Analyzing the Trade-off between Selection and Navigation in VR

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ABSTRACT

Navigation and selection, two of the main interaction modalities in Virtual Reality systems, have been widely studied in different contexts. Once a given virtual environment (VE) exceeds in extent beyond what can be easily reached with a given selection method from the current viewpoint, users have to navigate before they can select and then interact with targets, e.g., because distant objects appear too small to be selectable. Navigation is even more critical in very large VEs, such as a whole town. Many different VR techniques to navigate and select 3D objects have been presented, and each method has its own advantages and shortcomings. In previous work, attributes of navigation and selection methods have typically been investigated separately. However, in practice, many VR applications require both of these modalities to work together. To fill this gap, we compare different combinations of two navigation and two selection methods in VR, in this study. The aim of our work is to discover the trade-off between navigation and selection techniques and to identify which combination leads to better interaction performance in large VEs. We investigated the differences between the combination of two typical navigation methods (teleportation and flying) and two typical selection methods (raycasting and virtual hand). We conducted a user study with 5 participants to compare task completion time, selection error rate, and distance traveled, in a scenario where the selection tasks require navigation, as the targets are (initially) too far away. We also investigated simulator sickness and preference scores for these combinations. The results showed that, users could complete their task faster with the flying method and traveled less distance, compared to the teleportation method. However, the flying method caused also a greater sense of motion sickness in comparison with the teleportation. Additionally, the raycasting method exhibited a better performance in terms of time and (less) distance traveled, however, it significantly increased the error rate for the selection of targets. Our results suggest that on average users tend to select targets at a distance of 3.18 meters with the raycasting method and at 0.8 meters with the virtual hand method. Participants selected objects in these distances even though with raycasting they had the option to select targets at further distances. The outcomes of our study help researchers and VR designers to know more about advantages and shortcomings of each technique in different situations in the context of object selection, and give guidance for improving the interaction experience of users of VR systems.

CCS CONCEPTS

• Human-centered computing~Human computer interaction (HCI)~Interaction paradigms~Virtual reality • Human-centered computing~Human computer interaction (HCI)~Interaction techniques~Pointing • Human-centered computing~Interaction design~Empirical studies in interaction design

KEYWORDS

Navigation, Selection, Virtual Reality, Interaction Desgin

1 Introduction

Virtual reality (VR) systems simulate a 3-dimensional virtual environment (VE) that the viewer can experience and interact with. Applications of VR include entertainment, design, professional, and educational training. As VR's application areas are expanding, large and complex VEs are becoming more common. Object selection and navigation techniques, which are two of the most important interaction modalities, have been widely studied. Every different technique for navigation and selection results in different user performance in VEs. In such environments, selection takes place when a virtual cursor or ray intersects with a virtual object. Virtual hand selection involves intersecting the cursor associated with the hand (or more precisely the controller that the users holds) with a virtual object, but this method works only for objects that within arms-reach.Alternatively, selection through "ray casting" involves a ray emitted from the controller, similar to a laser pointer. If this ray hits an object, the user can select it, e.g., through a button press. Ray casting can be frustrating when objects are too small to be hit with the "virtual laser", i.e., when they are too far away. Thus, for large VEs, navigation before selection is inevitable. By way of illustration, suppose that we need to select a specific house located in a city on a virtual world map. If we are too far from the city, there are too many small houses clustered, making the selection task very hard. However, as we navigate closer to the house, we will at some point see it big enough to make selection easier.

Many selection and navigation techniques have been proposed in previous work and it is hard to tell which combination of navigation and selection technique results in the best user performance for a given set of circumstances. We are thus interested to know how such combinations affect user performance considering task completion time and errors. While many studies have introduced or evaluated either selection or navigation techniques [1, 2], to the best of our knowledge, no study has addressed the combination of these two interaction modalities to identify the trade-off between them. Instead, VR studies typically compare navigation and selection separately [2, 3, 4]. However, most VR applications rely on offering both navigation and selection methods to enable users to perform all needed tasks, and VR designers usually design their environments based on their previous experience and best practice, but with the lack of confirmed knowledge. Therefore, we investigated the combination of navigation and selection to identify the tradeoff(s) between them and give designers guidance for design of efficient VR environments.

To that end, we designed an experiment that enables us to investigate the combination of either one of two chosen selection techniques with one of two navigation techniques. A recent survey [5] classified VR selection techniques based on their action space (infinite/arm-scale) and we chose the most well-known object selection techniques from each category: Ray-casting (infinite) and Virtual hand (arms-scale). The virtual hand technique allows the user to select objects that are inside arm's-reach while the ray-casting method selects the object that the ray cast from the controller first intersects. Many selection techniques are variants of these two techniques. For example, Flashlight [6] is a variant of ray-casting and Go-Go [7] is a variant of virtual-hand method. We selected these two fairly generic techniques, to compare methods within different action spaces, while at the same time affording familiar selection methods with good performance. Among numerous candidate navigation techniques, we decided to choose Teleportation and Flight. In a comparison with three other ones, Flight was identified as the best navigation method in one recent study [8] and teleportation was also identified as being superior to other techniques in another study [2]. Thus, we selected these two methods to combine with the selection techniques. In essence, we want to know which combination of navigation and object selection methods is most efficient in VEs in different situations. Also, we want to discover the trade-off between navigation and selection in a large 3D VE in VR.

We analyzed the tradeoff between our technique combinations in terms of task completion time, number of errors, relative distance traveled before selection, and other application variables. However, even if a method performs better in such factors, it does not mean that it is free from other important factors such as motion sickness. Motion sickness is a serious issue for users and designers of VEs as it impacts the usability of these systems [9, 10]. Individuals who experience severe symptoms while using VR applications are less likely to adopt VR, which can reduce the overall usability of this technology. Thus, we have to also investigate motion sickness as a factor while analyzing the tradeoffs between our conditions. In addition, because we designed different conditions for our experiment, we have to design comparable tasks with (reasonably) equal task loads to avoid biases between conditions. To assess task load, we used the NASA Task Load Index (NASA-TLX). This tool is a survey to measure the task load (mental and physical load, and other factors) for each condition of the experiment. If we find significant difference between task loads, this may be an indication that we failed to maintain fairness between conditions.

1.1 Motivation and contribution

Although previous studies [2, 3, 4] compared the performance of selection methods and navigation methods in VR, we know little about the performance of the combination of navigation and selection methods. To this end, this study tries to identify the tradeoffs between locomotion and manipulation techniques in VR. The results of this study will show which combination(s) of techniques is best (among the ones that we chose) and will inform choices by VR designers among the various selection and navigation techniques. If we know how much time participants spend on navigation and selection for an interaction task at different distances, or what percentage of time navigation takes between a trial start and successful selection of a very distant target, we can make better decisions when designing large VR systems, instead of choosing interaction methods through trial and error. Consequently, we can create better VR experiences with increased user satisfaction. In addition, using the simulator sickness questionnaire, we will identify which combination causes the least amount of simulator sickness symptoms. All the results together will enable VR designers to improve the users' interaction experience.

1.2 Research questions and hypotheses

Our goal is to compare four distinct combinations of selection and navigation methods and to identify meaningful differences and tradeoffs between them. Based on our goals we define our research questions as follows:

- RQ1: How does the combination of different selection (virtual hand, raycasting) and navigation (teleportation, flying) techniques impact users' overall navigation and selection performance in VR?
- RQ2: Is there any difference in the rate of motion sickness between conditions and is there any relation between motion sickness and user performance?
- RQ3: Is there a preferred method (between our combinations) for participants to interact with the VR environment and select small targets at a far distance?

In addition, we formulated the following hypotheses in regard to the research questions. Our predictions are based on previously mentioned references, our previous experience in VR, and similar systems.

- H1 **-** The combination of teleportation and ray-casting will perform better in terms of time compared to the other three combinations.
- H2 **-** The ray-casting method will have a higher selection error rate compared to the virtual hand method.
- H3 **-** Participants will experience a stronger sense of motion sickness in the flying method compared to the teleportation method.
- H4 **-** Participants will prefer to use the combination of teleportation and ray-casting to interact with the VR environment.

In the next section, we will explain the methodology of our study, the experimental design, the apparatus we used, and the procedure of the experiment. In the following section we will describe all of the results, and subsequently analyze the results and discuss their meaning, and finally answer the research questions and the hypotheses.

2 Method

2.1 Participants

Initially, the participants for this study were supposed to have been recruited from University recruiting system. However, due to the outbreak of COVID-19 during the data gathering phase of the study, and considering the nature of VR studies, we had many limitations to gather data. Data gathering was conducted inside of an apartment, while considering all of the social distancing recommendations, and with the explicit consent of the participants. Also, all of the equipment that participants might come into contact with was sanitized before and after each participant, including the keyboard, mouse, desktop monitor, the VR headset, and the chair. We also reminded participants that they have the right to stop and leave the experiment at any point, without needing to feel bad about that.

Five participants, two male and three female, were recruited for the study (ages 24 to 30). Two of the participants had no previous experience in VR, one had limited experience in VR, and two were experienced. Since we compare each participant with themselves through a within group experimental design, it was not necessary for participants to have previous experience in VEs.

2.2 Stimuli and apparatus

We used a HTC Vive as the head mounted display (HMD) to present the VE to the participants. The VE that we used to investigate our research questions was designed in Unity3D. We designed our VE to enable us to compare task completion time and errors for each combination of the investigated selection and navigation techniques. Participants initially were placed at the center of the VE for the experiment. As our research focuses on the psychophysics aspects of the main interaction tasks (and not on search tasks), we designed a simple 3D environment, where all targets are directly visible, as clusters of small spheres within bigger spheres at various distances, see Figure 1.

During the experiment, participants could see a single cluster of objects in the VR environment from where their viewpoint. Participants were placed at a specific distance to the target and their goal was to select a highlighted small sphere within a cluster using the available navigation and selection methods. The size of clusters and the initial distance to the target for each task were chosen from 9 different trials (3 target sizes × 3 target distances). In each condition of the experiment, participants repeated the same task 5 times for each of the 9 trials, for a total of 45 repetitions. The order of interaction techniques and target size and distance combinations was counterbalanced. The reason behind using different sizes and distances was to make performing the tasks less dull for participants. We used counterbalancing to cancel potential order effects due to target size and distance in the results. In each task, the cluster was placed sufficiently far away from initial position of the participant in the VE to make it impossible to select it directly. Thus, they had to decide how far they wanted to navigate before selecting the target. Figure 1 shows different viewpoints of the VE, 3D clusters and target objects.

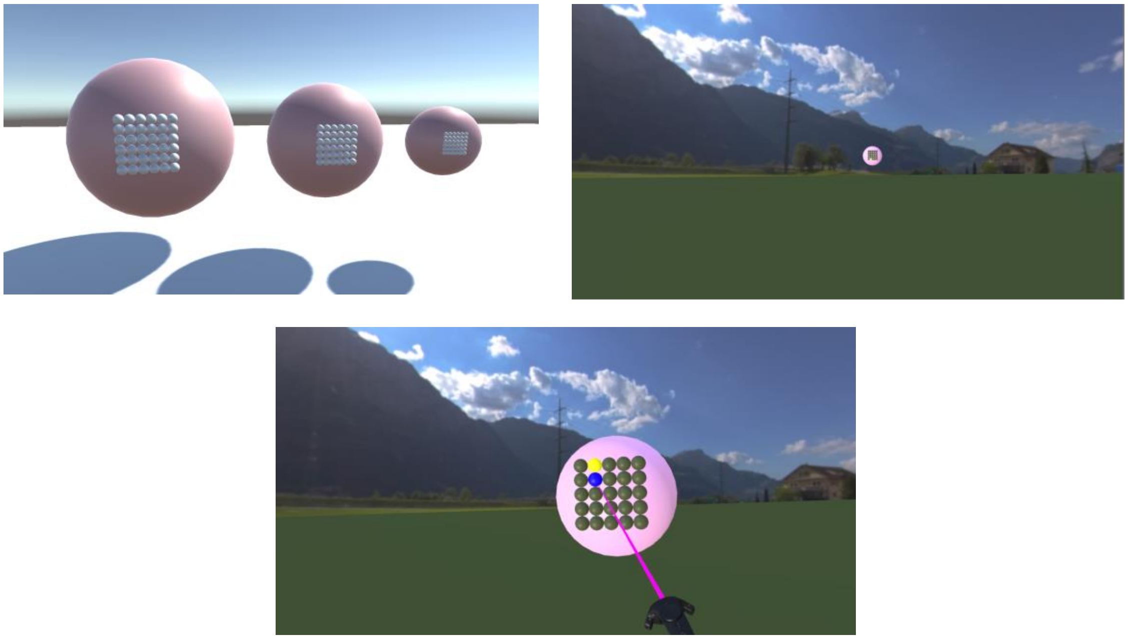

Figure 1: 3D clusters and target objects in different viewpoint. Top left: A close-up view of the illustration of three clusters in different sizes. Top right: how the environment looked at the start position. Bottom: selection of the target (yellow ball) using raycasting mode.

The VR controller held in the dominant hand was used for navigation, pointing, and selection, while the other one was used to switch between navigation and selection modes, and to change the speed of movement.

2.3 Navigation/Selection modes

For navigation we implemented two typical techniques: teleportation and flying. In the flying mode, participants could change their movement direction and speed, while with teleportation they jump to the position that they indicate. For selecting targets, participants used either raycasting (which selects the first target along a pointer ray) or a virtual hand, where they can "grab" a target that the controller intersects. While the virtual hand is limited to to targets within arms' reach, raycasting enables selections of targets at a distance (unless they are too small for that). In all trials, targets appeared initially intentionally small enough so that they could not be selected directly with either method. With raycasting, participants needed to point the ray associated with the VR controller at the targets to highlight and then select the object with a trigger press. With the virtual hand method, on the other hand, participants had to navigate to a position where they could reach the target, touch it with the selection sphere associated with the controller, and the select the object with a trigger press. Figure 2 shows an the appearance of the controllers in the two selection modes.

Figure 2: Appearance of the VR controllers in the 2 selection modes. Left: raycasting. Right: virtual hand.

2.4 Experimental design

The experiment used a 2 by 2 within-subjects design, where each participant experienced all four of the conditions, which corresponds to varying the navigation method and selection method. In each condition, participants had to perform nine trials (3 target sizes × 3 target distances), and each trial was repeated 5 time, for a total of 45 repetitions. After participants finished one condition, they moved on to the next one. We counterbalanced the order of conditions during the experiment to cancel any potential learning and/or frustration effects. We also counterbalanced the order of target sizes and distances to cancel any potential effects on the results. The variables of the experiment were as follows:

Independent Variables (IVs):

- Navigation Method: (2 Levels: Teleportation, Flying) – Categorical
- Selection Method (2 Levels: Ray-casting, Virtual hand) – Categorical

Dependent Variables (DVs):

- Task completion time (Continuous),
- Selection Error (Continuous),
- Total Distance Traveled (Continuous)
- Relative Distance Traveled (Continuous)
- Simulator Sickness Questionnaire (Ordinal)
- NASA Task Load Index (Ordinal)
- User self-reported preference score (Ordinal)

Experiment conditions:

- Condition 1: Teleportation + Ray-casting,
- Condition 2: Teleportation + Virtual Hand
- Condition 3: Flight + Ray-casting
- Condition 4: Flight + Virtual Hand

2.4.1 Task completion time, navigation time and selection time

Task completion time (in seconds) was measured from the instant that participants saw the target until they attempted to select it. To derive more detailed information about the individual selection and navigation actions, we also recorded the time for navigation and selection separately.

2.4.2 Selection error rate

Selection error was measured as the percentage of selection errors that participants made, while attempting to select the target. A selection error occurred when the trigger button of the controller was pressed, but the ray or the virtual hand cursor did not intersect with the object.

2.4.3 Total distance travelled and relative distance travelled

We recorded the total distance that participants navigated before the successful selection. Also, we defined the relative distance travelled as the percentage of the distance between the participants' original position and the position where they successfully selected a target divided by distance at which the target was initially presented.

2.4.4 Questionnaires

To address our research questions, we used two questionnaires to measure simulator sickness (SSQ) [11],and questions to elicit user preferences (Preference scores). In addition, to ensure the fairness between the tasks in each condition, we used the NASA TLX questionnaire [12].

2.5 Procedure

The experiment was performed in a single session and took approximately 45 minutes to complete. Participants started the study by signing the consent form and filling a demographic questionnaire. Also, participants were asked to fill a Simulator Sickness Questionnaire before the experiment to enable us to have a baseline to compare their SSQ scores to. Then we gave them written instructions for the study. Afterwards we placed the HMD on a participants' head and started the study.

Participants started the experiment in one of the four conditions and experienced first a training session, which helped them to understand the interaction technique and how to use it within the VE. In the training, participants experienced the same environment and the same tasks as during the main study. At the start of the main study phase, participants were asked to navigate as far as they needed to until they could select the intended 3D target with the current interaction condition. In addition, they were asked to perform the tasks as fast and as accurate as possible and to continue the experiment until they saw a sign indicating the end of that condition. They were free to switch between navigation and selection and to change the speed of the movement (in flying conditions) at any time.

In each condition, there were 45 repetition of the same task. We used targets (cluster of spheres) with different sizes and different distances to the initial position of the camera. After finishing each condition, participants were asked to fill a Simulator Sickness Questionnaire (SSQ) and task load (NASA TLX) questionnaire. Participants were given 5 minutes of rest between conditions. After they had experienced all four conditions, participants were asked to fill a preference questionnaire about their experience, their preference between our conditions, and the ease of use for each technique. After a final 5-minute rest, they filled a post SSQ. Finally, a debrief of the experiment was given to each participant.

3 Results

After the experiment, we analyzed the results with JMP 14.1. We looked for the meaningful differences, main effects, and the interaction effects. In addition, we performed post-hoc tests to find differences between different levels of the independent variables. The results were analyzed to answer the research questions of the study and accept or reject the hypotheses mentioned in section 1.2. In each subsection, descriptive statistics, including mean (M), standard error (SE), and standard deviation (SD) are reported followed by inferential statistics and explaining the overall trends in data. To save space and increase readability, the following abbreviations are used in the result section to indicate the four condition of the experiment: teleport (teleporting), fly (flying), ray (raycasting), and hand (virtual hand). Following the within-subject design of the experiment, we used two-way repeated measure ANOVA for to analyze most of the data.

3.1 Task completion time

To address the first hypothesis, we compared the task completion times between teleport/ray ($M = 4.65$, $SD = 1.01$, $SE = 0.45$), teleport/hand ($M = 7.22$, $SD = 1.29$, $SE = 0.57$), fly/ray ($M = 3.91$, $SD = 0.67$, $SE = 0.3$), and fly/hand ($M = 5.96$, $SD = 0.9$, $SE = 0.4$). A two-way repeated measure ANOVA with navigation and selection method as within-subject factors was conducted to compare the means of task completion time between groups. To check the normality assumption of the repeated measure ANOVA, we used a Shapiro-Wilk test for each of the four levels. The results showed that only the data for the teleport/hand condition does not follow the normal distribution (p = 0.04). Considering that the number of observations was equal in all of the levels, and the marginal probability of normality test, we believe that an ANOVA is robust enough to compare the results. Checking the sphericity assumption was not required because each repeated measure factor had only two levels. Unless there are differences in the distributions, we will not mention sphericity again in the next analyses to avoid repetition.

The result of the ANOVA showed that the average of task completion time was significantly affected by navigation method, $F(1, 4) = 14.19$, $p = .0196$, $\eta 2 = 0.78$, and selection method, $F(1, 4) = 86.76$, $p = .0007$, $\eta 2 = 0.89$, but was not affected by the interaction of navigation and selection, $F(1, 4) = 2.08$, $p = 0.22$, $\eta 2 = 0.34$. Post-hoc analyses using Tukey's HSD revealed that the average task completion time of teleport/hand was higher than fly/ray ($p = .0028$), and teleport/ray ($p = .0038$). Also, the time for fly/ray was lower than fly/hand ($p = .0089$). With the same selection method, we can also see a slight increase in time when participants used teleport as their navigation method instead of flying; however, these increases were not significant. Figure 3 illustrates the result for task completion time.

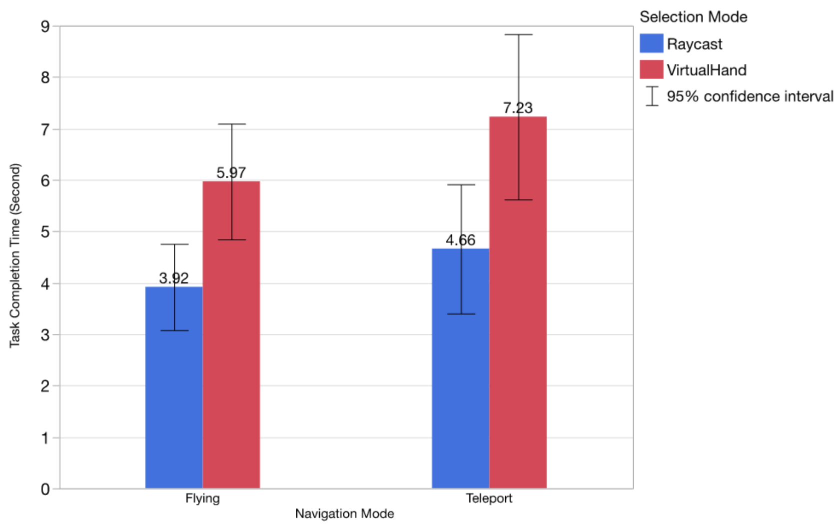

Figure 3: Average task completion time for all of the conditions. The time was lower with raycasting and slightly increased with teleportation compared to flying.

We also analyzed the times that participants spent navigating and in selection through repeated measure ANOVA on the navigation and selection times. All ANOVA assumptions were met for both analyses.

We found a main effect of navigation method ($F(1, 4) = 30.92$, $p = .0051$, $\eta 2 = 0.88$), and a main effect of selection method ($F(1, 4) = 9.33$, $p = .037$, $\eta 2 = 0.7$) for selection times. The same main effects for navigation method ($F(1, 4) = 9.97$, $p = .034$, $\eta 2 = 0.71$), and selection method ($F(1, 4) = 71.52$, $p = .0011$, $\eta 2 = 0.94$) were found for the navigation times. We could not find interaction effects for either selection time ($F(1, 4) = 0.07$, $p = .79$, $\eta 2 = 0.01$) or navigation time ($F(1, 4) = 3.5$, $p = .13$, $\eta 2 = 0.46$). Post-hoc analysis showed that selection time was lower ($p = 0.04$) with fly/hand ($M = 0.67$, $SD = 0.18$, $SE = 0.08$) than teleport/ray ($M = 1.44$, $SD = 0.38$, $SE = 0.17$). In addition, navigation time was lower (all $ps < 0.02$) with teleport/ray ($M = 7.22$, $SD = 1.29$, $SE = 0.57$) and fly/ray ($M = 7.22$, $SD = 1.29$, $SE = 0.57$) than teleport/hand ($M = 7.22$, $SD = 1.29$, $SE = 0.57$) and fly/hand ($M = 7.22$, $SD = 1.29$, $SE = 0.57$). Figure 4 shows the breakdown of navigation times, selection times, and task completion times (total time) for all of four conditions.

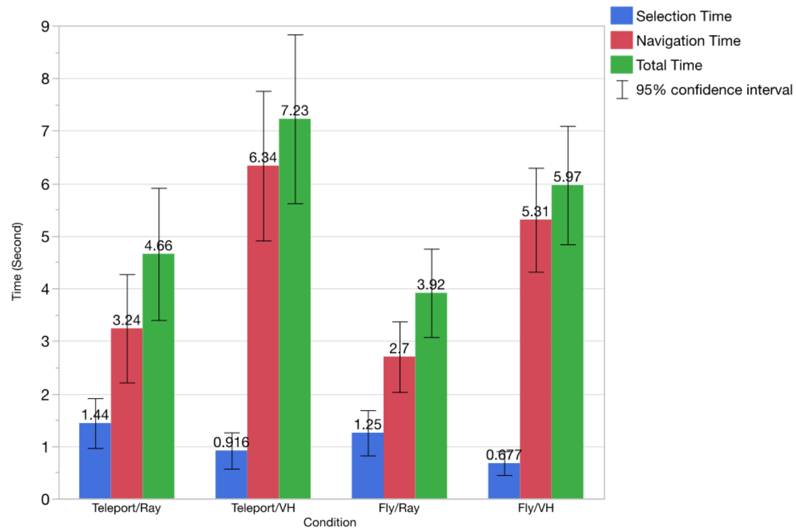

Figure 4: Average selection, navigation, and total times for all conditions.

3.2 Selection errors

For the second hypothesis, we compared the average percentage of selection errors between teleport/ray (M = 0.50, SD = 0.24, SE = 0.1), teleport/hand (M = 0.02, SD = 0.01, SE = 0.01), fly/ray (M = 0.39, SD = 0.2, SE = 0.08), and fly/hand (M = 0.02, SD = 0.01, SE = 0.01). A two-way repeated measure ANOVA (assumptions were met) showed a main effect of selection method ($F(1, 4) = 20.23$, $p = .0108$, $\eta 2 = 0.83$); however, the main effect of navigation method ($F(1, 4) = 4.55$, $p = .099$, $\eta 2 = 0.53$) and interaction of the two factors ($F(1, 4) = 5.47$, $p = .079$, $\eta 2 = 0.57$) were not significant. Post-hoc analysis using Tukey's HSD showed that the number of selection errors was significantly higher in teleport/ray comparing to fly/hand and teleport/hand ($p = 0.026$ for both). Fig 5 illustrates the difference in number of errors between all conditions.

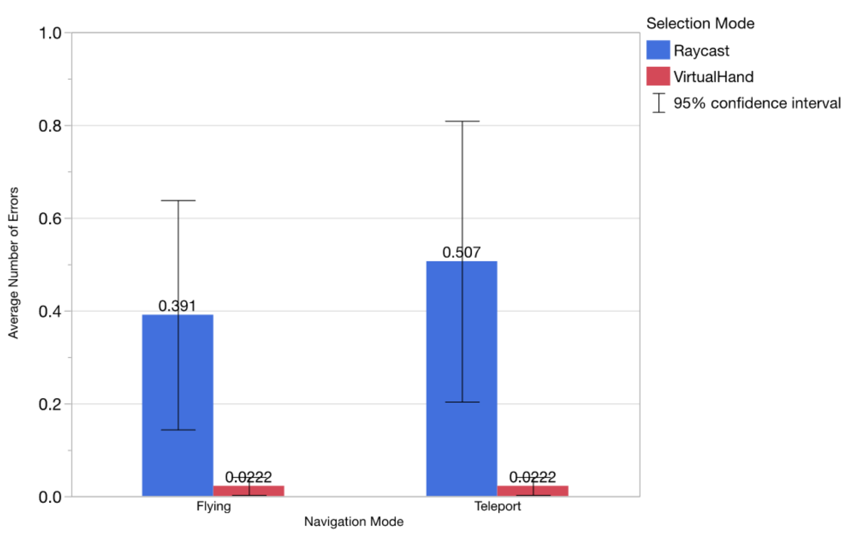

Figure 5: Average number of selection errors in all of the conditions. The higher error rates with raycasting are visible.

3.3 Total distance traveled and relative distance traveled and angular measure

As mentioned in section 2.4.3 and to gain a better understanding of the trade-offs between the combination of navigation and selection methods, we also recorded the total distance and relative distance that participants traveled before a successful selection. We used a two-way repeated measure ANOVA to analyze both dependent variables. For the analysis of the total distance traveled, a Shapiro-Wilk test showed that only the teleport/ray condition did not follow the normal distribution ($p = 0.042$). Considering the equal number of observations in all levels, and the marginal probability of the normality test, we believe that the ANOVA is robust enough to compare the results of this test. The normality assumption of the ANOVA was met for all data for the relative distance traveled.

The results of ANOVA showed main effects of navigation method ($F(1, 4) = 14.95$, $p = .018$, $\eta 2 = 0.78$) and selection method ($F(1, 4) = 39.34$, $p < .000$, $\eta 2 = 0.90$), without an interaction effect ($F(1, 4) = 1.96$, $p = .23$, $\eta 2 = 0.32$), for total distance traveled. Also, the test showed a main effect of selection method ($F(1, 4) = 56.31$, $p = .001$, $\eta 2 = 0.93$) but could not identify a main effect of navigation method ($F(1, 4) = 0.71$, $p = .44$, $\eta 2 = 0.15$) nor an interaction ($F(1, 4) = 1.02$, $p = .36$, $\eta 2 = 0.20$) for relative distance traveled. Post-hoc tests using Tukey's HSD showed a higher total distance traveled with the teleport/hand method (M = 63.51, SD = 3.67, SE = 1.64) compared to fly/ray (M = 53.78, SD = 0.52, SE = 0.23) and teleport/ray (M = 56.35, SD = 3.01, SE = 1.34), ps are $p = 0.007$ and $p = 0.027$ respectively. In addition, a post-hoc test showed that in the raycasting conditions participants traveled a lower percentage of the total distance before successfully selecting targets compared to the virtual hand conditions (all ps < 0.01). Figure 6 and Figure 7 show the average of total and relative distance traveled for all conditions respectively.

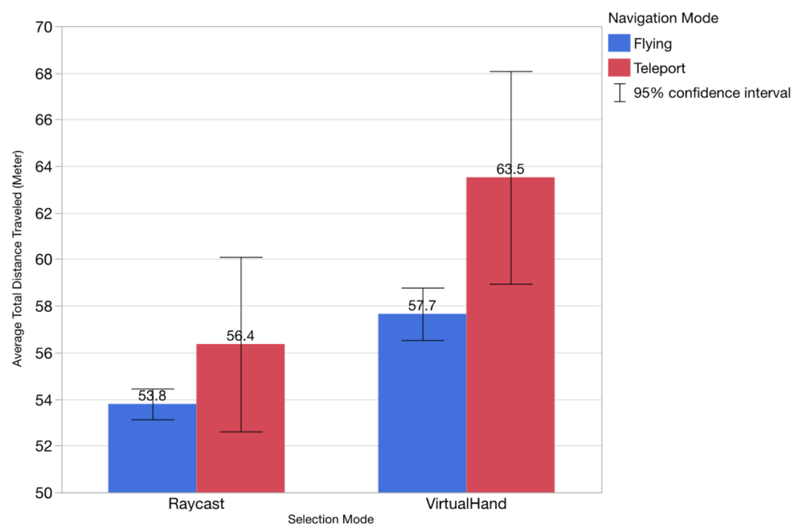

Figure 6: Average total distance traveled in all conditions. Total distances were higher for virtual hand than for raycasting methods.

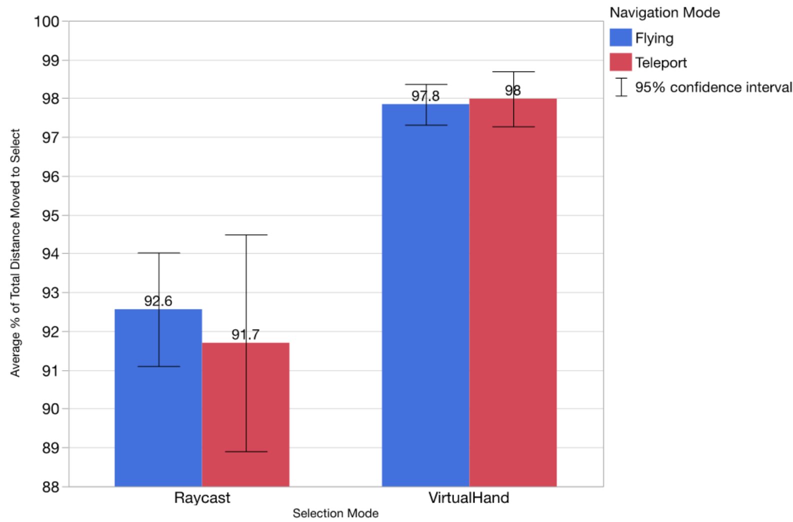

Figure 7: Average percentage of total distance to target traveled for all conditions.

3.3.1 Angular measure

We calculated the angle of the view of the target in the moment of successful selection in terms of distance to the target and the size of target. This angle in a far distance tends to zero and right next to the target tends to the maximum field of view of the HMD. We calculated the angles for all of the conditions to compare them. The results of ANOVA showed main effects of selection method ($F(1, 4) = 223.13$, $p = .0001$, $\eta 2 = 0.87$) and no effect for navigation method ($F(1, 4) = 0.598$, $p = .48$, $\eta 2 = 0.15$), nor interaction effect ($F(1, 4) = 1.38$, $p = .30$, $\eta 2 = 0.24$). Post-hoc tests using Tukey's HSD showed a lower angular measure for the raycasting conditions ($ps < 0.001$). Figure 8 shows the difference between average of angular measures for all four conditions.

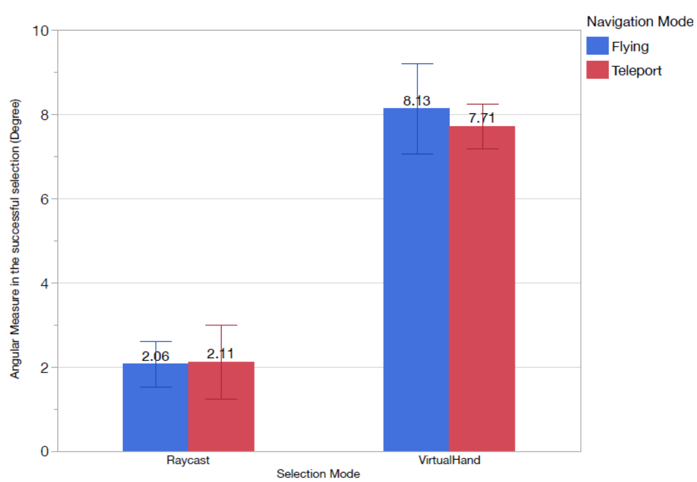

Figure 8: Average angular measure (in degree) for all conditions.

3.4 Simulator sickness

To address the third hypothesis, the results of simulator sickness questionnaire (SSQ) were analyzed in two different parts. The first part compared the SSQ score between the four condition of the experiment. For the second part, SSQ scores during experiments were compared with pre and post experiment SSQ scores.

3.4.1 First part: comparing SSQ between conditions

The SSQ score was calculated based on the questionnaire proposed by [11] for each condition. The questionnaires were filled by participants after finishing each condition. First, descriptive statistics for fly/ray ($M = 26.92$, $SD = 14.58$, $SE = 6.52$), fly/hand ($M = 25.43$, $SD = 15.28$, $SE = 6.83$), teleport/ray ($M = 10.47$, $SD = 4.87$, $SE = 2.18$), and teleport/hand ($M = 9.72$, $SD = 5.67$, $SE = 2.53$) conditions were investigated. Using two-way repeated measure ANOVA (all assumptions met) we found a main effect of navigation method ($F(1, 4) = 8.34$, $p = .044$, $\eta 2 = 0.67$). Yet, we could not identify a main effect of selection method ($F(1, 4) = 0.78$, $p = .42$, $\eta 2 = 0.16$) nor an interaction ($F(1, 4) = 0.28$, $p = .62$, $\eta 2 = 0.06$). Post-hoc tests did not identify any significant differences between levels. In general, SSQ scores were lower in the conditions that used teleportation for navigation compared to flying. Figure 9 shows the difference between average SSQ score for all four conditions.

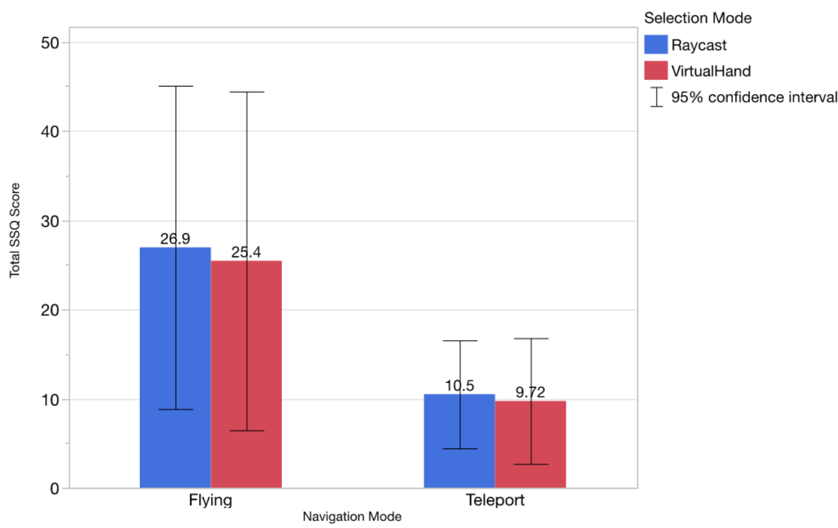

Figure 9: SSQ score for each condition. The score was higher with flying compared to teleportation.

3.4.2 Second part: comparing SSQ scores during experiment with pre-SSQ and post-SSQ

To compare the pre-experiment SSQ score with the ones during the experiment and the post-experiment score, we calculated the average of SSQ scores during the experiment ($M = 18.13$, $SD = 9.17$, $SE = 4.1$) from the scores of all four conditions. This score was compared to the pre-SSQ score gathered before the experiment ($M = 1.49$, $SD = 2.04$, $SE = 0.91$) and to the post-SSQ score gathered 5 min after finishing the experiment ($M = 11.22$, $SD = 5.91$, $SE = 2.64$). We used a one-way repeated measure ANOVA to analyze the results (assumptions were met). Results showed that the time when the survey was filled (main factor) affected the SSQ score, $F(2, 8) = 16.68$, $p = .0014$, $\eta 2 = 0.80$. Also, post-hoc tests using Tukey's HSD showed a lower score for the pre-SSQ compared to the SSQ score during the experiment ($p = 0.001$) and the post-SSQ score ($p = 0.024$). Figure 10 shows the results of the test.

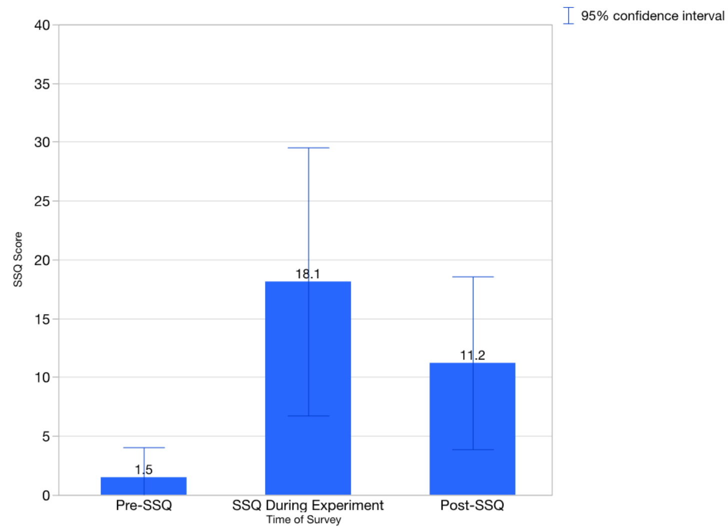

Figure 10: Comparing the SSQ scores before, during, and after the experiment. Results showed a significantly lower for the initial pre-SSQ compared to the other times the SSQ was administered.

3.5 Preference score

Finally, to address the fourth hypothesis, we asked the participants about their preferred method after they finished the experiment. They had to rate each method on a scale from 0 to 100 based on their preference for using that interaction method. The descriptive statistics for all four conditions are as follows: fly/ray (M = 76.18, SD = 21.56, SE = 9.64), fly/hand (M = 42.46, SD = 12.10, SE = 5.41), teleport/ray (M = 70.7, SD = 23.15, SE = 10.35), and teleport/hand (M = 44.08, SD = 28.08, SE = 12.56). We conducted a two-way repeated measure ANOVA (all assumptions were met) to analyze the results. Results did not show an effect for navigation method ($F(1, 4) = 0.03$, $p = .85$, $\eta 2 = 0.10$), selection method ($F(1, 4) = 3.8$, $p = .12$, $\eta 2 = 0.48$), nor an interaction effect ($F(1, 4) = 0.82$, $p = .41$, $\eta 2 = 0.17$).

3.6 NASA-TLX score

Using repeated measure ANOVA, we could not find a main effect of selection method ($F(1, 4) = 1.27$, $p = .32$, $\eta 2 = 0.24$), navigation method, ($F(1, 4) = 0.76$, $p = .43$, $\eta 2 = 0.16$), nor interaction effect ($F(1, 4) = 0.37$, $p = .57$, $\eta 2 = 0.08$).

4 Discussion and Conclusion

Here, we discuss the most important findings of this study, by looking at all findings from the mentioned analyses in section 3 and connecting them to the research questions and hypotheses.

The first research question of this work investigates the trade-off between the combination of selection and navigation methods in terms of task completion time and selection errors. Based on the results, task completion time is higher in the teleportation mode compared to flying, and in virtual hand mode compared to raycasting. The higher overall time with virtual hand was not unexpected since participants had to touch the target to select it, which means that they had to navigate longer to get closer to the target (relative to raycasting). However, the higher time with teleportation was surprising because participants could travel a substantial distance with just a click. Due to our observations of participants during the experiment, this increase in time was due to overshoot behaviors with teleportation. Participants sometimes overestimated the distance to the target and teleported themselves to the other side of the target cluster. Thus, they had to continue to navigate until they faced the targets again, which is the most likely explanation for the time difference between flying and teleportation. Even though they had to fly the whole distance in flying mode, their navigation was more precise. This difference is visible in Figure 4 in the difference between navigation times. Also, the difference in task completion time between virtual hand and raycasting was significant. Although selection times in the virtual hand mode were slightly lower than raycasting, since virtual hand forced participants to travel further, it increased the navigation time and as a result the total time. In terms of overall performance, raycasting methods performed significantly better. Between the two raycasting method, fly/ray performed better (M = 3.92) compared to teleport/ray (M = 4.66); however, this difference was not significant. Considering only the selection time, virtual hand performed better since participants had to first aim and then select objects with the raycasting method. To sum up, we can safely say that using raycasting techniques decreases the total selection time. Although the selection time is higher with raycasting, using it significantly decreases the navigation time which is the dominant factor. Thus, we have to reject the first hypothesis and can only claim that raycasting decreases the time.

In terms of errors, results showed lower error rates in the virtual hand conditions. The difference is substantial, since in raycasting methods participants made on average 40 selection errors in 90 trials, while with the virtual hand they only made 2 selection errors in 90 trials. This means participants made 20 times more errors with raycasting than with virtual hand. This result suggests using the virtual hand method where precision is important. Thus, raycasting had a higher selection error rate compared to the virtual hand method and we can accept the second hypothesis.

The results for the total distance traveled showed that with teleportation, participants navigated more than with raycasting methods. The same overshooting issue with teleportation that we mentioned in the task completion time also played a role here. Although we expected to see a lower distance traveled with the teleportation method, since using teleport participants moves them in a direct line, potentially over large distances, teleportation actually increased the total distance traveled. In addition, we expected to see that a lower total distance traveled with raycasting because participants could select objects from a distance, which reduces the navigation distance. However, an interesting result was the relative distance traveled. With raycasting, participants traveled about 92% of total distance (approximately 3.18 meters distance from target). For the virtual hand method, this number was around 98% (approximately in 0.8 meters distance from target), which is only 6% higher. This indicates that although participants had the option to select targets from a far distance with raycasting, they still preferred to navigate to a point reasonably close to the target and within a fairly consistent range of distances.

Motion sickness results indicated a significant difference between flying and teleportation methods. Results showed that some participants experienced a moderate to severe feeling of sickness during the experiment with flying. We also compared the SSQ score of the participants during the experiment with pre and post SSQs. There were significant differences between pre-SSQ and the other two levels which shows that the experiment, especially the flying modes, caused the greater sense of sickness. Surprisingly, even after 5 minutes, participants still experienced some of the symptoms. Thus, we accept the third hypothesis that participants experienced stronger sense of motion sickness in the flying method comparing to the teleportation method.

We could not find any difference between the preference scores given by participants. Although the average score for the raycasting methods (M = 73.44, SD = 21.29, SE = 6.73) was higher than for the virtual hand methods (M = 43.27, SD = 20.40, SE = 6.45), this difference was not significant. Also, we could not find any other relation between preference scores and the factors. Therefore, we have to reject the fourth hypothesis that participants preferred to use teleportation-raycasting to interact with the VR environment.

The NASA-TLX results showed no significant difference between our conditions. This means that the task load for each condition was similar to the other ones. This could support the design of our task and the fairness between conditions in terms of task load.

We gathered more detailed data in the experiment than mentioned above. For instance, we have the data for number of teleportations used, the average speed, precision of selection, number of switches between navigation and selection, and an angular measure of the target. Also, in the questionnaires, we gathered data about the ease of use of each method and the level of fatigue. To emphasize the important findings of the study and also to make this document more concise, we did not mention these details. However, in a future version, we will investigate all of these variables.

4.1 Limitations and future work

The first limitation of this study is that it investigates only two navigation methods and two selection methods. To generalize our results to apply to more types of VR systems, we need to compare the results of this study with other selection and navigation methods; however, due to large variety of methods, it may not be possible to compare all available methods. That being said, we chose four general and representative combinations of navigation and selection methods for our experiment. Thus, one possible future direction is this study could be comparing our results with other available and popular methods.

The second limitation of our work is the number of participants. Due to the outbreak of COVID-19 during the data-gathering phase of the study, and considering the limitations imposed by the physical apparatus of VR systems, we had to gather data from easily available people, including friends and family. Thus, we could only gather data from 5 participants at this time. The logical next step for our work is to gather more data, from at least 12-15 participants to ensure the validity of the experiment and strengthen our work.

One of the important contributions of this work was to identify the trade-offs between navigation and selection methods. The results of our experiment also showed that the best methods in terms of time were the worst methods in terms of error. Thus, one of our next steps is to analyze the results in terms of throughput [13], through which we can compare the benefits and disadvantages of each method with exact numbers.

5 Conclusion

In this study we investigated the trade-offs of using different combinations of selection and navigation methods in large VEs. We designed an environment to identify differences in terms of time error, total distance traveled, and relative distance traveled between four combinations of methods. We also gathered data about simulator sickness for our methods and compared it with pre and post SSQ scores. Finally, we analyzed participant preferences for each method.

Results suggest that there are advantages and disadvantages of using different methods. With flying, users could complete their task faster, and with a lesser amount of distance traveled compared to the teleportation method. However, the flying method caused a greater sense of motion sickness and corresponding symptoms in comparison with teleportation. Compared to the pre-experiment state, both methods caused motion sickness, but the flying mode was more impactful. For the selection part and although raycasting had a better performance in terms of time and distance traveled, it also suffered from a significantly increased error rate. Thus, we suggest using virtual hand in VR systems when selection precision is important. In addition, we were also able to identify that participants traveled approximately 92% (about 3.18 meters from the target) of the total distance to select targets in raycasting mode and 98% (about 0.8 meters from the target) in virtual hand mode. In addition, comparing angular measures shows a difference between raycasting and virtual hand, however, the interesting result is that participants need to have an angle of view of ~2° of their targets to select them using raycasting. VR designers could use these results in the design of new VR interaction methods. It is worth mentioning that we used the default Unity 3D setting where the unit for distance measures is one meter and, therefore, these results can be applied to other scales through simple unit conversion.

In the future, we will analyze other factors, such as throughput to compare the advantages and disadvantages of each method in more detail. We will also re-analyze all of our findings with data from more participants.

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