Out-of-Reach Interactions in VR

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Abstract

Object selection is a fundamental task both in our everyday life and when interacting with virtual objects. There are several approaches to object selection, which are used in tabletops all the way to virtual environments. However, when objects are very distant from the user, the current approaches are not able to provide adequate levels of speed and accuracy. Approaches to surpass the limitations of these techniques often favour the use of selection volumes to ray-casting and arm-extension. Even with the use of selection volumes, distant object selection still poses a challenge, as these volumes are prone to unwanted selections. We will focus on this challenge. We surveyed several selection techniques which were then compared based on our taxonomy. To overcome the problems of the selection techniques studied, we developed PRECIOUS. It combines progressive refinement with cone casting and is capable of selecting objects at various distances. Using a travel technique, chosen based of an evaluation conducted between three techniques, we bring the user closer to the object he intends to select. PRECIOUS was then compared with other approaches on distant object selection. The results indicate that even though it does not provide the faster completion times, the significant absence of incorrect selections and the consistent completion times across all scenarios make it an appropriate approach to out-of-reach selection.
Keywords: Out-of-reach Selection, Travel Technique Evaluation, User-Centered Design

1. Introduction

Immersive Virtual Environments (IVEs) have been the object of considerable interest in the latest years. The development of new hardware has allowed for the development of techniques and applications that can make use of these environments.

In recent years there has been an accelerated advance in virtual reality technology, mainly with the appearance of new low-cost stereoscopic hardware such as the Oculus Rift[1] and the Samsung Gear VR[2]. This hardware, also called head-mounted displays (HMD), has seen great advances in the recent years and now users are able to use them wirelessly using a smartphone as the display. These advances also assisted in the increased research in mid-air interaction.

Interaction techniques developed for IVEs aim to give users a suitable approach to object manipulation. These techniques can be divided in three phases: selection, transformation and release. In our work we focus mainly on the first phase.

Most approaches to object manipulation are not focused on the interaction with objects that are out of arms-reach. But when interacting with objects in IVE's, there is no guarantee that all objects will be within arms-reach. This means that users have to rely on techniques designed to select these objects, or move in the real world to a position closer to the virtual object.

The interaction with objects that are out of arms-reach still pose some problems. These techniques follow, in general, three different approaches: ray-casting , arm-extension and volume selection.

Ray-casting based techniques suffer from hand and tracker jitter, where a small hand movement can have a severe impact in the manipulation of the objects. This problem is augmented when considering out-of-reach selection, as the objects that are further away will suffer more from the jitter. On the other hand, arm-extension techniques provide users with a more accurate approach to object selection. But in turn, they require more movements which can lead to fatigue. Volume selection techniques can effectively deal with some problems that are presents in ray-casting and arm-extension techniques, but there is a lack of research when the objects are out of arms-reach.

We focused on the problems that selections techniques currently have, seeing that users have to se-

[1] www.oculus.com

[2] http://www.samsung.com/global/galaxy/wearables/gear-vr/

lect an object in order to perform transformations on it. Our intention was not to solve the hand and tracker jitter problems, but to tackle the problems that ray-casting, arm-extension and volume based techniques currently have. With the work of this thesis we intended to answer the following research question:

Does the combination of progressive refinement and cone casting improves user performance in out-of-reach objects' selection tasks in VR?

2. Related Work

To understand how to better design a 3D interaction technique we reviewed the relevant related work in the area. We make a comparison between the relevant techniques regarding object selection, with a focus on comparing the reach of each technique.

The initial concept of progressive refinement introduced by Kopper et al. [8] in the form of the SQUAD technique was extended in other works of the literature. The Continuous Zoom technique [2] provided better selection times when compared to Discrete Zoom [2], SQUAD and ray-casting. The Zoom and Expand techniques [6] also perform higher than the standard ray-casting and SQUAD techniques, but focus on dense environments. The Expand technique also provided better selection times than the Zoom. The similarities between these techniques are represented in our taxonomy. The reach of these techniques is screen-space, as they work on a 2D large scale display with a 3D perceived space and 3D user input.

The Go-Go technique [12] is the earliest approach on arm-extension techniques. It provides arms-reach selection in a 3D environment with a 3D input space. Only single objection is available, using a direct approach.

In World in Miniature [15], users have access to all objects in the 3D environment. Users control the copy of the environment using 3D input and can select objects using a direct approach. Even though the whole environment is available, there is a limit to its size, so we consider this techniques' reach as scaled. Voodoo Dolls [11] gives users the possibly of selecting an object using a direct approach in the 3D environment to create a doll representing that object. It can select objects at distances greater than the reach of the users arms, using a pinching gesture. Both Prism + Go-Go [1] and the Scaled HOMER [16] improve previous work by increasing precision when interacting with objects. Both techniques only allow single object selection using a direct approach, but the reach of the techniques is considered scaled.

The Vacuum technique [3] stands out as the only technique with 2D input and that is used in a 2D perceived space and which allows infinite object selection using a 2D cone in a tabletop. Also gives the possibility of selection multiple object with a direct approach. The Stretch Go-Go [4] technique improves on the previously mentioned Go-Go, by being able to extend the virtual arm until infinite. The Spotlight [9] technique was developed as means to select objects without using a mathematical ray, using a cone instead. A bat is used as 3D input and a desktop is used to display the 3D environment. Even though more than one object can fall within the selection volume, only a single object can be selected, using a direct approach. The Aperture and Orientation techniques [7] were developed to advance the state of the art by using and HMD as their display. They improve the disambiguation method used in the Spotlight technique, by using either rotation of the object, and also they change from where the cone volume originates. Both technique can only select one object using a direct method, using the bat as the 3D input.

Even though we do not focus on multiple object selection, the following techniques provided good insight on what type of environments multiple selection techniques should be used. The 3D Magic Wand [14] technique was compared against the brush and lasso techniques for multiple object selection in IVEs. It gives users arms-reach selection, using a direct approach. Two other types of technique were developed for MOS, serial and parallel [10]. The serial techniques are only capable of selecting a single per operation, and on the parallel techniques more than object could be selected. One of the serial techniques used was ray-casting, making us consider this techniques' reach as infinite. All three techniques select the objects based on a direct approach.

Despite the various studies that have been done on object selection, there is still a shortcoming of approaches for out-of-reach object selection. Even though some techniques are capable of this, there is a lack of approaches that focus specifically on distant objects. That being said, with the proposed work of this dissertation we aim to tackle this challenge.

3. Travel Techniques Evaluation

We surveyed ways of moving an user in the virtual world, and the section that follows relates to two interconnected domains of previous research, travel techniques and the causes of cybersickness in VR environments. Another crucial issue when considering travel technique design is cybersickness. We studied three different techniques for travel in immersive virtual environments. Our objective with this evaluation was to understand what impact these techniques had on the users, and which one was more suitable when changing the position of a user in a virtual environment.

Teleport Technique

The Teleport technique [5], also known as infinite velocity, translates a person instantaneously from their current position to the next checkpoint, as depicted in Figure 1A. Their results show that people were unable to process the information regarding the target direction accurately when using this technique.

Linear Motion

This technique consists of moving the user along a linear path for two seconds with a constant velocity, until the next checkpoint (Figure 1B). The velocity choice is based on previous work [13] and varies between 30 m/s and 50 m/s depending on the checkpoint distance.

Animated Teleport Box

We developed the Animated Teleport Box technique with the objective to combat the negative effects of the Teleport technique. Two 1.5 second animations were played when a user was being translated from their current position to next checkpoint. The first one animated the Box to rise up and surround the user, and the second one executed the same animation but in the inverse direction. The box has 2.3 meters on each side so that users would not feel too confined to the box when travelling. We

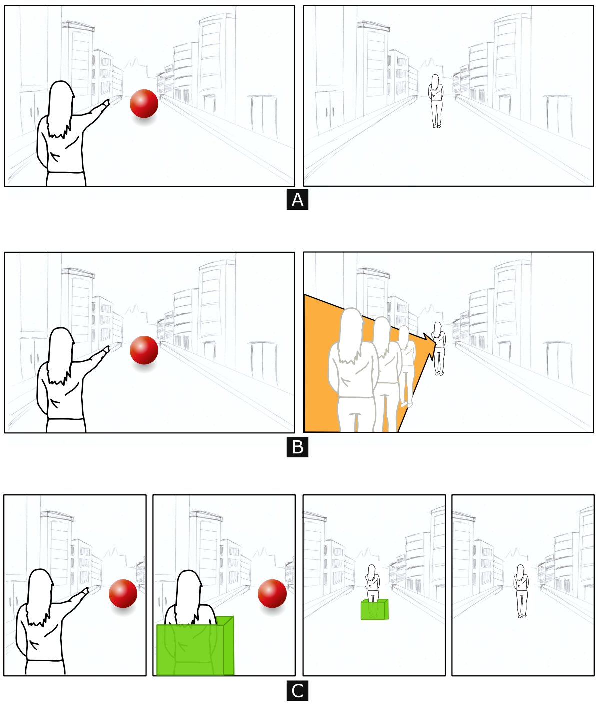

Figure 1: Travel techniques: A) Teleport; B) Linear Motion; C) Animated Teleport Box.

Figure 2: Virtual Environment.

employ the elevator metaphor, with the intention of not showing the users that they were being moved and as a means of decreasing the disorientation that might be felt after being teleported, as depicted in Figure 1C.

3.1. Task Design

To validate the techniques described above, we completed a user evaluation. Our aim was to understand which of the techniques were preferred by the users, and also the amount of impact that each had on users. The virtual environment was a model of the city of Osaka, Japan (Figure 2), which was populated with six coloured spherical checkpoints to where the users would be travelling to.

3.2. Setup and Prototype

In our experiment we used a Samsung GearVR head-mounted display. The Samsung GearVR has 96 degrees of field of view and is composed by a Samsung Galaxy S7 smartphone which has a resolution of 2560x1440 pixels and a refresh rate of 60 Hz. Thus, featuring motion sensors in a form of a gyroscope and a accelerometer to allow its user to move the head with 3 degrees of freedom inside the VE.

Figure 3: Participant of the experiment.

Twenty participants completed the user evaluation, two of them were females. The participants' age ranged from 19 to 31 years old, with a mean of 24. Seven of the participants already had previous experience with virtual reality visualisation (Figure 3).

3.3. Methodology

Each user evaluation session adopted the same protocol, starting the initial briefing with a quick explanation to the experiment and also with a description of the techniques. To avoid biased results from users becoming familiarised with the techniques and used to the environment, the techniques were presented in a partial random order, so all permutations were exhausted.

During each travel, the users were told where the next checkpoint would be (to their left or right) and were also instructed to point to said checkpoint before travelling using of the techniques. We gave this instruction to ascertain if users lost their frame of reference to the checkpoint they were pointing to. The users had no control over the path they would take, and would only be in charge of pointing to the checkpoints. We allowed the users an adjustment period to the environment of one minute, before travelling to the first checkpoint, to make sure they knew where they were and where they were being moved to. Each session took on average thirty minutes, which ended with a brief questionnaire about their experience.

3.4. Results and Discussion

We present the main observations made during the evaluation sessions, as well as the difficulties and suggestions given by users. Additionally we discuss the analysis and the results obtained.

We first conducted a Shapiro-Wilk to test our data for normality. Afterwards a Friedman non-parametric test was conducted to look for statistical significance between the three tested techniques. When statistical differences were found, we conducted a Wilcoxon Signed-Ranks Test to look for statistical significance on each pair of techniques with the Bonferroni correction. For a better comparison regarding task performance, we subtracted the animation times from the total time following the formula: $T' = T - \alpha \times (n-1)$, where T is the total time, α the path time (3 seconds in the animated box, 2 on the linear motion, and zero on the teleport) and n the number of travels (6 in our case). This represents the recovery time that users needed after each travel. Figure 4 shows both the total time of each travel and the recovery time needed by users after each travel. By looking at Figure 4 we can notice a slightly better performance on the Animated Teleportation Box technique, but without statistical significance. Because of that we can state that efficiency is similar in all the tested techniques.

Regarding questionnaires' data (Table 1) we found that users felt more physical discomfort using the Linear Motion Technique (Z=-2.699, $p < 0.01$ against Animated Teleport Box and Z=-2.386, p=0.017 against the Teleport). Despite of the discomfort caused by the Linear Motion, participants stated it as their favourite technique in most cases, Because of the similarity between user preferences on both Animated Box Teleport and Teleport we conducted an additional test on the total times of the test task. This test confirms a better result on such condition with the Teleport as it does not need additional time among the movement between positions (Z=-3.114, $p < 0.01$ between Animated Box and Z=-2.578, p=0.01 against Linear Motion).

4. Proposed Technique: PRECIOUS

PRECIOUS combines cone casting and progressive refinement to provide a quick and accurate selection technique (Figure 5). The cone volume is used to select the objects in the scene. By pointing in the direction of an object and closing their hand, the users can then open his hand to select the objects are fall inside the cone. The size and aperture of the cone can also be changed. We incorporate progressive refinement in our technique when the user makes a selection and three or more objects are inside the cone. We studied three travel techniques in VR and from the results of this test, we chose to use the Teleport technique (also called infinite velocity).

To help users better understand which objects are inside the cone volume, their bounding boxes are shown as a partially visible green cube. While maintaining the hand closed, the user is able to modify the cone. To execute a selection action, the user has two choices: single or multiple object selection. To perform a single object selection the user simply opens his hand. On the other hand, if a multiple

	Animated Teleport Box	Linear Motion	Teleport
Easiness	5 (1)	5 (1)	5 (1)
Satisfaction	4 (2)	4.5 (2)	4 (2)
Physical discomfort*	1 (1)	2 (3)	1 (1)
Visual discomfort	1 (1)	2 (2)	1 (1)

Table 1: User preferences: Median (Interquartile Range). * indicates statistical significance.

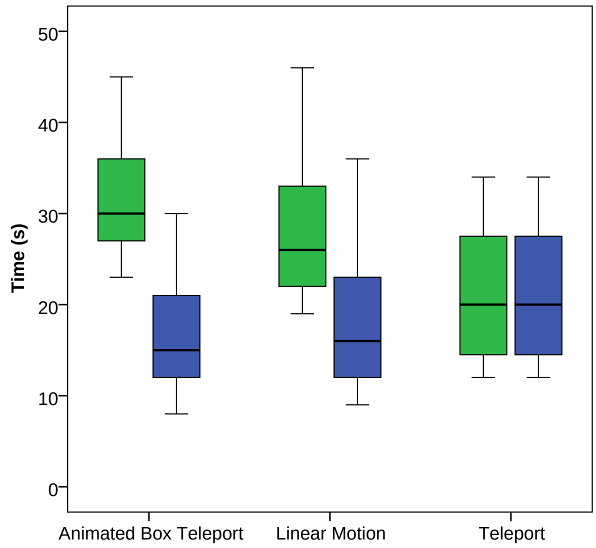

Figure 4: Box-plot representing the time elapsed on each task. Green box-plots represent total time, and blue the time excluding techniques' animations.

section is to be performed, the user has to close his hand with more pressure. In the following sections we describe in greater detail how the selection process works on PRECIOUS.

5. PRECIOUS Validation

To validate our technique we compared it against two techniques from the literature, Stretch Go-Go [12] and Spotlight [9]. We implemented these technique in our prototype as they provide a good baseline for the tests,as they are adequate for out-of-reach selection and capable of infinite reach.

The Stretch Go-Go technique was developed as a means to overcome the limitations of the Go-Go technique [12]. In the latter, the reach of the virtual hand in the virtual environment was limited by the length of the user's arm. The Stretch Go-Go technique allows infinite stretching of the virtual hand using only arm motion for control, so that all objects in the environments can be reached. The space around the user is divided into three concentric regions. The user's natural hand position is considered to be in the middle region. As users stretch their hand outside into the outermost region, the arm begins to grow at a constant speed in that direction. When the arm is moved to the innermost region, the arm retreats at that speed. In the middle region, the arm length remains the same. By mapping the position of the physical hand to the virtual hand velocity, any arm length can be achieved. To aid the user, a gauge is shown which indicates the current region and the proximity of other regions (Figure 6 Left).

The Spotlight technique was intended to overcome the main issue of ray-casting, which is low accuracy when targeting objects that are out-of-reach from the user [9]. The technique employs a method called "spotlight selection" in order to make the selection softer than a mathematical ray, so that some error was tolerated when aiming. A bat was used as a prop when using the selection volume. A selection cone is first established with its apex at the bat and its axis at the X-axis of the bat. Objects that fall inside the cone are candidates for selection. When more than one object is inside the cone an anisotropic distance metric is calculated as a disambiguation mechanism. If two objects are at equal Euclidean distance from the bat, the closest to the center line of the cone is selected. If otherwise the two objects produce the same angle at the bat with the center line, the object with the smaller Euclidean distance is selected. Figure 6 (Right) shows the visual feedback given by the Spotlight technique. Users can see which objects are candidates for selection as their bounding box be shown as a partially visible green parallelepiped.

5.1. Tasks

Participants were requested to complete four tasks for each technique. They all consisted of selecting a cactus in our virtual environment (Figure 7). With the exception of the buildings that composed the environment, all objects were selectable. In order to avoid long session times, we restricted the duration of each task to three minutes. If participants reach the time limit they would be informed they could stop, and we took this as an unsuccessful attempt.

The tasks were designed to be increasingly difficult, as the cactus would be placed further away from the users initial position or surrounded by more objects. Every time users selected an object that was not the cactus, we would log it as an incorrect selection.

5.2. Setup and Prototype

The setup used in our user evaluation is comprised of several non-evasive and affordable tracking hardware. We are able to capture the rotation of the users hand and head, as well as the position of the body.

For hand rotation tracking we use an IMUduino, a custom hardware that includes an IMU and Bluetooth LE modules. The device is placed in the users hand using an acrylic clip. It also gives user control over 3 DOF for hand rotation and features a pressure pad, which can detect if the hand is open or closed. This pressure pad is also able to distinguish two pressure levels when being pressed. These pressure levels allowed us to separate what operation the user wanted to perform. The device communicates with a standalone script that sends the data

Figure 5: PRECIOUS - Selection technique for out-of-reach objects. A) Cone intersecting various objects. B) Refinement. C) Single objet selection. D) Final phase with an object selected.

over Wi-Fi to our head-mounted display.

For body position tracking we use three Kinect V2 depth cameras. Each Kinect camera is connected to a computer which analyses the data regarding 12 joints of the users skeleton. We also apply a double exponential smoothing filter[3], to try and hinder the jitter and noise from the data received. This data is then forwarded to our centralised unit, where these joints positions are converted into joint rotations, and then delivered to the Samsung Gear VR head-mounted display using Wi-Fi.

For head tracking we use a Samsung GearVR head-mounted display. On a first evaluation a Samsung Galaxy S7 smartphone was used, but given the problems that arose when using the IMUduino in conjunction with the tracking data from the Kinects', we chose to use a Samsung Galaxy S6 smartphone. It gives the user 96 degrees of field of view and is composed by a smartphone which has a resolution of 2560x1440 pixels and a refresh rate of 60 Hz. Thus, featuring motion sensors in a form of a gyroscope and a accelerometer to allow its user to move the head with 3 degrees of freedom inside the VE.

The Samsung Gear VR also served as a calibration instrument. The user was instructed to raise his left hand above his head and touch the pressure button located on the right side of the device with his right hand. When this action was performed, our Body position tracking unit would know which person in the room was the user.

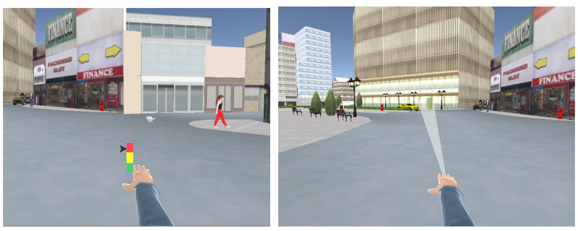

Figure 6: Left: Stretch Go-Go Technique. Right: Spotlight technique.

[3]Skeletal Joint Smoothing White Paper: `http://msdn.microsoft.com/en-us/library/jj131429.aspx`, last visited 17th October 2016.

5.3. Apparatus and Participants

The experiment was carried out in our laboratory in a controlled environment, using the setup specified in the previous section. In this evaluation we had a total of 18 participants (2 female), with ages between 18 and 40 years old with the majority (62%) being between 18 and 25. The majority held at least a Bachelor degree (62%). When asked if they had ever experience virtual reality, 39% said that they never had, and only 28% of users said that never used a gesture recognition system, such as the Microsoft Kinect or the Wii Remote.

5.4. Evaluation

A user study was conducted to properly evaluate the quality of the approach developed against those from the literature.

During the experiment we gathered objective data, with the use of a logs of each task and subjective data in the form of questionnaires. The logs registered information regarding the completion time for each task and the number of incorrect selection made. Additionally, we also calculated the success rate for each user evaluation, and would consider it a failed test if the user exceeded the time limit. The first test we performed was the Shapiro-Wilk test, to ascertain the normality of the data. A repeated measures ANOVA test with a Greenhouse-Geisser correction was then carried out to find significant differences in normal distributed data. We used this test for three out of the four tasks. Additional Friedman non-parametric tests with Wilcoxon Signed-Ranks post-hoc tests were also conducted. In both the ANOVA and the Friedman non-parametric tests post-hoc tests used Bonferroni correction (corrected sig. = sig x 3).

5.4.1 Objective Data

We measured the total time that participants took on each task, as well as the number of incorrect selections made. The time was taken in seconds and is depicted in Figure 8. We also registered the number

(a) Task 1

(b) Task 2

(c) Task 3

(d) Task 4

Figure 7: Tasks performed by the participants.

of incorrect selections, described in Table 2. The success rate of the techniques was also analysed, and is detailed in Figure 9

We found statistical significance in the completion time of all tasks (Task 1: $\chi^2(2)$=17,375, p<.0005; Task 2: F(1.013,8.102)=18.327, p=.003; Task 3: $\chi^2(2)$=19, p<.0005; Task 4: t(9)=-3.802, p=.004). In regards to the number of incorrect selections, we found statistical significance only in Task 4: $\chi^2(2)$=25.064, p<.0005.

When comparing the completion times in the first task, post-hoc test showed that the Spotlight approach (avg=10s) was faster than both PRECIOUS (avg=18s, Z=-2.430, p=.045) and Stretch Go-Go (avg=63s, Z=-3.479, p=.003) and PRECIOUS to be faster than Stretch Go-Go (Z=-3.574, p<.0005).

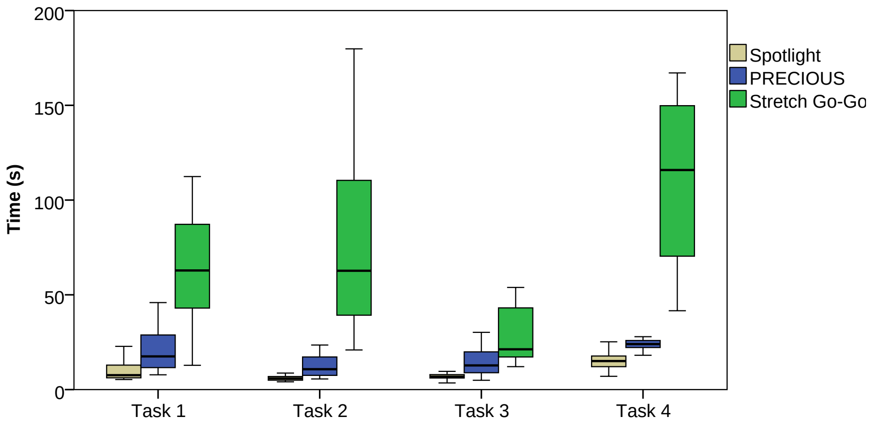

Figure 8: Completion time of the four tasks using the three techniques, in seconds. The graphic presents the median, first and third inter quartile ranges (boxes) and 95% confidence interval (whiskers).

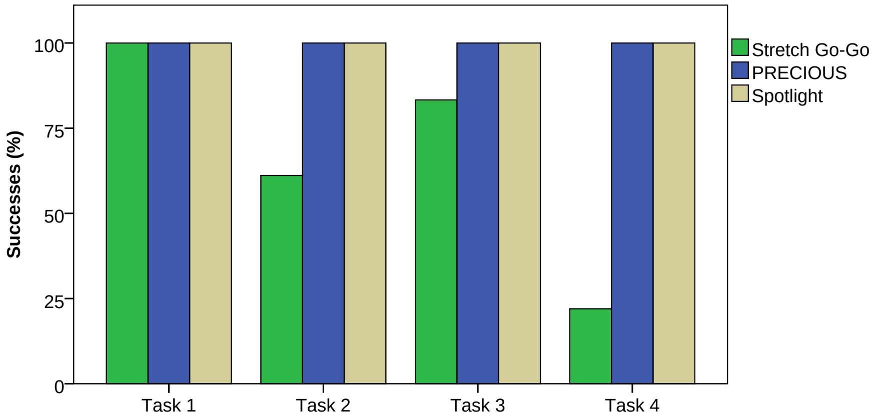

Figure 9: Success rate for the four tasks using the three techniques, in seconds. The graphic presents the median, first and third inter quartile ranges (boxes) and 95% confidence interval (whiskers).

For the second task, Spotlight was also faster than other two approaches, PRECIOUS (avg=11s, Z=-2.926, p=.009) and Stretch Go-Go (avg=63s, Z=-2.666, p=.024). This tasks reveals the flaws associated to the Stretch Go-Go technique, as the object was positioned further away from the user, the success rate dropped to 61.1%.

In the third task, the Spotlight (avg=7s) was faster than PRECIOUS (avg=11s, Z=-3.030, p=.006) and also Stretch Go-Go (avg=21s, Z=-3.296, p=.003). As expected, when the object is moved closer to the user the success rate of Stretch Go-Go increased to 83.3%.

On task number four, the Spotlight approach (15s) was also the faster than PRECIOUS (avg=24s, Z=-3.21, p=.003) and Stretch Go-Go (avg=115s, Z=-3.317, p=.003). To analyse this task we had to conduct a Paired T-Test, as there were insufficient data from Stretch Go-Go for a Friedman test. This task also reveals that when objects are to close together some incorrect selections occur when using the Spotlight technique. In this task the success rate of Stretch Go-Go is very inferior to the other techniques and there were only 4 participants that were able to complete this task before the time limit was met.

5.4.2 Subjective Data

On the questionnaires users were asked about their experience with each technique. They were asked about the difficulty of the techniques, the fun factor, if they felt tired and if there was any discomfort. Additionally they were asked if the control of the cone in the Spotlight and PRECIOUS was difficult, and if controlling the virtual hand in Stretch Go-Go was easy or not. The questions were asked in the form of a Likert Scale from to 1 to 5, 5 being the favourable value, and the answers are depicted in Table 3. Both the Median and the Inter quartile Range are represented in the table.

When analysing the results from the questionnaires, we identified significant differences in ease of use ($\chi^2(2)$=23.524, p<.0005), fun factor ($\chi^2(2)$=27.180, p<.0005), fatigue felt ($\chi^2(2)$=18.582, p<.0005) and the discomfort felt ($\chi^2(2)$=22.189, p<.0005). Participants heavily recognise that Stretch Go-Go was harder to use (Spotlight: Z=-3,673, p<.0005, PRECIOUS: Z=-3,556, p<.0005), also less fun (Spotlight: Z=-3,660, p<.0005, PRECIOUS: Z=-3.572, p<.0005), more tiring (PRECIOUS: Z=-3.441, p=.003) and more discomforting (Spotlight: Z=-3.342, p=.003, PRECIOUS: Z=-3.475, p=.003).

In regards to the questions about the difficulty of using the cone in the Spotlight technique, participants responded positively ($\bar{x}$ = 4, iqr=1). When questioned about the easiness of controlling the virtual hand, the answers corroborated the previous results ($\bar{x}$ = 1.5, iqr=2). When answering the questions regarding PRECIOUS' cone, users did not give important significance to the control of the aperture ($\bar{x}$ = 3, iqr=1). Controlling the reach of the cone was answered affirmatively by most users ($\bar{x}$ = 4, iqr=2). The teleport technique used to move the users in each test was answered positively ($\bar{x}$ = 5, iqr=0).

5.5. Discussion

It is observable that Stretch Go-Go is an ineffective approach when objects are out of the users reach. The time it takes to stretch the virtual hand plays an important part in the success rate of this technique, as when users missed the object they needed to adjust the position of the virtual hand. In the final task is where this is more evident, as the object is placed further away from the user where controlling the virtual hand becomes impractical.

Each task had an increasing level of difficulty, as the object would either be placed further away from the user (Task 2 and 4) or closer to other objects in environment, making it harder to perform a selection without errors (Task 3 and 4). Adding the data regarding the number of incorrect selection we can assert that even though the Spotlight approach is faster, it is more prone to errors when the difficulty of the task increases. Throughout all tasks Spotlight shows that it is the faster technique, even though some selection errors are present when the difficulty of the task increases. In some selections tasks, having an unwanted selection can have a great impact on the results.

All the objects in the environment had a box collider as their bounding box. Some comments by users were made in this regard, as some objects' bounding box was larger than their model, which could have had some impact in the tasks.

The complexity of PRECIOUS, mainly the need to increase and decrease the reach of the cone, had an impact in the completion time. We consider that the combination of progressive refinement with cone selection to be a superior technique, but the added difficulty of controlling the reach and the aperture of the cone pose a greater handicap than previously though. We can also attribute a higher completion time to the refinement process chosen. Using another approach, as those introduced by Bacim et al. [2] could lead to a decrease in these times.

6. Conclusions

The task of selecting an object is present in our everyday life. From desktop interfaces to virtual environments, there is a need to select an object before changing it in any way. With the recent research in the new, more affordable hardware, there is a greater interest in exploring approaches for object interaction in virtual environments.

When considering the current approaches for object selection in immersive virtual environments, few tackle the problem of selecting objects at great distances. The most common approaches of ray-casting and arm-extension suffer from jitter problems when the intended object is too far from the position of the user. Volume selection techniques on the other hand can more effectively deal with this problem, but when the environment is cluttered some unwanted selections may occur.

Technique	Task 1	Task 2	Task 3	Task 4
Stretch Go-Go	0 (0)	0 (0)	0 (0)	0 (0)
Spotlight	0 (0)	0 (0)	0 (0)	1.5 (3)
PRECIOUS	0 (0)	0 (0)	0 (0)	0 (1)

Table 2: Number of incorrect selections: Median (Inter quartile Range).

To deal with these problems, we developed PRECIOUS, a combination of progressive refinement and cone casting that allows users to select objects at various distances. To incorporate progressive refinement in our selection process, by allowing the user to select more than one object using the cone volume, and then refine his selection with those fewer objects. We moved the user in the virtual environment using Teleport, a travel technique for virtual reality [5]. This technique was chosen based on an evaluation conducted, with the objective of determining the optimal way to move a user in a virtual environment.

A formal user evaluation was then conducted, where PRECIOUS was compared with two other selection techniques. With the results from this evaluation we determined that Stretch Go-Go is an impractical technique when selecting objects that are very distant from the user (further than the size of a room). On the other hand we leaned that the Spotlight technique can provide faster completion times on standard selection tasks, but when the environment is not sparse it is prone to incorrect selections. Regarding PRECIOUS we can state that, even though it was not the fastest of the three techniques, the lack of errors and the uniform completion times across all scenarios tested, make it a suitable technique to select objects out-of-reach.

6.1. Future Work

In this work there were some aspects that can be considered worthy of improvements or alternatively can originate future work:

From the results of the user evaluation, a possible next stage could be adjusting the type of control on the selection cone. Either removing the control over the reach of the cone, and having its reach be infinite, or by fine tuning the aperture of the cone.

The Stretch Go-Go technique is not efficient when the selections involved distant objects. Some improvements can be made to overcome this, such as changing the virtual hand and adopting a spherical volume that scales the further it is from the user. Changing the direction vector used and the approach used to bring the hand closer and further away from the user can also be done to arrive at a faster and more reliable technique.

We combined cone casting and progressive refinement for the first time in virtual reality. There are different progress refinement techniques that can be explored [2].

A natural next step is combining PRECIOUS with a manipulation approach. This would create an all around approach for object manipulation at any distance.

	Stretch Go-Go	Spotlight	PRECIOUS
Easiness *	1 (1)	4.5 (1)	4 (1)
Satisfaction *	2 (1)	5 (1)	4 (1)
Physical discomfort *	2.5 (2)	5 (1)	5 (1)
Visual discomfort *	3 (1)	5 (1)	5 (1)

Table 3: User preferences: Median (Inter quartile Range). * indicates statistical significance.

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