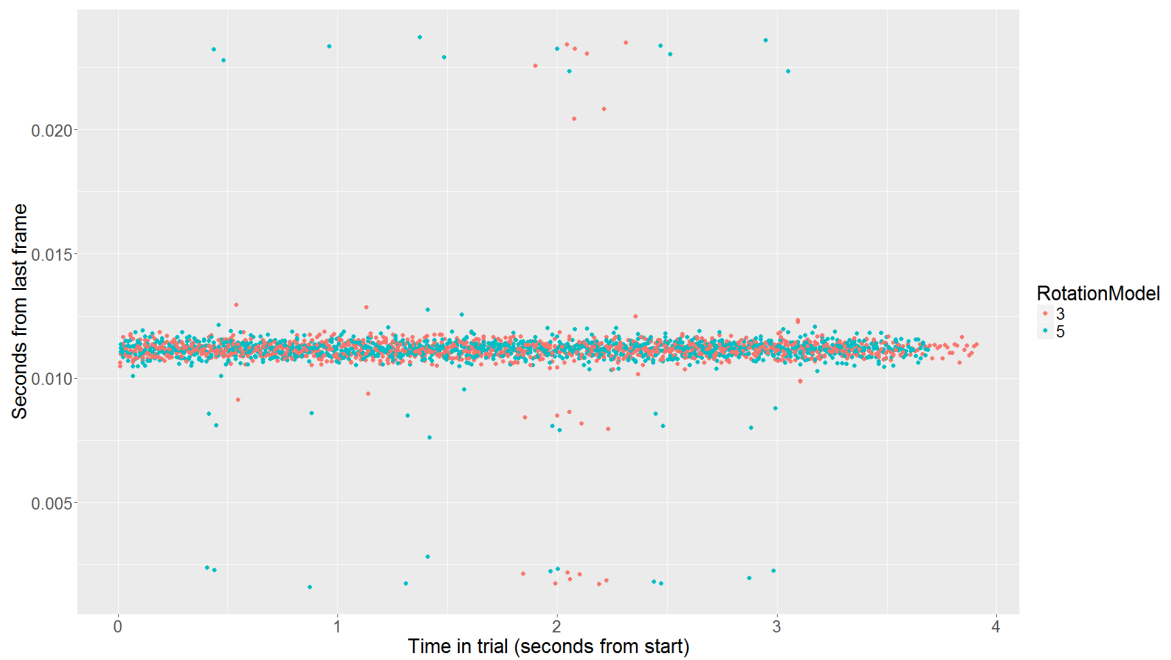


Figure 11: Distribution of frame rates over trial time when making sudden movements.

Finally, the researchers ran a shorter experiment on the hypothesis, that this strange behavior was being caused by Unity having issues with turning the rotatable environment by a very small degree, which did happen when either RM3 or RM5 changed directions. In this experiment, the researcher tried to move very slowly on all RM4 (see Table 1 for explanation) trials to try to recreate this anomaly with another, so far unaffected rotation model. The data clearly shows that these deviations in frame rate also were present with the RM4 model this time (see Figure 12). This seemed to sufficiently confirm the hypothesis and the researchers moved on to inspect how this problem affected the data.

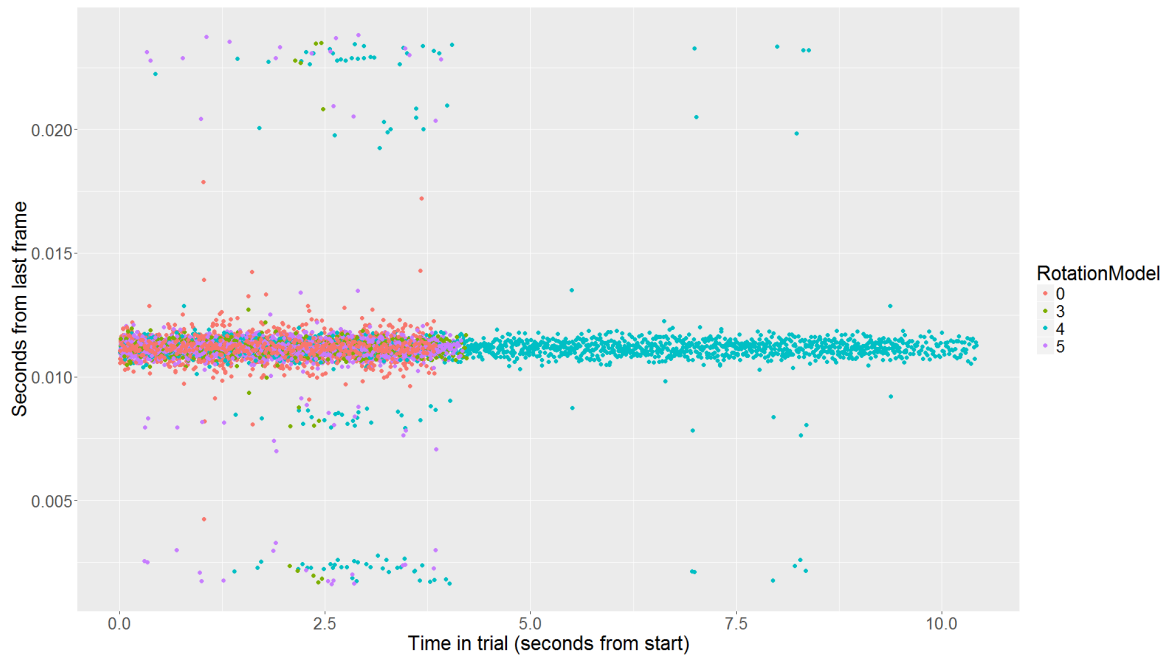


Figure 12: Distribution of frames when moving very slowly through RM4 compared to other problematic rotation models.

It was found that the hardware location sampling and the internal time from last frame calculations ran slightly out of sync during these experiments, which caused mismatches at the 90 frames per second level. It was confirmed that this was indeed only an error in frame attribution by calculating the summary distance traveled on the X-axis, which showed that all trials always summed up to 3.6 meters, which is the distance the data is recorded for. It was found that the measurement accuracy could be easily addressed by lowering the resolution of the data to 10 frames per second, summarizing the events of every 10 frames into a single frame.

4.2 Units of Measurement

Observations during the experiments showed that people's reaction to the environment was not uniform. All people fell on a spectrum in terms of the strategy they used. On the one side of the spectrum, effects of the environment manifested themselves by the subject uncontrollably slowing down and moving significantly slower to be able to complete the trial. On the other side of the spectrum, people maintained their baseline speed but were significantly more erratic in their movements. Due to this it should be clear that at least two separate measured attributes are needed to adequately quantify the results of each trial.

The first unit of measure that was opted for was the time it took to complete the trial. This seems intuitively reasonable as it could be observed that subjects tended to slow down when faced with a RM which made completing the trial more difficult.

Additional metrics were required to gage how erratic the movements of the subject were. One good candidate for this seemed to be the absolute distance traveled during the experiment. Upon further inspection this highly correlated with time taken to complete the trial. This suggested, that more Y (up and down) and Z (left and right) axis movement was accrued simply by the experiment lasting longer. To counteract this, this thesis opts for the use of average absolute speed (in this paper defined as absolute distance traveled divided by time taken to complete trial) on the Z and Y axes to gage how erratic the movements of the

subjects were during the trial. Uncontrollable movements should logically manifest themselves on these axes, as subjects are instructed to move “as straight and evenly as possible”.

Absolute average speed on the Y axis was also invalidated as a useful unit of measurement, as it was negatively correlated with trial time. All trials which featured higher trial times also featured lower average speed on Y axis, presumably due to slower walking naturally having a smaller Y axis component. Standard deviation of speed on a given trial was also disregarded as an option, as while it is useful when comparing two trials of approximately the same completion time, it loses that intuitive usefulness when comparing two trials with radically different completion times.

This thesis focuses on only two factors for objective measurement of the effects ofvection - trial completion time and “straightness” of the walking represented by absolute Z-axis speed.

4.3 Data Processing

The data was first read in for every individual experiment and the resolution of the data was lowered to 10 frames per second, the reasoning of which was explained at the end of the last subchapter. Additionally, in this step movement speed estimates were added for the X, Y and Z axes based on the change in location and the time from the last frame. This step also added general movement speed estimates for each frame.

After this the data were summarized into a generalization about the experiment. This information included trial completion time, absolute distance traveled on the X, Y and Z axes and total absolute distance traveled, average speed on the X, Y and Z axes and general average speed, standard deviations of speed for the X, Y and Z axes and general standard deviation of speed, average absolute speed for the X, Y and Z axes and general absolute average speed.

As each subject had their own baseline movement speed and pattern the researchers found that comparing different subjects simply by the raw time it took for them to complete a task was not a realistic goal. Based on this information all experiments were standardized by dividing every metric with the baseline RM0 average. This means that if for some experiment $T=2$, it took the subject two times longer to complete the trial than their average baseline, RM0, attempt to do so. When calculating baseline averages, the first two trials were excluded, as these were very often outliers because subjects were still getting familiarized with the experiment.

Due to the complexity of representing rotated objects in 3d space, which caused jumps of 180 degrees when changes in rotation were recorded, and the fact that the program did not save the initial rotation of the subjects head when starting a trial, no data about rotations were processed in this thesis.

4.4 Results

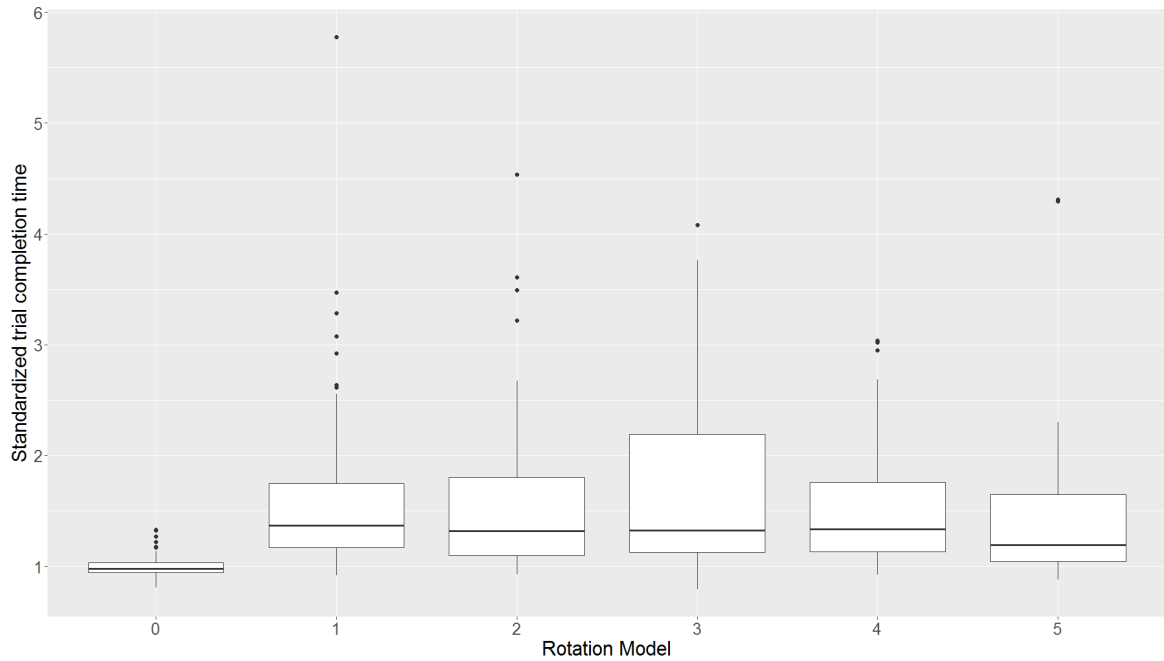


Figure 13: Boxplot depicting relationship between RM and trial completion time

Figure 13 depicts the relationship between trial completion time and the rotational model applied to the environment during the trial. A one-way ANOVA test controlling for variation in multiple within-subject measurements showed that rotation model affects trial completion time significantly ($p < 0.001$). Independent two-group T-tests revealed that there is a significant difference in trial completion time between RM3 and RM5 ($p < 0.05$). All rotation models had a significant ($p < 0.001$) effect on trial completion time compared to RM0. No other pairs within RM1-5 revealed statistically significant differences in trial completion time.

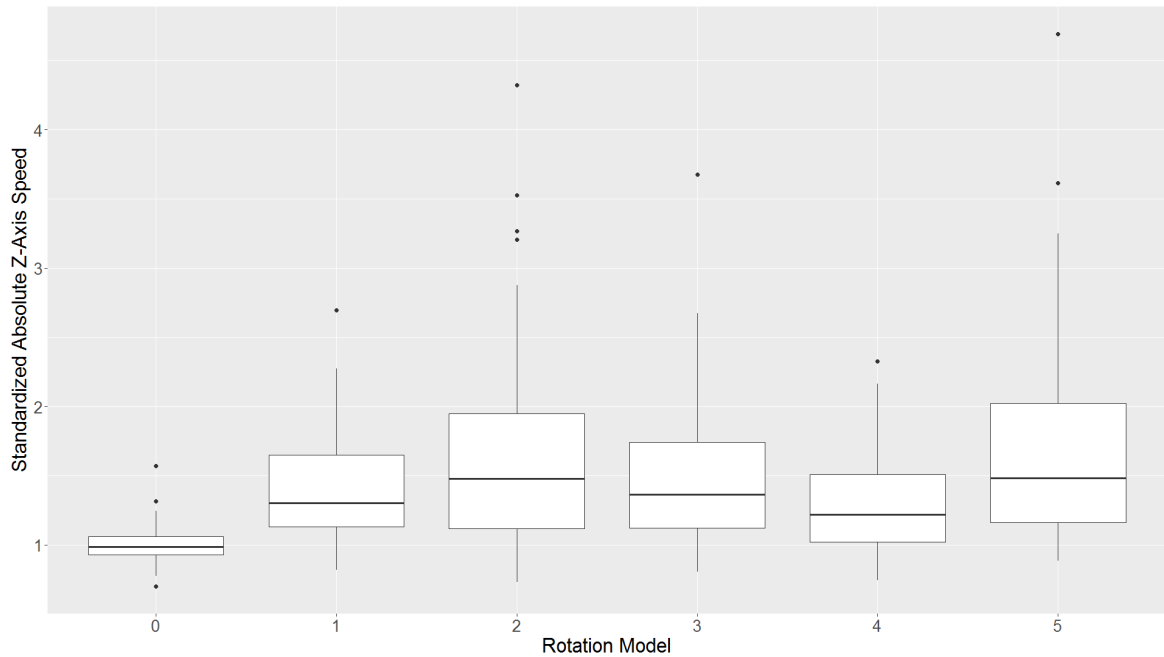


Figure 14: Boxplot depicting relationship between RM and absolute speed on Z axis

Figure 14 depicts the relationship between average absolute speed on the Z (left and right) axis. A one-way ANOVA test controlling for variation in multiple within-subject measurements showed that rotation model effects average absolute speed on the Z axis significantly ($p < 0.001$). Results of all the t-tests can be found in Table 2.

Table 2: Statistical significance between RM when inspecting avg. abs. Z-axis speed

	RM0	RM1	RM2	RM3	RM4
RM1	***				
RM2	***	*			
RM3	***	NS.	NS.		
RM4	***	NS.	**	*	
RM5	***	*	NS.	NS.	**

Signif. codes: *** $p > 0.001$; ** $p > 0.01$; * $p > 0.05$

The two rotatable environments, ‘city’ and ‘vortex’, did not display any statistically significant differences in trial completion time or average absolute speeds on the Z axis. The first environment which was presented to each subject exhibited significantly higher trial completion times ($p < 0.001$), but did not feature a significant change in absolute speeds on the Z axis.

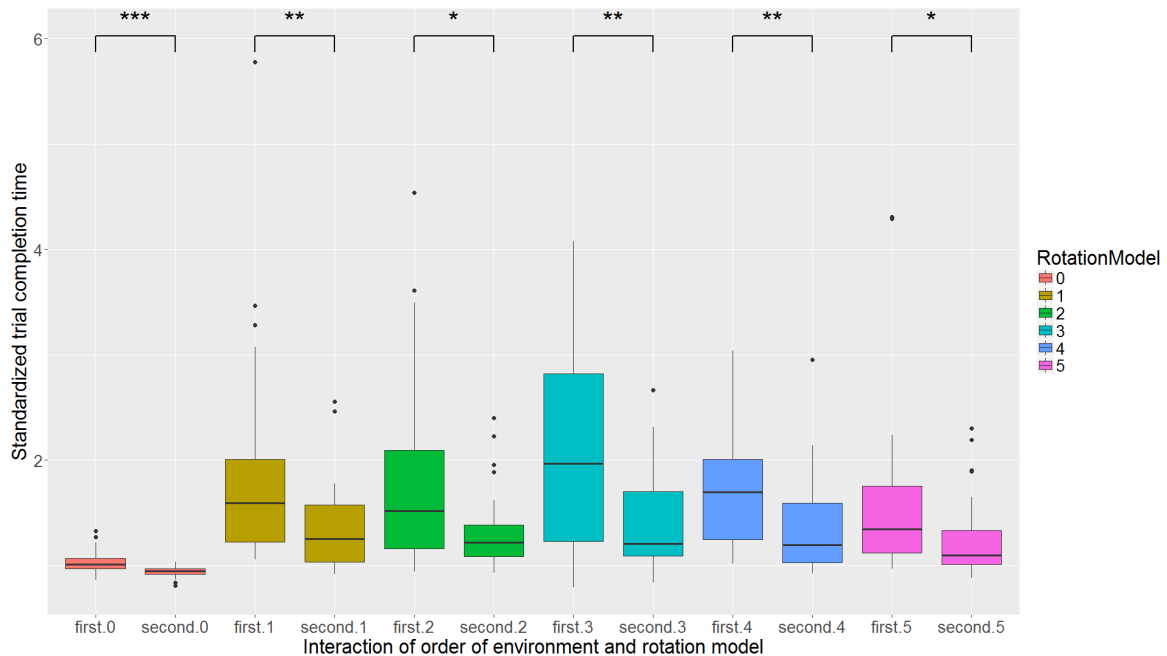


Figure 15: Differences in RM trial completion time when comparing first and second environment. Significance levels denoted at top of figure.

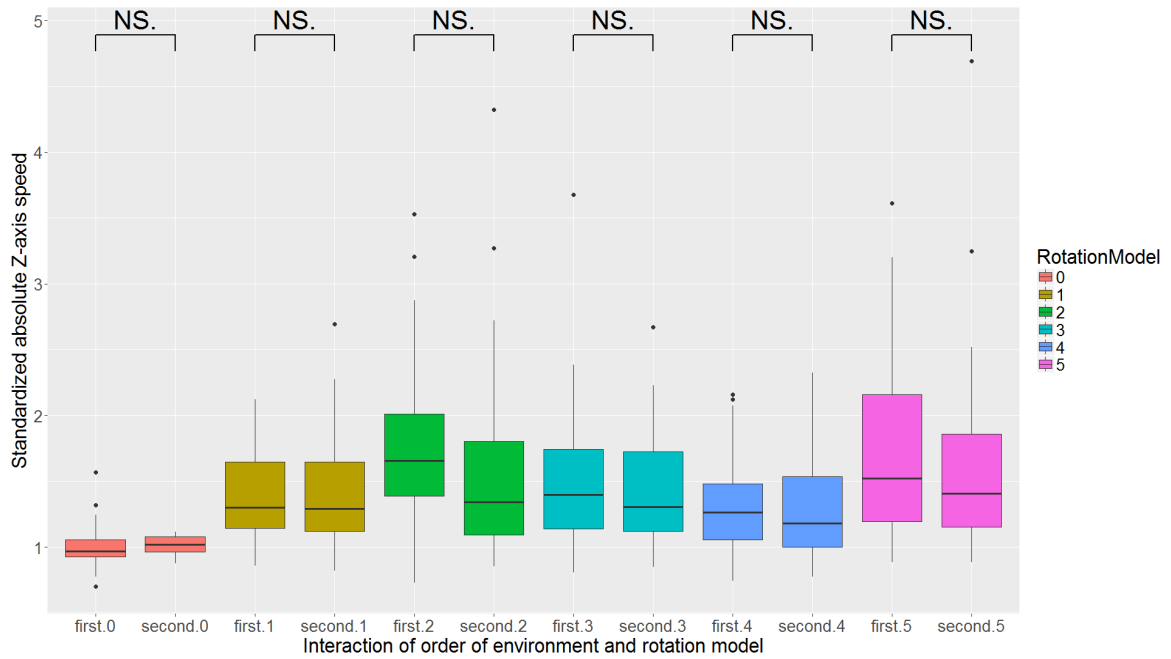


Figure 16: Differences in RM trial average absolute speed on Z axis when comparing first and second environment. Significance levels denoted at top of figure.

When granularly comparing the effects of the first and second environment on trial completion time, (see Figure 15) trial completion times are significantly reduced for all rotation models. Trial completion time for RM0 (no rotation of the environment) also is reduced significantly ($p < 0.001$). No significant changes could be observed when comparing the effects of the first and second environment on the average absolute speed on the Z axis (see Figure 16).

When controlling for multiple within-subject measurements, gender, age and whether the subject had to take off their glasses did not have a statistically significant impact on the main measured variables.

4.5 Discussion

The goal of this thesis was to create a virtual reality experiment which would be a viable alternative to subjective reporting when studying the effects ofvection, as this would allow more accurate and realistic deductions to be made on the subject.

In the results described in the previous subchapter it is possible to observe that certain variables have a statistically significant difference from RM0, which clearly points to the fact that the intensity of the reaction to illusory roll-axisvection, and by proxy the intensity of the perceived illusory roll-axisvection might viably be objectively measured using commercially available virtual reality headsets. The statistical significance of the measurements also confirms that the created environment does effectively generate illusory roll-axisvection in subjects.

Significant differences from RM0 could be observed across all rotational models when observing both trial completion time and “straightness” of walking, which in this thesis was represented by average absolute Z-axis speed. No conclusive statements can be made about the ordering of intensity between different rotational models, but it could be observed that RM4 had significantly less impact than other rotational models in terms of absolute Z-axis speed.

The strong initial effects of RM3 could be reasonably explained by the fact that the rotational model seemed to contain the most believable example of deceleration compared to the rest of the rotational models which technically featured it (RM5 and partially RM4). This might have caused a sudden movement to compensate for the perceived deceleration. The novelty of this seems to rapidly diminish (see Figure 15). The relatively small effects of RM4 seem to be explained by the fact that the subjects seemed to possess more intuitive control of the rotational model, and thus might have been able to attenuate the movement of the environment. Attenuation of self-induced movement has been shown to happen in regular circumstances (Laak et al., 2017) so it seems to be a plausible explanation in this situation.

Desensitization to the experiment seemed to happen relatively fast, as subjects became much more capable of completing the trials with about the same time as the baseline with no stimulus (see Figure 14), however no significant changes could be observed in the “straightness” of walking represented by the absolute Z-axis speed (see Figure 15), which seems to imply that absolute Z-axis speed might be a more robust measurement of the effects of roll-axis illusory vection for walking subjects. It should also be mentioned that there was a downward trend in RM0 completion times, which could be a combination of multiple factors like better familiarization with the experiment format and impatience.

Gender has been observed to be a significant factor in earlier research about vection which has used subjective reporting (Bodenheimer et al., 2016), but based on the experiments conducted in this thesis, the results fail to observe any significance that gender plays on the effects of vection. This is likely caused by the skewed gender distribution in this paper, as very few generalizations can be made about any gender differences with a sample size of 4 women and 11 men.

The environment did not seem to play a significant role in the intensity of the illusory roll-axis vection induced. The graphical fidelity of the environment might not have been good enough to fully immerse the subjects into the virtual world. The ‘city’ environment might not have solicited the sense of being in a city due to the low representational fidelity. Additionally, it is possible that the sample size was not big enough but that the environment did play a very small role in the intensity of vection perceived. Repeating these experiments with environments which feature more realistic graphics might lead to significant results, but the conducted research did not manage to show any difference.

If any research is continued this subject, the researchers recommend to make the space where the experiments are conducted as safe as possible. While the experiments in this thesis all ended without any people or equipment being harmed, there was a very significant risk taken with this paper. The researchers would recommend to fully pad the walls in case subjects accidentally run or fall into them during the experiment. The researchers had to terminate one experiment due to a very real risk of the subject hurting themselves or damaging the equipment. Alternatively, a weaker stimulus could be used, but this might be easier to fully ignore. Using a larger room might be good for both safety and measurement reasons.

4.6 Included Files

There is a collection of files that are included with this Bachelor's thesis: the experiment data, the script used to analyze the experiment data and the full Unity project created for the purposes of this thesis.

The experiment data and data analysis scripts are in the “Results” folder of the attached file. The R script named “analysis” is provided as an HTML document for easy viewing, as an IPYNB document for viewing in Jupyter Notebook and as an R file for general use. The Unity project is in the folder called “Unity” under the project name “Twilt” and can be easily

imported into Unity. SteamVR needs to be installed on the system and an HTC Vive headset connected to the computer to run the program. The script that facilitates and records the experiment is located under the name “rotator.cs” inside of the “Assets” folder in the “Twilt” folder.

5. Conclusion

In this work a Unity program for the HTC Vive was created to facilitate and measure an experiment about roll-axis vection. An experiment was conducted on 18 volunteers to demonstrate the viability of such a program. Analysis of the data revealed that trial completion time and average absolute Z-axis (left and right) speed can be used to quantify the effects of illusory roll-axis vection on subjects who are tasked to move a set distance in a straight line. Summarily this showed the viability of using commercial virtual reality headsets for measuring the effects of vection.

In the experiments two different environments and 5 different ways of rotating the environment (referred to as rotation models) were used. While the ordering of intensity between rotation models remained largely inconclusive, the experiment data showed that a rotational model which the subjects had the most intuitive control over seemed to display less deviation from the baseline on compared to other rotational models used in this paper.

Though this thesis did not manage to display any significant difference in response when comparing different rotating environments, it did hint at some interesting tendencies. More research can now be done by psychologists and computational neuroscientists to discern what role the nature of the rotating environment and self-motion plays in the perception of vection.

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Appendix

I. RotateSpace method from rotator.cs

```
private void RotateSpace(int rotationModel)
{
    // These setting manage rotatable
    float X = 0;
    Delta = Time.deltaTime
    switch (rotationModel)
    {
        case 0:
            X = 0;
            break;
        case 1:
            // CONSTANT SPEED
            X = 60f;
            break;
        case 2:
            // CONSTANT SPEED CHANGE DIRECTION ON INTERVAL
            float Speed = 60f;
            float Change = Speed * (Right ? 1 : -1);
            if (RotationVector.x + Change * Delta > Interval ||
                RotationVector.x + Change * Delta < -Interval)
            {
                Right = !Right;
                Change = Speed * (Right ? 1 : -1);
            }
            X = Change;
            break;
        case 3:
            // CHANGES SPEED BASED ON LOCATION
            X = (VRCam.head.position.x) * 60f;
            break;
        case 4:
            // CHANGES SPEED BASED ON USER SPEED
            X = (VRCam.head.position.x - LastPosition) * 7800f;
            LastPosition = VRCam.head.position.x;
            break;
        case 5:
            // DYNAMIC SPEED CHANGE DIRECTION ON INTERVAL
            X = Mathf.Cos(Roto) * Interval - RotationVector.x;
            Roto += Delta / 0.5f;
            break;
    }
    IncrementVector(X * Delta);
}
```

II. Update method from rotator.cs

```
void Update () {
    if (VRCam == null){VRCam = SteamVR_Render.Top();}
    if (Rotatable == null) { Rotatable = GameObject.Find("rotatable");}
    if (VRCam && Rotatable)
    {
        switch (State)
        {
            case 0:
                SetColor(Line, RED);
                SetColor(Startpoint, GREEN);
                SetColor(Endpoint, RED);
                // Waiting to move to point
                if (IsClose(Startpoint.transform, VRCam.head, 0.4f))
                {
                    State = 1;
                }
                break;
            case 1:
                SetColor(Line, RED);
                // Standby for next experiment
                if (IsClose(Startpoint.transform, VRCam.head, 0.4f))
                {
                    SetColor(Startpoint, YELLOW);
                    SetColor(Endpoint, YELLOW);
                    T = T + Time.deltaTime;
                    if (T > 5.0f)
                    {
                        // Transition state
                        State = 2;
                        T = 0f;
                        Mode = TodoModes[0];
                        TodoModes.RemoveAt(0);
                        if (VerboseLog)
                        {
                            Debug.Log("Experiment nr "
                                + ExperimentNumber.ToString()
                                + " started with model as RM"
                                + Mode.ToString());
                        }
                    }
                }
                else
                {
                    SetColor(Startpoint, GREEN);
                    SetColor(Endpoint, RED);
                }
                break;
            case 2:
                // Rotational model started, subject waiting
                RotateSpace(Mode);
                if (IsClose(Startpoint.transform, VRCam.head, 0.4f))
                {
                    SetColor(Startpoint, YELLOW);
                    SetColor(Endpoint, YELLOW);
                    T = T + Time.deltaTime;
                    if (T > 5.0f)
                    {
                        // Transition state
                        SetColor(Startpoint, RED);
                        SetColor(Endpoint, GREEN);
                        SetColor(Line, WHITE);
                        State = 3;
                        T = 0f;
                    }
                }
            case 3:
                // ... (this case is not fully visible in the provided code)
        }
    }
}
```

```

    }
    else
    {
        SetColor(Startpoint, RED);
        SetColor(Endpoint, RED);
    }
    break;

case 3:
    // Waiting for subject to leave vicinity
    RotateSpace(Mode);
    if (!IsClose(Startpoint.transform, VRCam.head, 0.50f))
    {
        State = 4;
        Position = VRCam.head.transform.position;
        Rotation = VRCam.head.transform.eulerAngles;
        ExperimentData = new List<string>();
    }
    break;

case 4:
    // Subject walking to endpoint
    RotateSpace(Mode);
    Delta = Time.deltaTime;
    T = T + Delta;

    // Capture data
    ExperimentData.Add(GetDataString());
    Position = VRCam.head.transform.position;
    Rotation = VRCam.head.transform.eulerAngles;
    // Check if reached endpoint
    if (IsClose(Endpoint.transform, VRCam.head, 0.9f))
    {
        // Save data
        using (StreamWriter sw = File.AppendText(TargetFilePath))
        {
            foreach (string line in ExperimentData)
            {
                sw.WriteLine(line);
            }
        }
        // If out of experiments
        if (TodoModes.Count == 0)
        {
            if(Scenes.Count != 0)
            {
                // There are scenes left to be changed to
                ExperimentNumber = ExperimentNumber + 1;
                InitializeNewRotatable();
                State = 0;
            } else
            {
                // Out of trials to be conducted
                // Write metadata about experiment
                string MetaPath = Path.Combine(BasePath,
                                                "metadata.csv");
                bool MetaExisted = File.Exists(MetaPath);
                using (StreamWriter sw = File.AppendText(MetaPath))
                {
                    if (!MetaExisted)
                    {
                        sw.WriteLine("FileName,TimeStart,"+
                                    "TimeEnd,Age,Gender,TookOffGlasses");
                    }
                    sw.WriteLine(Timestamp.ToString("yyyy-MM-" +
                                                    "dd-hh-mm-tt")
                                + ".csv" + "," +
                                +Timestamp.ToString() + ",")
                }
            }
        }
    }

```

```

        + System.DateTime.Now.ToString() + ","
        + Age + ","
        + Gender + ","
        + TookOffGlasses);
    }
    if (VerboseLog)
    {
        Debug.Log("EXPERIMENT FINISHED! "+
            "Please let the subject know.");
    }
    State = 5;
}

} else
{
    // If there is still science left to be done
    State = 0;
    RotationVector = new Vector3(0f, 0f, 90f);
    Rotatable.transform.eulerAngles = RotationVector;
    ExperimentNumber = ExperimentNumber + 1;
    SetColor(Endpoint, RED);
}
T = 0;
}
break;

case 5:
    // Experiment is over, both
    // points alternating green and yellow
    T = T + Time.deltaTime;
    if (Mathf.RoundToInt(T) % 2 == 0)
    {
        SetColor(Startpoint, GREEN);
        SetColor(Endpoint, GREEN);
    } else
    {
        SetColor(Startpoint, YELLOW);
        SetColor(Endpoint, YELLOW);
    }
    break;
}

} else
{
    Debug.Log("Headset or rotatable not found "+
        "(ignore if not being flooded by this message)");
}
}

```


III. Informed consent form

Uuritava informeerimise ja teadliku nõusoleku vorm

Uuringu nimetus: Tasakaaluja teadvusteoriate uuringud virtuaalreaalsuse abil.

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