



A comparison of interaction models in Virtual Reality using the HTC Vive

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The authors declare that they are the sole authors of this thesis and that they have not used any sources other than those listed in the bibliography and identified as references. They further declare that they have not submitted this thesis at any other institution to obtain a degree.

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ABSTRACT

Virtual Reality (VR) is a field within the gaming industry which has gained much popularity during the last few years. This is caused mainly by the release of the VR-headsets Oculus Rift [1] and HTC Vive [2] two years ago. As the field has grown from almost nothing in a short time there has not yet been much research done in all VR-related areas. One such area is performance comparisons of different interaction models independent of VR-hardware.

This study compares the effectiveness of four software-based interaction models for a specific simple pick-and-place task. Two of the interaction models depend on the user moving a motion controller to touch a virtual object, one automatically picks them up on touch, the other requires a button press. The other two interaction models have the user move a laser pointer to point at an object to pick it up. The first has the laser pointer emitted from a motion controller and the second has it emitted from the user's head. All four interaction models use the same hardware, the default HTC Vive equipment.

The effectiveness is measured in three metrics, time to complete the task, number of errors made during the task, and the amount of participant enjoyment rated on a scale from one to five. The first two metrics are measured through an observational experiment where the application running the virtual environment also logs all relevant information. The user enjoyment is gathered through a questionnaire the participant answers during the experiment.

These are the research questions:

- How do the interaction models compare in terms of accuracy and time efficiency when completing basic pick and place tasks in this experiment?
- Which interaction models are subjectively more enjoyable to use according to participants?

The results of the experiment are displayed as charts in the results chapter and then further analysed in the analysis and discussion chapter. Possible sources of error and theories about why the results turned out the way they did are also discussed.

The study concludes that the laser pointer based interaction models, 3 and 4, were much less accurate than the handheld interaction models, 1 and 2, in this experiment. All interaction models except 4 achieved about the same test duration while interaction model 4 lagged several seconds behind. The participants liked interaction model 1 the most, followed closely by 3. They disliked 4 the most and rated 2 at a point in the middle of the rest.

Keywords: Virtual Reality, HCI, Interaction Methods, Motion Controllers, Object Interactions

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1 INTRODUCTION AND RELATED WORK

1.1 Background

Virtual Reality (VR) is a field within the gaming industry which has gained much popularity during the last few years. Previously, consumer VR only had a short emergence in the 1990s but due to lacklustre technology did not take off and no further attempts were made in more than ten years [3]. The modern era of virtual reality started when the successful crowdfunding campaign of the Oculus Rift VR-headset raised over 2.4 million US dollars in 2012 [1]. After two years of development Oculus VR, the company behind the Rift, was bought by Facebook for 2 billion US Dollars, solidifying the market's confidence in the development of VR.

Since the start of the Rift's development, many other companies have created their own solutions, most notably Samsung with their smartphone-powered Gear VR [4] and HTC joining Valve to create their 3D-space tracked HTC Vive [2].

This has led to a great variety in the VR-environment, offering many different new technologies in headsets, controllers and other associated devices such as the Vive's Lighthouse 3D-tracking stations. The result of this great variety has been increasing room for great innovation in the development of new techniques in the area such as new interaction techniques.

1.2 Motivation

As the virtual reality field has grown from almost nothing to a considerable part of the overall gaming industry in a short time, there has not yet been much research done in many VR-related areas.

One such area is interaction models. While there has been some research performed in developing and evaluating new hardware solutions almost no work has been made on comparing different software implementations of interaction models. It is an important area to research as it could be valuable information for game developers designing VR-products. They are likely to want to implement an interaction system that makes use of the relatively standardised VR-setup of a headset and two motion controllers, and they would want to know which implementation fits them best.

1.3 Aim and objectives

This study will compare the effectiveness of four software-based interaction models for simple pick and place actions. None of these models require any hardware other than the default HTC Vive equipment.

The aim is to compare the different interaction models in terms of accuracy, time efficiency and how enjoyable they are to use by participants.

- Creating a VR environment with the props needed for the experiment in Unity.
- Implementing application logic for data gathering and task completion.
- Implementing the interaction models in the application.
- Acquire a room to hold the experiments in.
- Making advertising for the experiments and distributing it to visible places in the university. (Figure D-1).
- Perform experiments.
- Compile data into scientific report

1.4 Research questions

- How do the interaction models compare in terms of accuracy and time efficiency when completing basic pick and place tasks in this experiment?
- Which interaction models are subjectively more enjoyable to use according to participants?

1.5 Previous work

Almost all previous work fit into two different categories which do not fulfill the goals of this study.

The first category of studies is comparing different similar hardware implementations using the one software interaction model, such as Suznjevic et al. [5]. Their study compared the HTC Vive and Oculus Rift's motion controllers using an identical software-side implementation. This study aims to do the opposite, comparing software implementations of interaction models.

Another study along the same lines was made by Teather and Stuerzlinger [6] who compared two different motion controller based techniques and a control method using a computer mouse. Just like with the previously mentioned study, there were no direct comparisons between purely software based implementations.

The second category of studies contains comparisons of new technology such as hand-based controls or eye-based controls with a standard control method such as a motion controller. Gusai et al. [7] have for instance developed a hand tracking system which they compared to a standard Vive motion controller. As the models compared use completely different kinds of controllers one cannot separate the software implementations and judge them against each other independently as the software implementations cannot be tested on the same hardware.

Another similar study by Martínez et al. [8] created a 3D-tracked glove with several haptic feedback points in different key points of it. They activated when the user touched virtual objects to attempt to give them a much more accurate feel of the objects they were holding. The study compares their implementation to several others including the standard HTC Vive controllers, just like the previously mentioned study, there is no way of separating the software implementation there and judge it on its own merit.

None of these types of studies have examined VR control methods with a purely software comparison. In preparation for this bachelor thesis a literature review was made, *Review of object interaction methods in Virtual Reality* [9] and concluded that a study like this one needed to be made. The study compiled as much previous work as could be found on the topic and realised this relatively unexplored research area.

2 METHOD

2.1 The virtual environment

The virtual environment is made up of a small room 2 x 3 meters in size containing a few objects. In front of the participant is a glass table with ten cubes on it. To the right of the participant there is a large bucket containing water. The motion controllers also exist as virtual objects if they are turned on and have line of sight to the tracking stations. They follow the position of their real-world counterparts with high precision. *Figure 1* shows an overview of the environment without the VR equipment connected, so they are not visible.

It also contains several invisible game objects such as the player camera which follows the participant's head movements and sound effect objects which are used to signal to the participant both when they've made progress and when they have finished one of the tests completely.

There is also an application controller object which handles the central logic system of the application. This includes keeping track of all test conditions, communication with other interactive objects, and logging all relevant events and statistics to file.

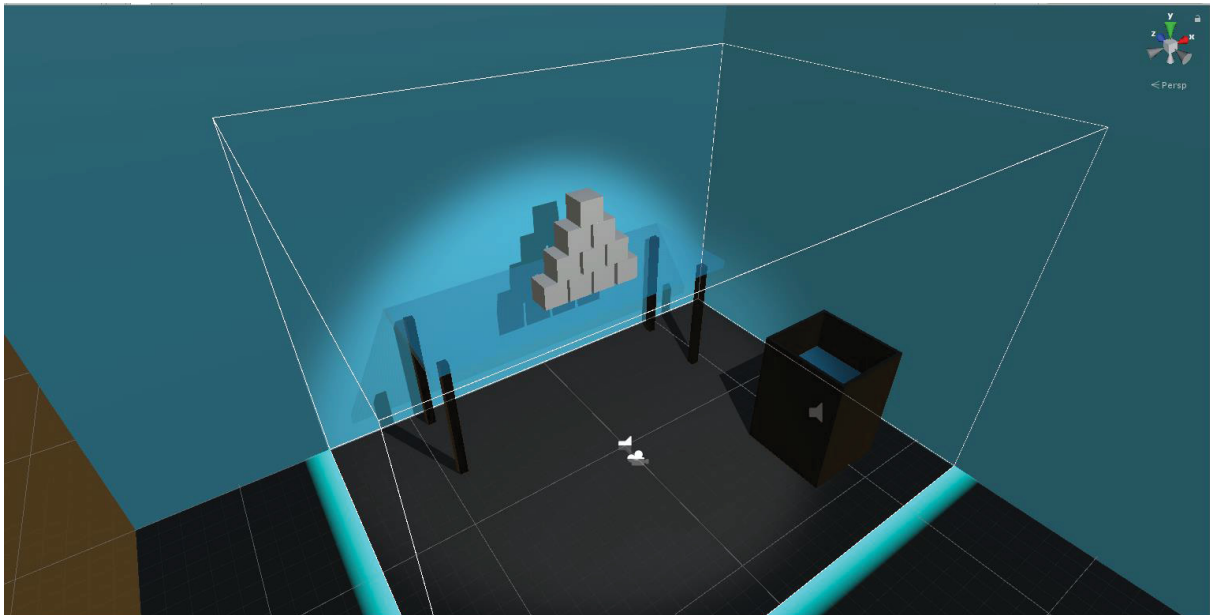


Figure 1 - The virtual environment seen from the Unity Editor's Scene view

2.2 Technical specifications

The application is created in the game engine Unity, version 2017.3.1f1 [10], and all scripts are written in the C# programming language [11]. The Virtual Reality headset support is provided through the SteamVR API [12], specifically using the SteamVR plugin for Unity v1.2.3 [13]. This plugin provides

motion tracking and rendering for the Vive without the programmer needing to do much more than drag the included objects into their Unity project.

Experiment system specifications:

CPU: Intel® Core™ i7-6700K

RAM: 16GB DDR4

GPU: Nvidia GeForce GTX 980

Storage: Corsair Force LS SSD

The experiment application is available as a public repository here:

<https://github.com/KarlOfDuty/VRIM-TestEnvironment>

2.3 Participant tasks

The participants are tasked with moving the cubes on the table into the bucket next to them. The cubes must be moved in a specific order and a cube gets highlighted in red when it is the next one to be moved. They are told to perform this task as quickly as possible while also making as few errors as possible. Errors are defined as either the participant picking up the wrong cube, picking up the correct cube but dropping it or attempting to pick up a cube but not being close enough.

The experiment tests four different interaction models. Each interaction model is tested with two different cube sizes, one with bigger, easier to select cubes and one with smaller cubes requiring a greater sense of accuracy. The larger size is thus more focused on the time metric and the smaller size focused more on the accuracy metric. This makes eight tests in total for each participant. All interaction models require the participant to press the top menu button on the controller to start the experiment and the logging of their actions.

2.3.1 Interaction model 1 (IM1)

The user uses an HTC Vive motion controller [14] to pick up cubes by touching them with the controller and holding down the trigger. The user then moves their controller to the target bucket and releases the trigger to drop the box. This is one of the most common interaction models currently used in PC-based Virtual reality such as in the SteamVR Home [15] application which serves as base environment for SteamVR.

2.3.2 Interaction model 2 (IM2)

The user touches cubes with a Vive motion controller like in interaction model 1 but they are automatically picked up on touch without having to press any buttons. The user can then press and immediately release the trigger to drop the cube. This interaction model is seemingly not used as much as interaction model 1 but some high-profile games such as Rec Room [16] use it as an alternative when players must hold objects for a longer time.

2.3.3 Interaction model 3 (IM3)

The user uses a laser pointer extending from the top of a Vive motion controller to move the cubes. A cube is picked up by holding the trigger when the laser pointer hits it. The cube is then suspended in the air in the same position relative to the controller as when it was picked up. The cube is dropped by releasing the trigger. This interaction model is commonly used to navigate in menus, which it is used for in both previously mentioned applications, SteamVR Home and Rec Room.

2.3.4 Interaction model 4 (IM4)

The user uses a laser pointer identical to interaction model 3 but extending from the user's head. The user again can pick up cubes by aiming at them with the head-mounted laser and holding down the trigger on a Vive motion controller and drop them by releasing the trigger. This is not common with PC-based VR setups but is usually used in other setups like mobile VR games or others that do not feature motion controllers. One such game is the Until Dawn spinoff game "The inpatient" [17] which uses this interaction model coupled with a PS4 controller.

2.4 Questionnaire

The screenshot shows the first page of a questionnaire titled "Interaction models questionnaire". It features two main sections: "Participant Information" and "VR Experience".

Participant Information:

- Participant ID ***: A text input field with the placeholder "Your answer".
- Gender ***: Radio buttons for Female, Male, Other, and Prefer not to say.
- Age group ***: Radio buttons for Under 18, 18-24, 25-34, 35-44, 45-54, 55-64, and 65+.

VR Experience:

- How experienced are you with with VR devices? ***: A 5-point Likert scale with radio buttons. Labels: "Never used one" (1), "Very experienced" (5).
- Which headsets have you used?**: Checkboxes for Samsung Gear VR, Oculus Rift, Sony Playstation VR, Google Cardboard, HTC Vive, and Other: _____.

Figure 2 - First page of questionnaire

The screenshot shows the second page of the questionnaire, containing eight Likert scale questions. Each question is followed by a 5-point scale with radio buttons and labels "I strongly disliked it" and "I liked it a lot".

- (1L) How would you rate your enjoyment of this interaction model? *
- (1S) How would you rate your enjoyment of this interaction model? *
- (2L) How would you rate your enjoyment of this interaction model? *
- (2S) How would you rate your enjoyment of this interaction model? *
- (3L) How would you rate your enjoyment of this interaction model? *
- (3S) How would you rate your enjoyment of this interaction model? *
- (4L) How would you rate your enjoyment of this interaction model? *
- (4S) How would you rate your enjoyment of this interaction model? *

Figure 3 - Second page of the questionnaire

The subjective metric user enjoyability is measured using a questionnaire where participants rate their experience with the interaction models. After each of the eight tests the user rates their enjoyment of using the interaction model with that specific size of cubes (Figure 3). The rating is entered on a Likert scale of a value from one to five, where one is the lowest amount of enjoyment and five is the highest.

The questionnaire is also used to gather some other basic information at the start of the experiment. The first entry is an ID which is also entered into the logging system of the virtual environment, so a questionnaire submission can be tied to the participant's logs. There are also entries for some basic non-identifying personal information: gender, age range and previous experience with VR devices. See *Figure 2* for more details.

2.5 Consent form

Before the participant can start filling out the questionnaire they have to read and agree to the consent form. It is the following:

“The participant will be using the Virtual Reality headset HTC Vive to complete simple pick-and-place tasks in a virtual environment. There will be minimal movement involved but some users may experience motion sickness due to not being used to Virtual Reality.

The user may stop the experiment at any time and does not have to provide a reason why. The user is encouraged to take a break if they do start to suffer from motion sickness.

The information gathered is completely anonymous and can not be used to identify an individual.”

3 EXPERIMENT

3.1 Introduction to the experiment

The participant is welcomed into the room and asked to sit down in front of a laptop where they read the consent form and fill in the first page of the questionnaire. The participant ID is given to them by the operator who also enters it into the logging system.

They then move to the computer running the environment and are shown the different components of the virtual environment. They are also told of the mechanics of the environment, that the cubes will turn red one by one and are to be moved to the bucket. They are then told about the metrics and how they are measured and that they should try to complete each task as quickly as possible with as few errors as possible.

3.2 Introduction to VR

They then proceed to the middle of the designated VR space of the room and puts on the Vive headset. They receive instructions on how to fasten the head strap properly, so they are comfortable and that the lenses are not blurred.

The participant is handed a motion controller and the operator runs each interaction model once for about 30 seconds. The operator explains how it works and lets the participant try it out for a few seconds before switching to the next one. They are also told to take a step back to the center of the room after each test, so they always begin at the same point.

3.3 Information on software bugs

They are also informed of two bugs caused by the experiment system having an outdated version of both Unity and SteamVR compared to the development system. These bugs were not found until shortly before the experiment began so they could not be removed in time. As they do not have any impact on the results the experiment went ahead with a short disclaimer about them given to the participants.

The first bug is that at the start of interaction model 2 the trigger counts as being held down even if it is not until it is pressed once. The participants were simply told to press it at the same time they pressed the start button.

The second bug is that both tests for interaction model 4 must be started, then shut down, then have the operator restart a motion controller and then start the test again or the laser pointer will not have any tracking and just remain stationary on the floor. This does not impact the participant but means a slight delay for the start-up process of the tests while the operator performs the restart.

3.4 Performing of tasks

The participant then performs each task, once with the larger cubes and once with the smaller cubes, in order of the interaction models' designations.

In between tasks, the user is asked how they would rate the interaction model in that task and the operator enters it into the questionnaire. This is because it would be difficult for the participant to take the headset on and off between each test. To start each test, the operator runs a scene which places the participant in the virtual environment, and the participant presses the start button on top of the controller when they are ready to go.

Participants are not required to make comments about the interaction models, but such comments are noted by the operator if they decide to.

4 RESULTS

4.1 Participants

The experiment had 17 participants in total, all of which completed all tasks with the four interaction models once with the large cubes and once with the large ones. This brings the total number of tests to 136 all of which were performed in a single day.

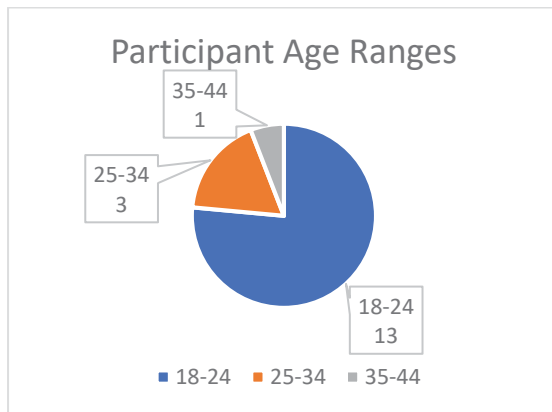


Figure 4 - Age distribution of participants

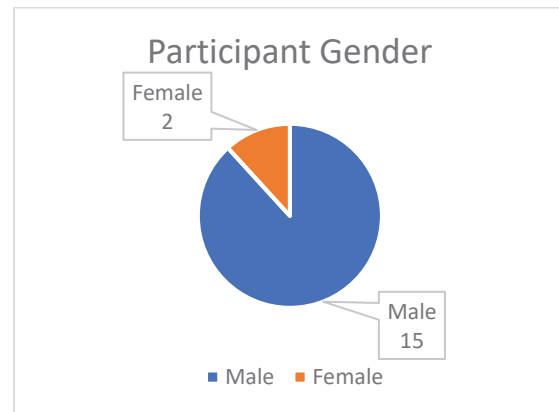


Figure 5 - Gender distribution of participants

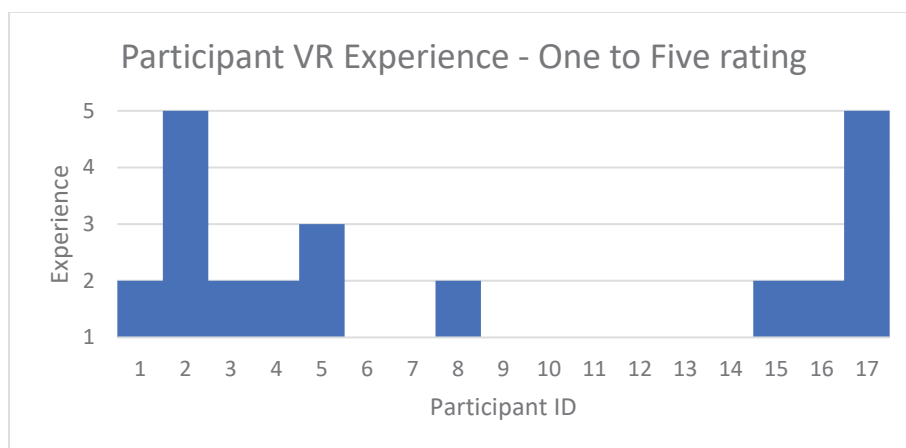


Figure 6 - Previous VR-experience per participant

Almost all participants were male, and a large majority were in the age range of 18 to 24 years old. This is an expected outcome as it is similar to the age and gender distribution in the programming courses of the building where the tests were performed. Of the 17 participants only 2 had a lot of experience with Virtual Reality. One had a moderate amount and 6 had a small amount of prior experience.

4.2 Time efficiency

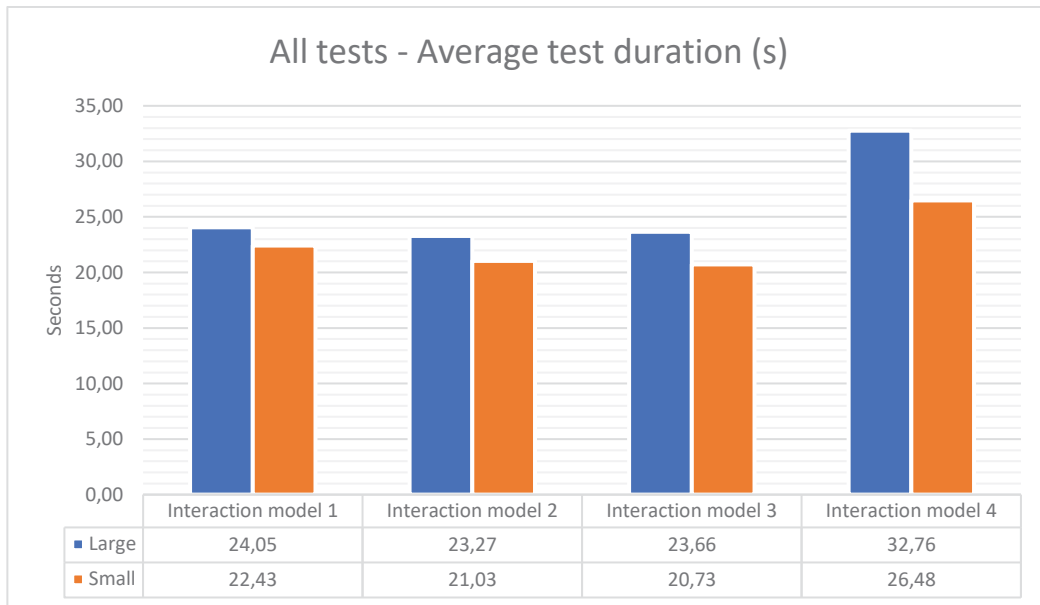


Figure 7 - Average test duration in seconds from all tests

Most of the time metrics turned out similar with a difference between each other of only about one second on average. The only major exception is completing the task using interaction model 4, taking about nine seconds longer on average with large cubes and about four to six seconds longer with small cubes.

4.3 Accuracy

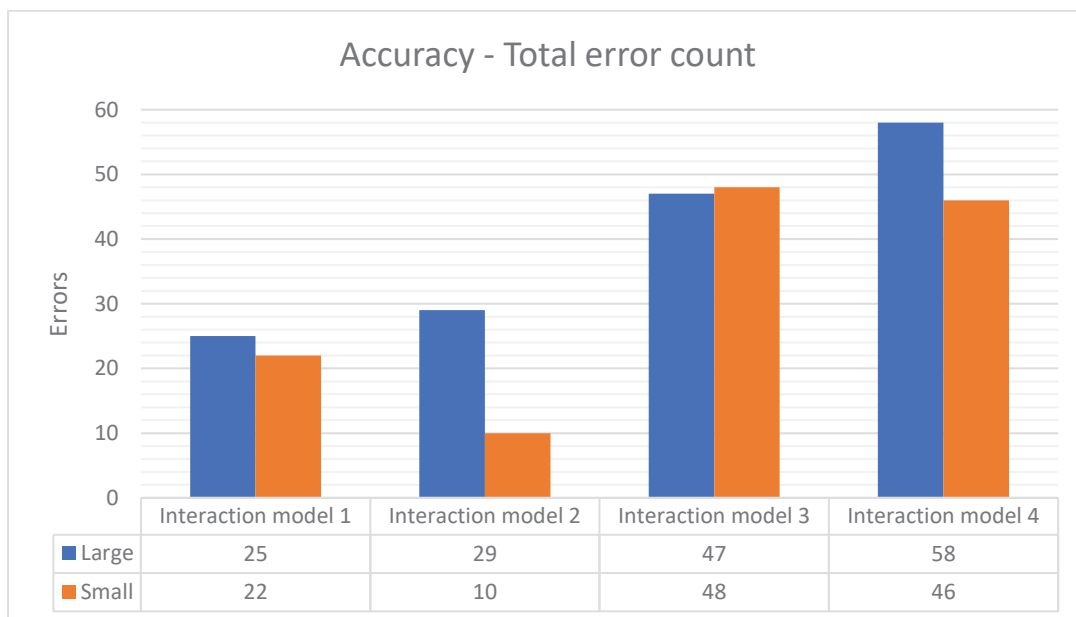


Figure 8 - The total amount of errors in all tests

The laser-pointer based interaction models cause a large majority of the errors made in both types of tests. They both individually cause more errors in the smaller cubes experiment than the other two interaction models combined.

Interaction model 2 caused almost three times more errors using the large cubes rather than the small cubes.

4.4 Enjoyment

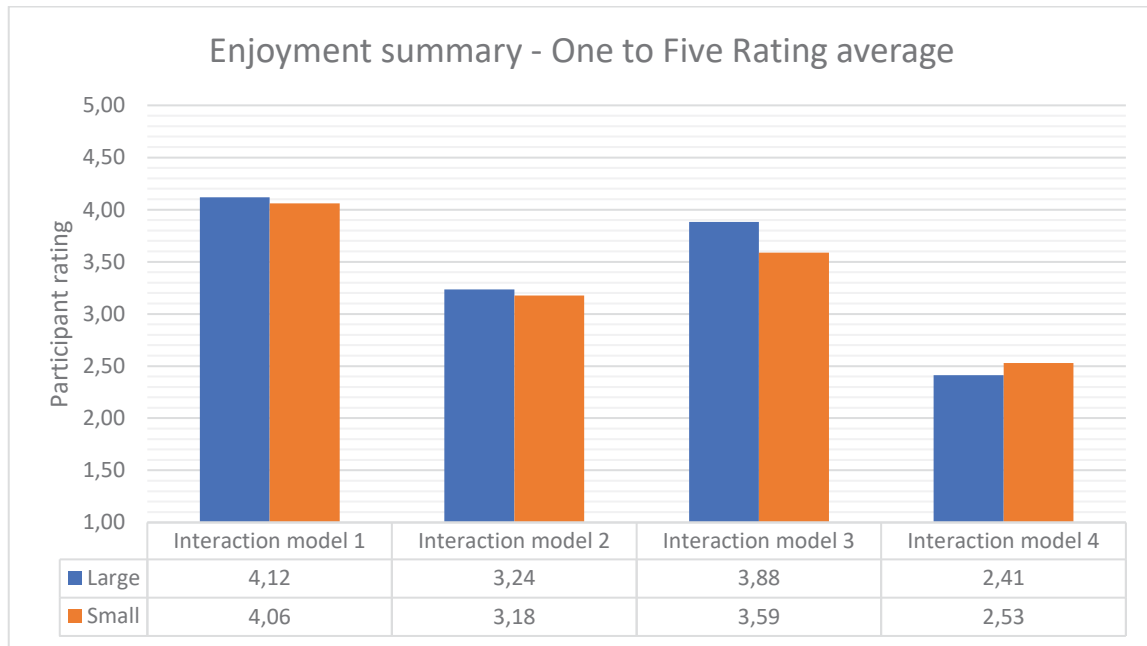


Figure 9 - The average participant rating of each interaction model

Interaction models 1 and 3 were clearly more liked by the participants when it comes to the larger boxes with an average score of 4.11 and 3.88 respectively. Interaction model 2 was not enjoyed quite as much with an average rating of 3.24 and interaction model 4 by far the least enjoyed at an average rating of 2.4.

The statistics for the small cubes are approximately the same as for the large cubes other than a fall in the enjoyability of interaction model 3 from 3.88 to 3.58.

5 ANALYSIS AND DISCUSSION

5.1 Accuracy

Both laser pointer-based interaction models 3 and 4 are more error prone than the hand-based interaction models 1 and 2 (Figure 8). This could be contributed to the fact that it is more difficult to hold the laser steady than it is to hold the controller itself steady. The smallest rotation of the controller could make the end of the laser pointer move several centimeters while the controller itself is remaining relatively still.

The second interesting point of the accuracy results is that interaction model 2 created almost three times more errors with the large cubes than with the small cubes. This may be because the participants were used to pressing the trigger as they pick up an object from the previous interaction model rather than just touching it. This would result in the participant accidentally dropping the object and having to pick it up again, registering as an error.

5.2 Time efficiency

The large difference in duration between interaction model 4 and the others (Figure 7) may be explained by the difficulty in the user turning their head with as high accuracy and speed as with moving their hands. This coupled with the higher difficulty to maintain accuracy with the laser-pointer based interaction models would require the participant being more careful and taking more time to stabilize their aim.

Interaction model 3 does not have this same time discrepancy even though it also uses the laser pointer method of picking up cubes. It is theorized that the much smaller hand movement required to move a cube with the laser pointer saves enough time to make up for the time lost by the decrease in accuracy. The head mounted version may not benefit from this as much as the hand mounted version as it would be much more difficult to perform the fast rotation required over and over with their head without getting disoriented or getting exhausted muscles in the neck area.

5.3 Enjoyment

Interaction model 4 is clearly the interaction model most disliked by the participants (Figure 9). This makes sense as it is the worst rated in both other metrics and its performance would definitely have an impact on the enjoyability of using it. One participant who was overall positive commented that it was an interesting concept “sort of like using an invisible force” but also said it was straining their neck enough to already make it uncomfortable to use even for the less than two minutes of the test duration. Several other participants also complained about neck strain and similar issues.

Interaction model 2 was moderately liked by the participants with a rating approximately right in the middle of the top and bottom rated interaction models. One participant commented that dropping the cubes felt strange in comparison with the first interaction model. They did not elaborate, and it was not inquired further as to what exactly the cause of it was at the time, but it has later been theorized that it has to do with the trigger being pressed. Interaction model 1 has a slight advantage in that holding down the trigger to hold an object and then letting go to release that object is a natural action as it translates accurately to the virtual action it represents.

Interaction model 2 however makes no physical difference for the user holding an object versus not holding anything as the picking up and holding onto an object is done automatically. The releasing of

an object has the opposite physical action associated with it, pressing the trigger, and thus closing the hand more tightly around the controller. It may be that this cognitive dissonance causes the uncomfortable feeling while releasing objects described by the participant.

Both interaction model 1 and 3 were highly rated. This makes sense as they both fix or combat some of the issues previously mentioned about their counterparts, interaction model 1 with the more natural grabbing than 2 and interaction model 3 with the more comfortable and accurate movement than 4. Interaction model 3 did however see a small drop in enjoyment with the smaller cubes which may suggest that the accuracy difficulties with interaction model 3 had an impact on the participants' enjoyment of it.

5.4 Participant background

The participants entered their gender, age group and prior VR experience in the questionnaire before the experiment.

As only two participants were female (Figure 5) it is difficult to make any specific performance comparisons to the male participants. The two logs I do have (Figures A3, B3 and A11, B11) show relatively average results with a few spikes here and there like most of the other graphs with no common features specific to them.

Three quarters of the participants were in the age group 18-24 (Figure 4). Like with the gender groups, there is not enough data to find any patterns in the results. There is only one 35-44 participant so that is by definition impossible to find a pattern from. The three participants in the group 25-34 (Figures A3, B3 A13, B13 and A15, B15) also do not have any data anomalies specific to them.

One interesting point is that the two participants who called themselves very experienced with VR (Figure 6) with a rating of 5 out of 5 had two of the three best scores in interaction model 1 when it comes to time efficiency (Figures A-2 and A-17). These top three scores were several seconds better than the participant ranked fourth so at this first glance one might consider that the skill of the more experienced players made them much faster with the interaction model that is most common today. This is however likely to be a coincidence as one of the top three participants (Figure A-4) in this specific statistic entered themselves as very inexperienced at a rating of 2 of 5.

5.5 Experiment deficiencies

5.5.1 The Interaction model 2 trigger bug

The most obvious issue with the experiment is the number of bugs found when the experiment took place. This bug occurs when initiating interaction model 2 there is a bug caused by the different Unity and/or SteamVR version installed on the experiment system. It causes the trigger of the controller to detect as if it is already pressed down at the start. This means the interaction model would not allow the user to pick up a cube as it thinks the user is holding the trigger which is interpreted as the participant trying to drop the cube. This was resolved by simply asking the participant to click the trigger once at the start of the interaction model 2 tests. This triggers the release event for the trigger returning it to the proper state allowing the tests to continue as intended without any effect on the results.

5.5.2 The interaction model 4 tracking bug

This bug also stems from the Unity and SteamVR version difference between the development and the experiment system. When interaction model 4 tests are started the laser-pointer is stuck at the centre of the room and does not move with the headset as it is supposed to. It is unknown why this only happens with the head mounted laser-pointer and not with the controller mounted one, but I theorize that the headset may not have loaded when the laser-pointer is created for some reason. This is fixed by turning the test on, then turn it off. Then one of the Vive controllers must be restarted then the test is turned back on and the laser-pointer works. For this reason, the controller that the participant is not currently using is kept next to the operator, so they can quickly go through these steps. It is unknown why this procedure is effective. It was accidentally discovered when troubleshooting the issue before the first experiment started and is not expected to have affected the results in any way.

5.5.3 The Interaction model 1 logging bug

This is not an issue with the experiment itself, but with the log file created by it. The logging system was accidentally set to write all cube pickups as the participant picking up the wrong cube. The data could still be corrected because there are always exactly 10 correct pickups, all others count as errors as they either mean that the user picked up the wrong cube or picked up the correct cube but dropped it accidentally. While some more statistics could have been gathered from having this distinction logged correctly it was not needed for the metrics and the different error types were mostly added to the log to make sure errors were logged correctly during development. This bug would also have no effect on the result.

CONCLUSION

The main conclusion to be drawn from the experiment is that Interaction model 4 has performed decisively worst of all interaction models. It took around six seconds longer on average to complete the task (Figure 7), it produced more than a third of all errors (Figure 8) and it was much lower rated than the other interaction models (Figure 9). It may be caused by a combination of issues. Participants complained that their necks were strained from the constant rotation back and fourth and the need for accurate steady aim using their heads. This could be a source of both decreased performance and lower user enjoyment which may contribute to a need to take more frequent breaks during VR gaming.

As interaction model 2 showed a giant improvement in accuracy going from the large cubes to the smaller ones, the opposite of the expected result, it suggests that running all tests back to back may have influenced the results of the large cube tests. Several participants commented that their first error/s were because they were used to interaction model 1 making them press the trigger as they were only given time to practice at the start the experiment they may have gotten used to one interaction model and then had issues adapting to the next one. Having a practice round before each interaction model in addition to the one before the entire experiment may have been beneficial. It makes sense that interaction model 2 was the only one with a visible effect as it is similar to interaction model 1 and thus confused participants who instinctively tried to use the controls from the previous test. For this reason, the interaction model 2 result should be seen as less trustworthy than the other ones.

Interaction model 3 did moderately well in time efficiency and user enjoyment. It was only narrowly beaten by interaction model 2 in the test duration and interaction model 1 in the user ratings. It did however do poorly in the accuracy metric, especially when using the small cubes (**Error! Reference source not found.**) where it produced slightly more errors than interaction model 4. It would seem like participants were able to still execute the tests quickly using interaction model 3 even though they were not able to be accurate with it.

Interaction model 1 was the top-rated interaction model, both when it comes to using large and small cubes. It also did fairly well in both other metrics, only about one second longer in test duration on average and only slightly more errors than interaction model 2. It did well overall and the participants rating seems to reflect that.

There were also several bugs in the test environment but none of them could conceivably have impacted the result of the experiment in any way.

To answer the research questions:

- *How do the interaction models compare in terms of accuracy and time efficiency when completing basic pick and place tasks in the experiment?*

The laser pointer based interaction models, 3 and 4, were much less accurate than the handheld interaction models, 1 and 2, in this experiment. All interaction models except 4 achieved about the same test duration while interaction model 4 lagged several seconds behind.

- *Which interaction models are subjectively more enjoyable to use according to participants?*

The participants liked interaction model 1 the most, followed closely by 3. They disliked 4 the most and rated 2 at a point in the middle of the rest.

FUTURE WORK

Future work would have to be done with a larger sample size. The data from the 17 participants is not enough to make any generalisation of the performance of these interaction models at large. Another experiment with a much larger sample size would need to be done to verify the results of this thesis.

As there may have been cross contamination between tests, where interaction model 1 may have influenced the first result of interaction model 2, there should be a practice round before starting each test to make sure the participant is ready for it.

There should also be more tasks for the participants to complete. Using several more varied tasks would show which interaction models function well with different use cases. This could for instance be using the task of interacting with a menu interface and the task of interacting with objects in a 3D-world. One could then compare the results between them to find which interaction model works best with which task.

It would also be useful to use the interaction models with a different hardware setup such as the Oculus Rift to confirm that the different interaction models work equally well using different VR-headsets and controllers.

In the future it would also be useful to evaluate if the interaction models perform any differently with new more advanced hardware. For instance, if input delay is reduced by some amount hand-eye coordination may be improved or if using wireless VR headsets may have the opposite effect. There are also new more advanced tracking methods such as the Vive's 2.0 tracking base stations coming out shortly which may improve controller accuracy to some extent.

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APPENDIX A – TEST DURATION PER PARTICIPANT

All figures in this chapter describes the number of seconds each test lasted for a participant, blue for the tests with large cubes and orange for the tests with small cubes. The horizontal axis represents the four interaction models.

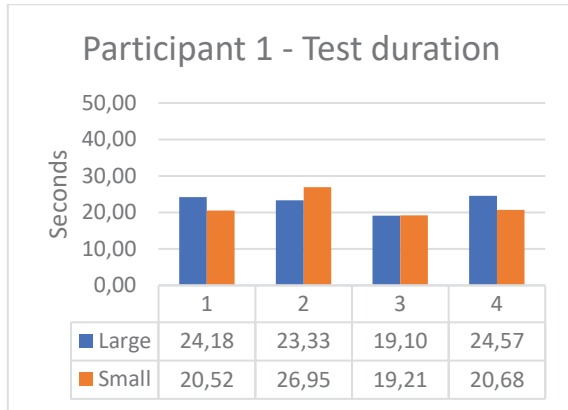


Figure A-1

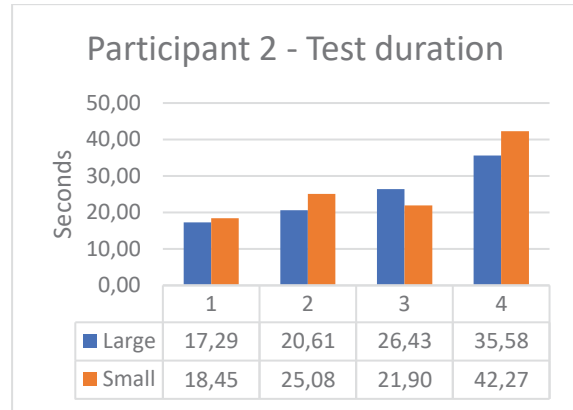


Figure A-2

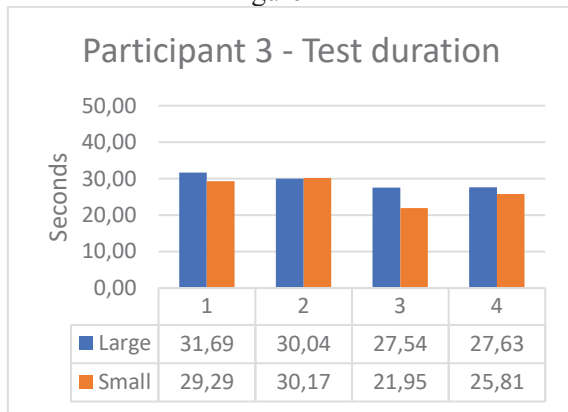


Figure A-3

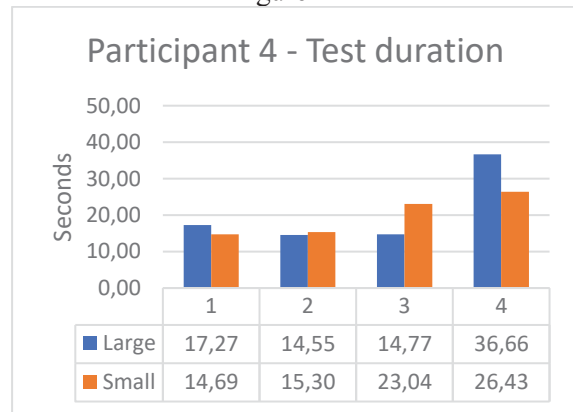


Figure A-4

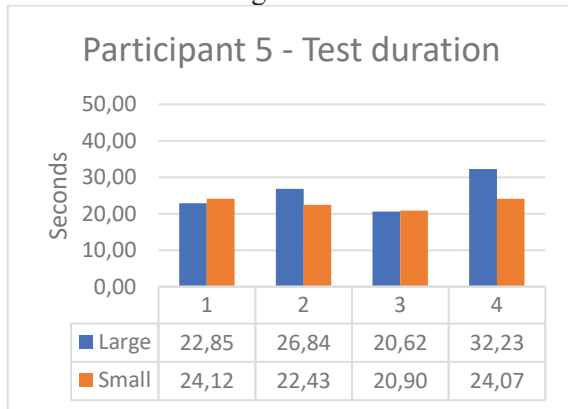


Figure A-5

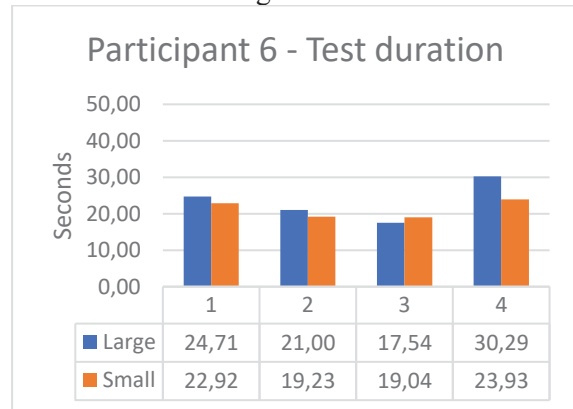


Figure A-6

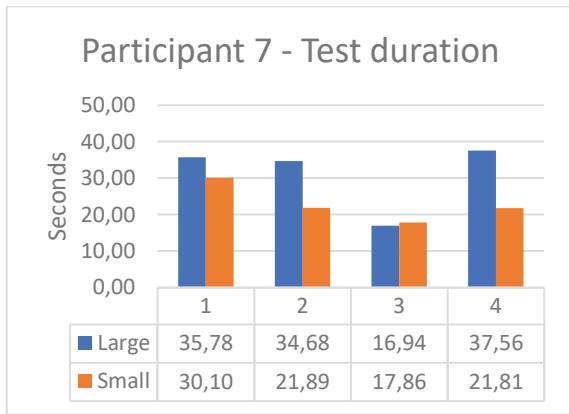


Figure A-7

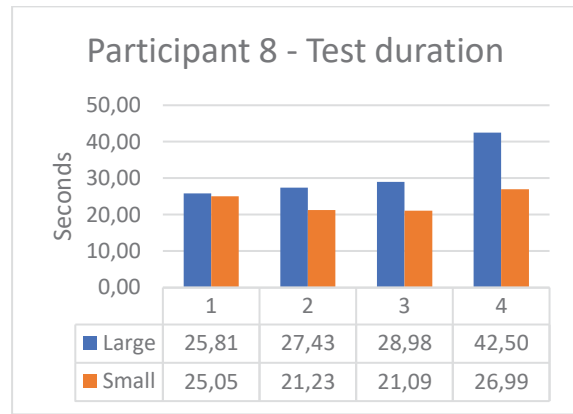


Figure A-8

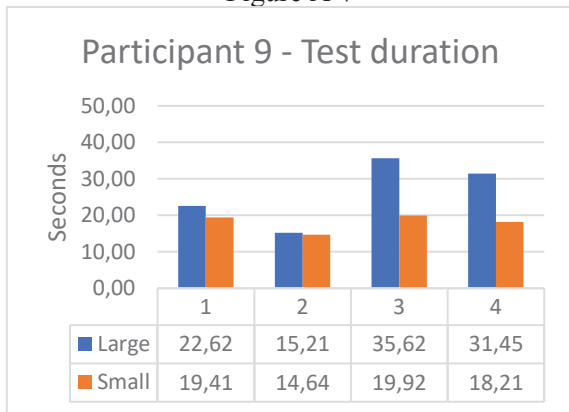


Figure A-9

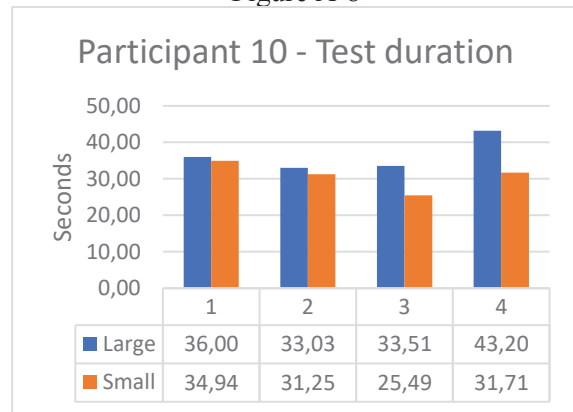


Figure A-10

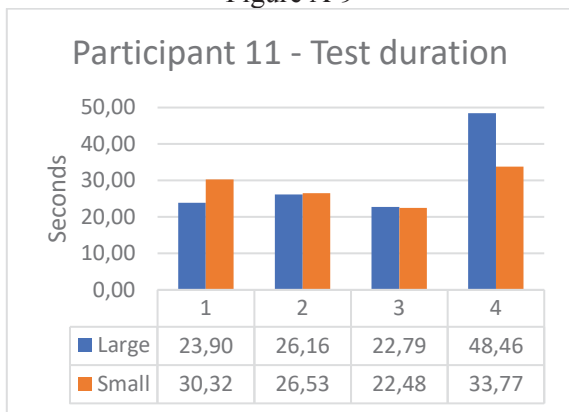


Figure A-11

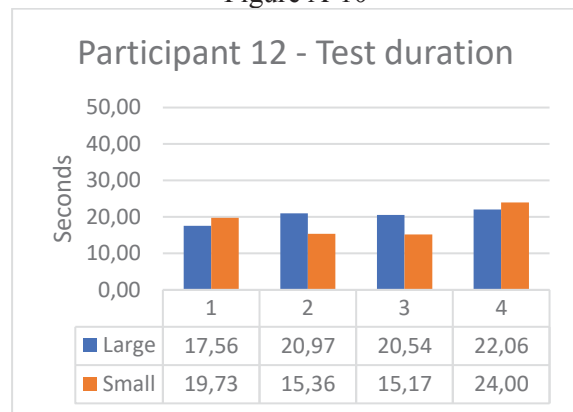


Figure A-12

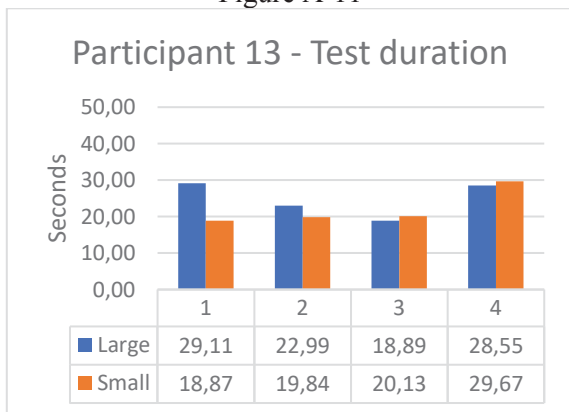


Figure A-13

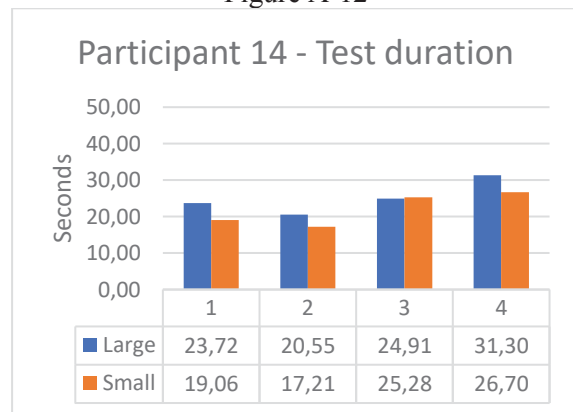


Figure A-14

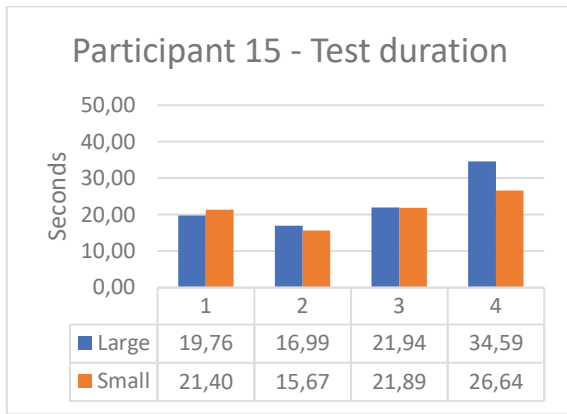


Figure A-15

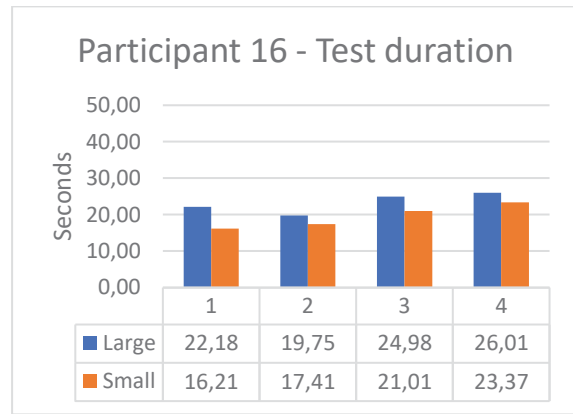


Figure A-16

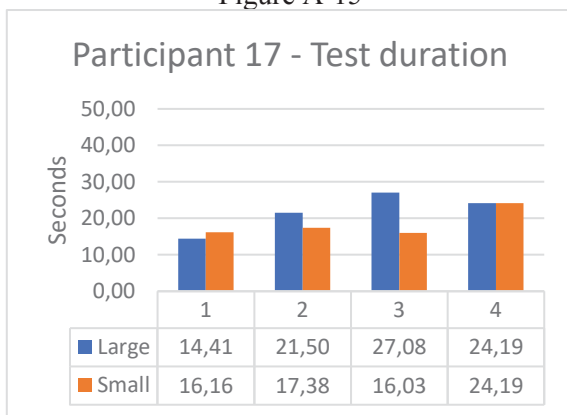


Figure A-17

APPENDIX B – ACCURACY PER PARTICIPANT

All figures in this chapter describes the number of errors made by a participant, blue for the tests with large cubes and orange for the tests with small cubes. The horizontal axis represents the four interaction models.

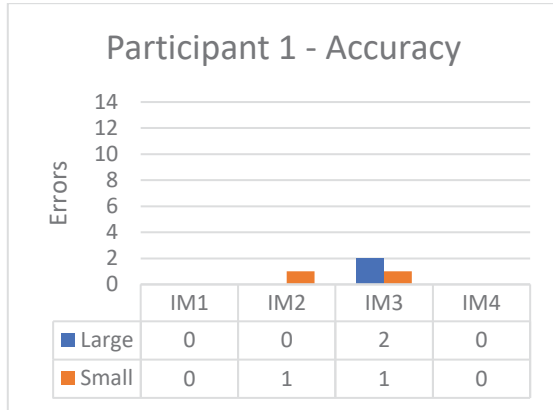


Figure B-1

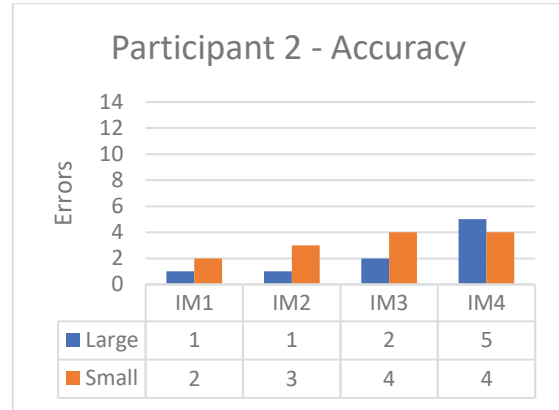


Figure B-2

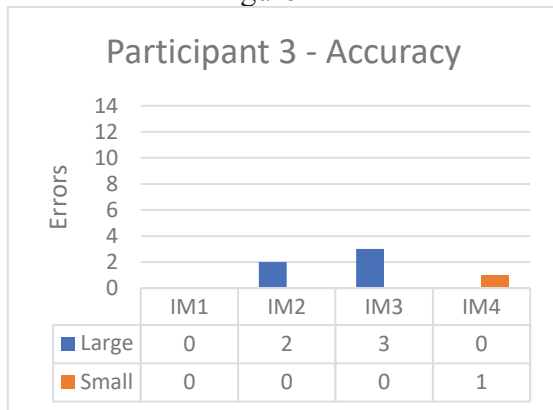


Figure B-3

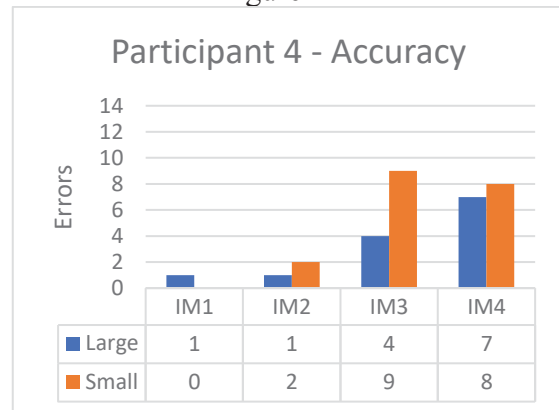


Figure B-4

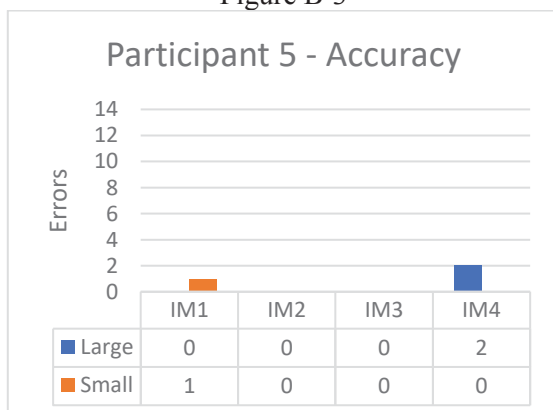


Figure B-5

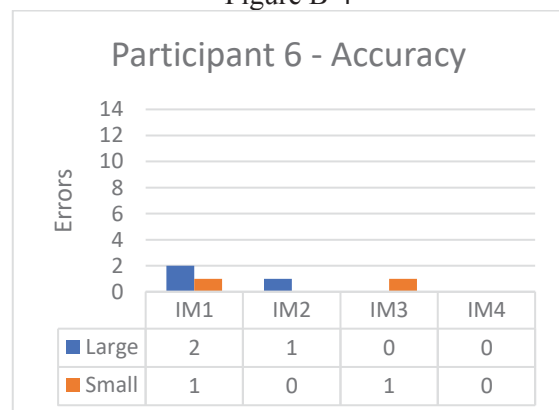


Figure B-6

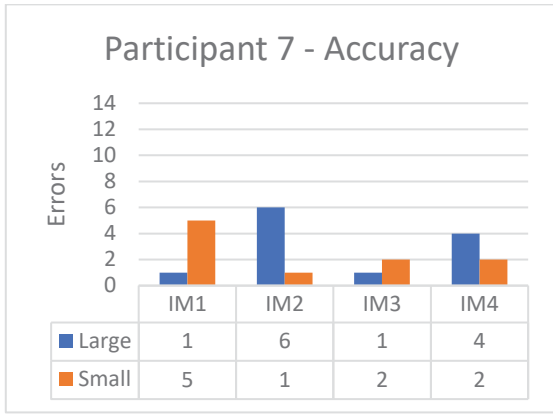


Figure B-7

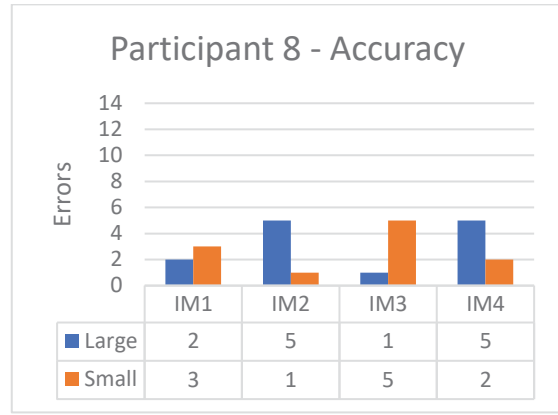


Figure B-8

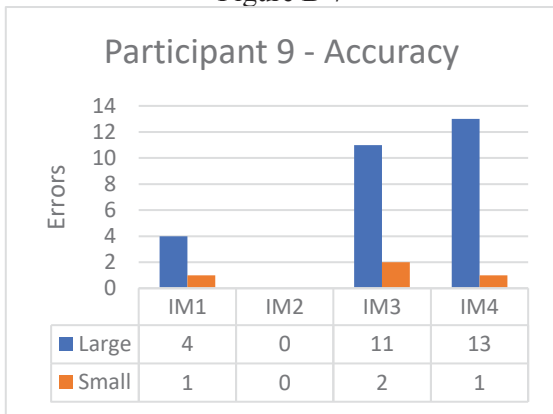


Figure B-9

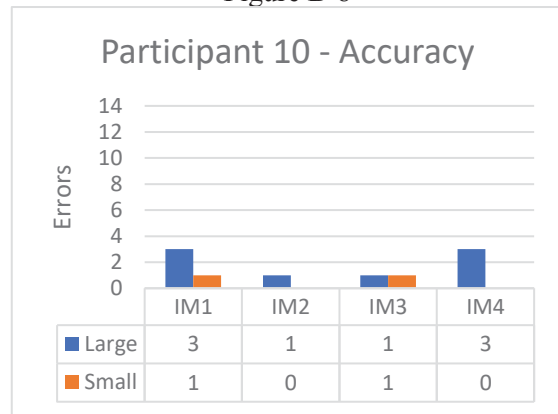


Figure B-10

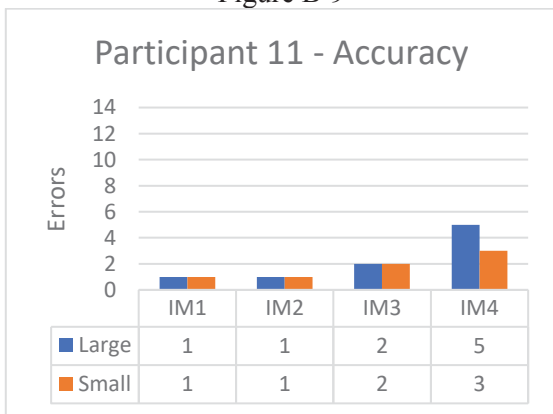


Figure B-11

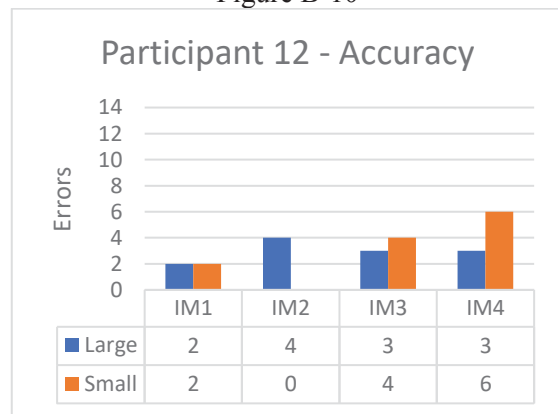


Figure B-12

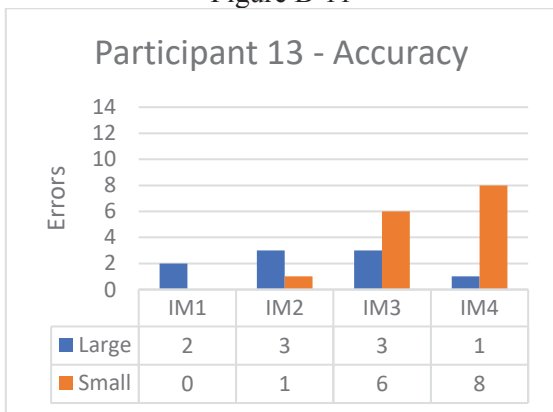


Figure B-13

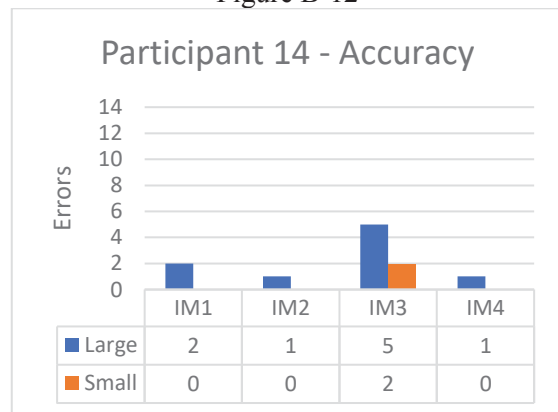


Figure B-14

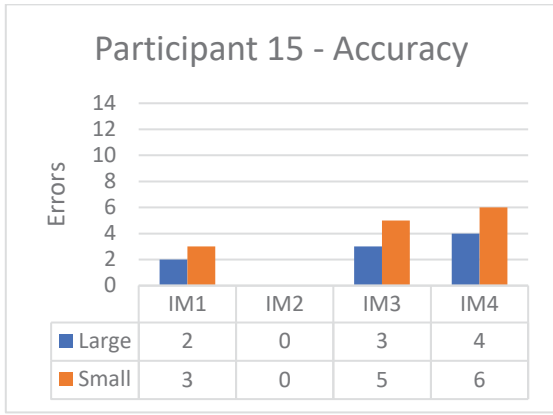


Figure B-15

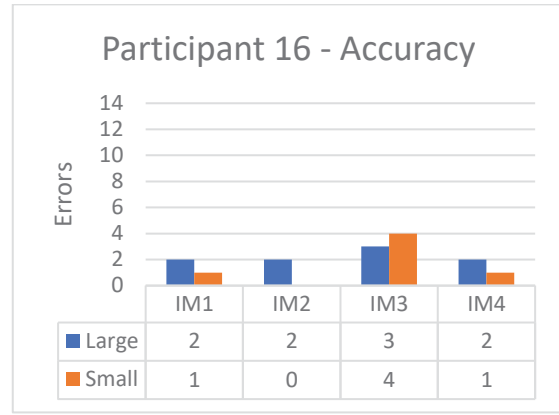


Figure B-16

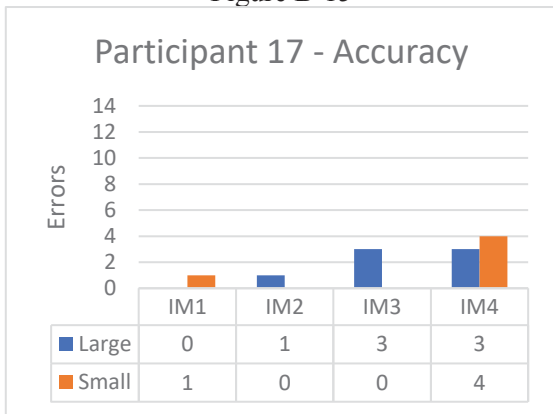


Figure B-17

APPENDIX C – ENJOYMENT RATING

All figures in this chapter describes the enjoyment rating made by a participant on a likert scale of one to five, blue for the tests with large cubes and orange for the tests with small cubes. The horizontal axis represents the four interaction models.

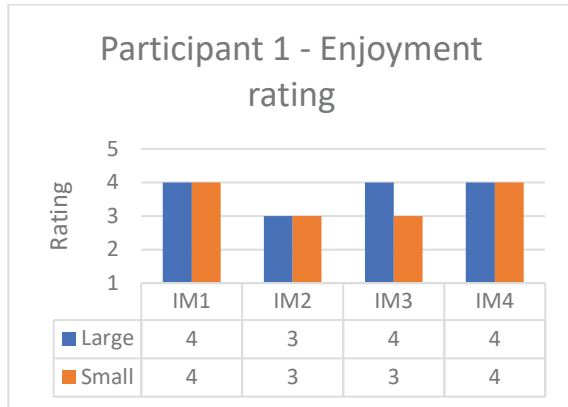


Figure C-1

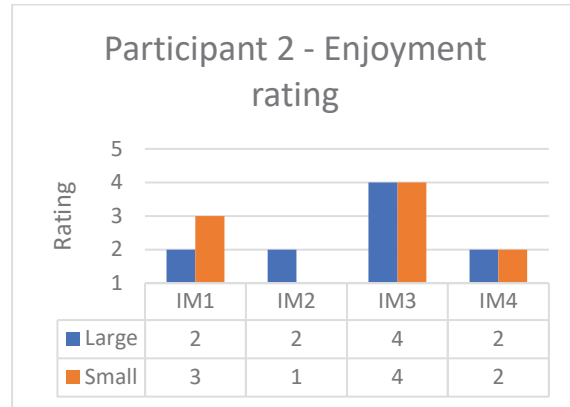


Figure C-2

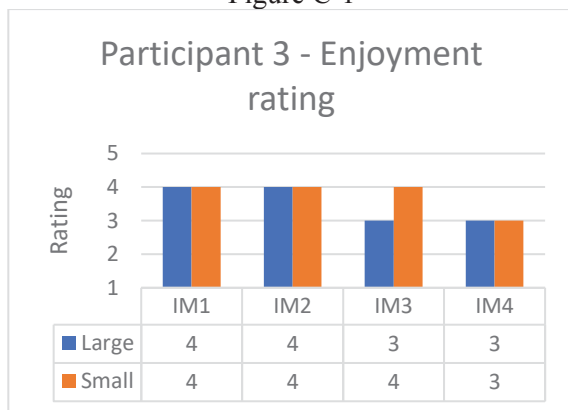


Figure C-3

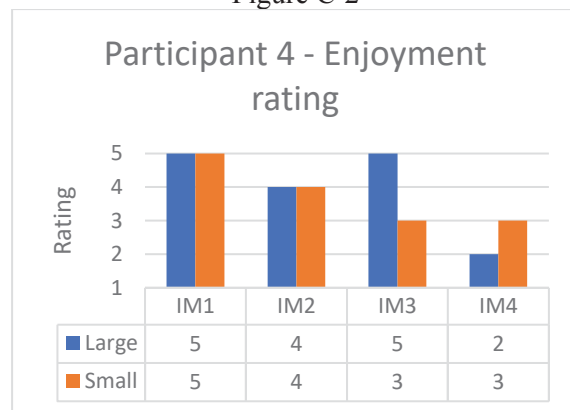


Figure C-4

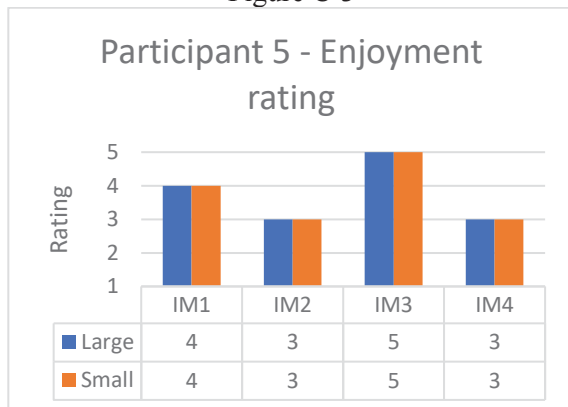


Figure C-5

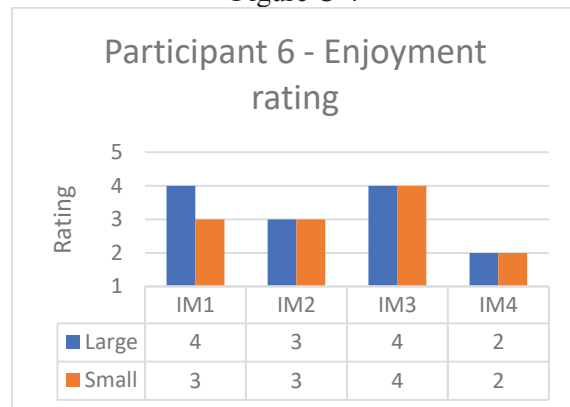


Figure C-6

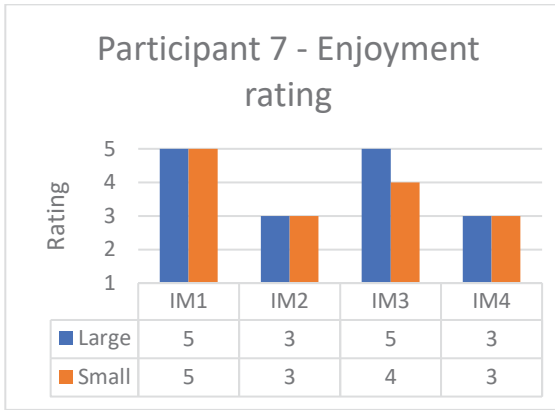


Figure C-7

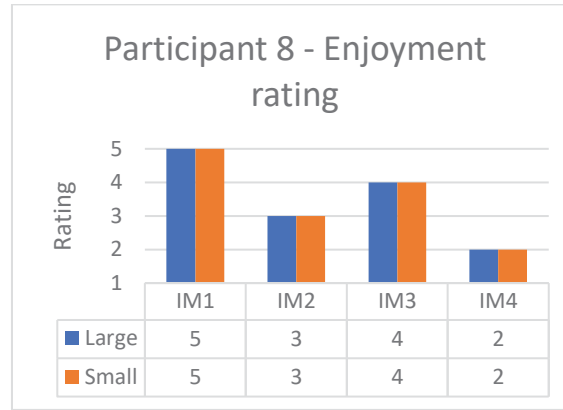


Figure C-8

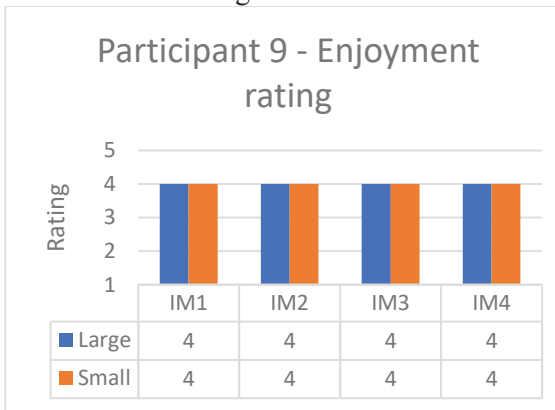


Figure C-9

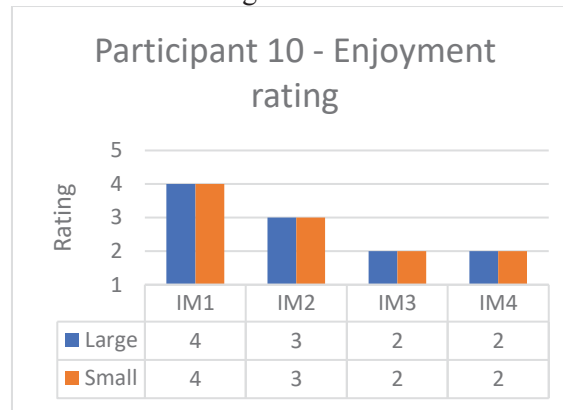


Figure C-10

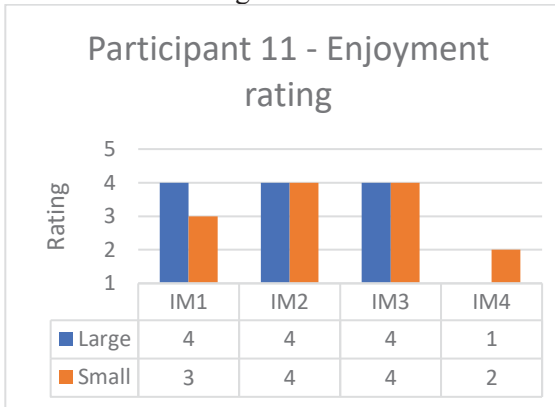


Figure C-11

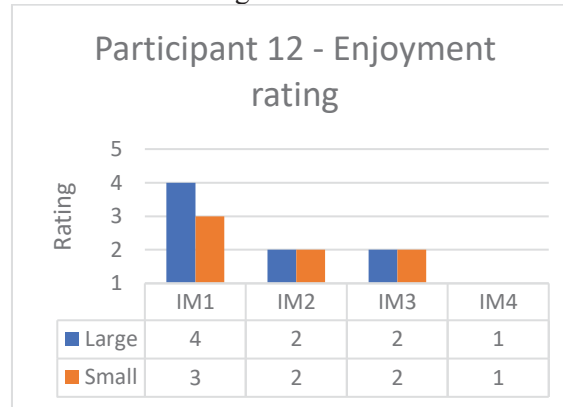


Figure C-12

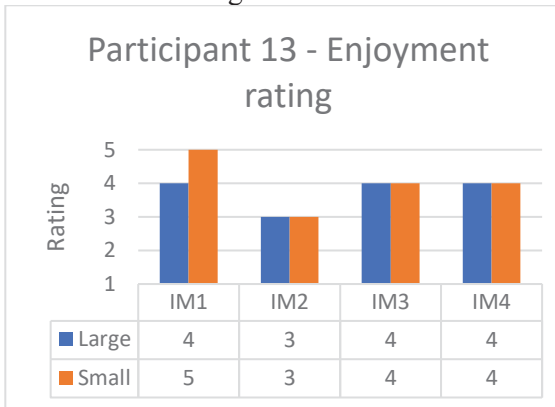


Figure C-13

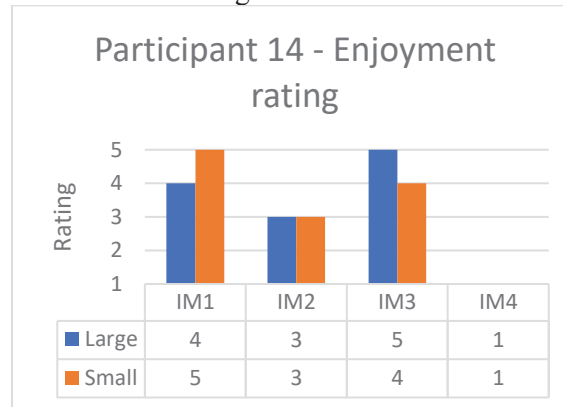


Figure C-14

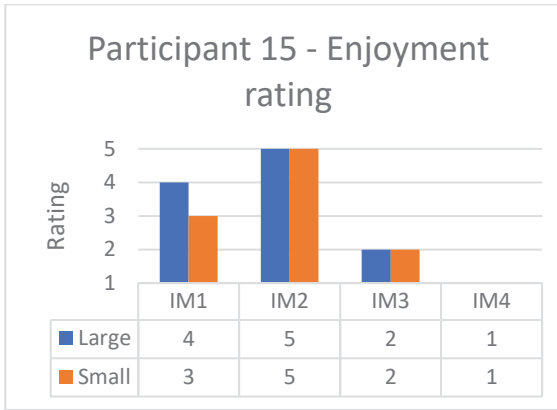


Figure C-15

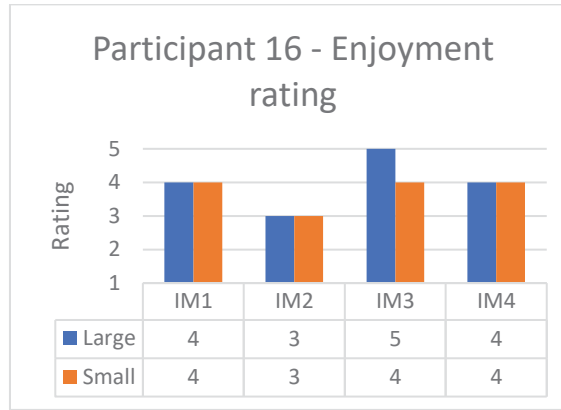


Figure C-16

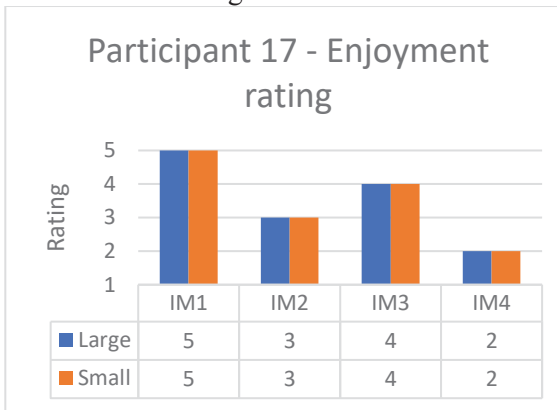


Figure C-17

APPENDIX D – ADVERTISEMENT POSTER

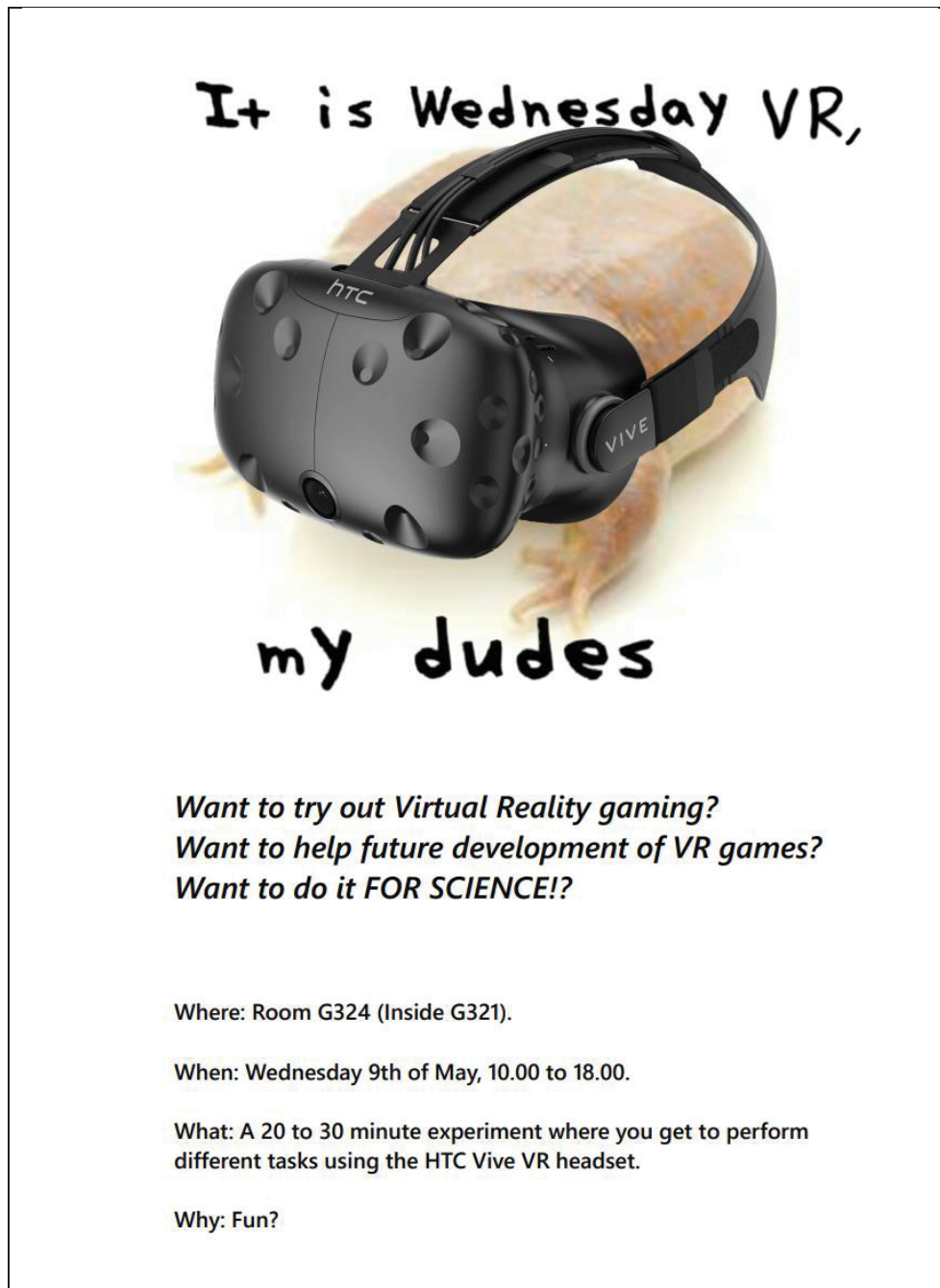


Figure D-1: Poster used to advertise the experiment.

