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Design and evaluation of a novel out-of-reach selection technique for VR using iterative refinement

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ABSTRACT

In interactive systems, the ability to select virtual objects is essential. In immersive virtual environments, object selection is usually done at arm's length in mid-air by directly intersecting the desired object with the user's hand. However, selecting objects outside user's arm-reach still poses significant challenges, which direct approaches fail to address. Techniques proposed to overcome such limitations often follow an arm-extension metaphor or favor selection volumes combined with ray-casting. Nonetheless, while these approaches work for room sized environments, they hardly scale up to larger scenarios with many objects. In this paper, we introduce a new taxonomy to classify existing selection techniques. In its wake, we propose PRECIOUS, a novel mid-air technique for selecting out-of-reach objects, featuring iterative refinement in Virtual Reality, an hitherto untried approach in this context. While comparable techniques have been developed for non-stereo and non-immersive environments, these are not suitable to Immersive Virtual Reality. Our technique is the first to employ an iterative progressive refinement in such settings. It uses cone-casting to select multiple objects and moves the user closer to them in each refinement step, to allow accurate selection of the desired target. A user evaluation showed that PRECIOUS compares favorably against state-of-the-art approaches. Indeed, our results indicate that PRECIOUS is a versatile approach to out-of-reach target acquisition, combining accurate selection with consistent task completion times across different scenarios.

1. Introduction

Identifying an object to which we want to refer is a fundamental task in our everyday life. When interacting in virtual environments, object identification is essential, so that the system can understand which virtual object should users' actions be applied to. Indeed, every action performed on a virtual object can be decomposed into three stages: selection, manipulation and release [1]. Here, we focus on the first. Object selection is traditionally done in WIMP-based interfaces by placing the cursor on top of the object and clicking, or, more recently, by directly touching it on an interactive surface. In virtual environments that support mid-air hand tracking, object selection is usually performed by intersecting the object with the hand or a representative virtual cursor. As expected, this approach is not suited for cases where the desired object is placed outside arms-reach.

To overcome physical constraints, arm-extension techniques allow users to select out-of-reach objects. A different approach, which requires less physical movements and thus causing less fatigue, consists in pointing using ray-casting. Yet, with this approach, the more distant the object is, the lesser accuracy users have, since a small hand tremor or tracker jitter can drastically move the ray away from the desired object. Techniques where the ray is exchanged with a cone have been proposed to reduce this effect, increasing the selection space. Nevertheless, they still have drawbacks: if the aperture of the cone is too small the same problem of the ray arises, and if it is too big several objects will be intersected, requiring disambiguation techniques.

Selection techniques that improve upon ray or volume casting have been proposed to interact with large scale displays. For instance, with iterative progressive refinement users can select a group of objects, which are then shown in smaller groups on the screen. The user can repeatedly select one of the smaller groups until there is only one object left. As an alternative, zoom techniques can make objects appear closer, easing selection tasks. However, these techniques cannot be naively used in immersive

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virtual environments (IVEs): such kind of refinement might disrupt user immersion, and zoom approaches can cause discomfort.

In this paper, following recent developments that made Virtual Reality (VR) technologies more reliable, affordable and widespread, we focus on the challenge of selecting out-of-reach objects in IVEs. Building upon the state-of-the-art, we propose a new taxonomy for techniques' reach and progressive refinement approach regarding the nature of the disambiguation process. This process can be continuous or composed by single or multiple iterative discrete steps. With open challenges identified, we propose PRECIOUS, a novel approach that offers iterative progressive refinement in VR as a mean for accurate and time consistent selection of far placed objects. We allow the user to select groups of objects using a cone-casting approach, then we instantaneously move the user closer to the objects. This process can be iteratively repeated, until the user can select the desired object at ease.

2. Related work

Object selection in virtual environments has been subject of research for long. Argelaguet and Andujar made a thorough survey regarding that topic [2]. Here, we will only refer the more relevant works for our paper. To discuss them, we created a new taxonomy that clarifies some selection properties.

Our taxonomy, illustrated in Fig. 1, complements those proposed by Bowman and Hodges [1], Poupyrev and Ichikawa [3] and Kopper et al. [4]. The first [1] classifies the feedback given, how to indicate the object and how to confirm the selection. The second [3] classifies techniques according to interaction metaphors, while the latter [4] classifies the progressive refinement strategy. Our taxonomy focuses instead on cardinality, i.e. the number of objects selected, reach and offers a new nomenclature to the strategy followed for the progressive refinement.

Techniques that can only select one object are classified as having Single Cardinality. On the other hand, those that are capable of selecting multiple objects, are referred to as having Multiple Cardinality. The latter can be further decomposed into Serial and Parallel [5].

2.1. Selection reach

Reach represents how far from the user the object selection can be done. Techniques where the environment is displayed in a traditional non-stereo screen are classified as Screen-Space. These approaches allow users to select a point on the screen and the object portrayed in such position will be selected, independently of how far it is. An example of this is the eyeball in hand technique [6], where the user controls a virtual camera which is viewed in a 2d display allowing also screen-space selection. This metaphor can also be used on multitouch displays where the selection is made by directly touching the object of interest using one or more fingers [7].

Arm-length refers to techniques where the length of the users arm limits where the user can reach objects for selection. Mendes et al. [8], for instance, propose and evaluate a set of techniques to directly interact with objects in mid-air using a stereoscopic tabletop.

Techniques that are classified as Scaled are the ones where the extent of users' reach is greater than its arms length, but can not reach infinite. Scaling effect is usually achieved by using an anisomorphic control-display ratio [2]. An example of this are arm-extension techniques such as the Go-Go technique [9], where the reach of the virtual hand is interactively modified when the user goes beyond a certain threshold distance. Both Prism + Go-Go [10] and the Scaled HOMER [11] improve the Go-Go technique by increasing precision when interacting with objects. In World in Miniature [12], users have access to all objects in the 3D environment. Users control a miniature copy of the environment and can select objects from this representation within arms reach. Even though the whole environment is available, there is a limit to its size, so we consider this techniques' reach as scaled.

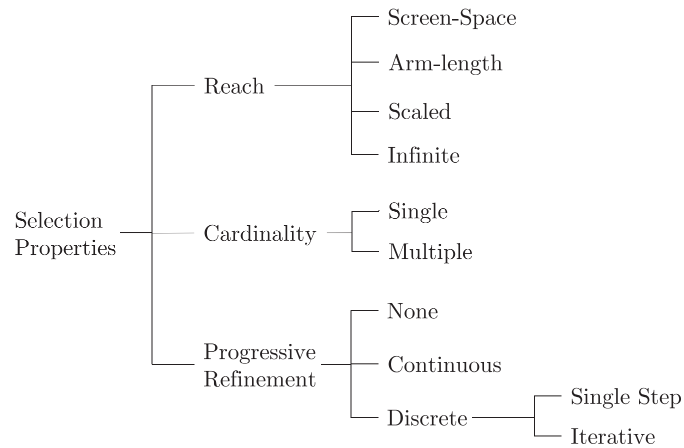


Fig. 1. Our taxonomy of selection techniques' properties.

Infinite reach classify techniques where there is no limit to where objects can be so that users are able to select them. A common example of this is the ray-casting technique where the selection of objects are made through the intersection with the object and a mathematical ray. The Vacuum technique [13] improves ray-casting by using 2D input to select one or multiple objects using a 2D cone in a tabletop. The Stretch Go-Go [14] technique improves on the previously mentioned Go-Go, by being able to extend the virtual arm until infinite.

2.2. Progressive refinement

In some cases, the selection can be imprecise and lead to an undesired selection of multiple objects. This can be overcame by using a Progressive Refinement strategy in the selection process. Progressive refinement was first introduced by Kopper et al. [4] and refers to the process of gradually reducing the amount of selectable objects among a larger group. This strategy is divided in two phases: the first, which defines the group of interest and the second, which consists in disambiguating between the objects within the group by selecting fewer objects. The progressive refinement strategy can be done by a continuous process (Continuous) or by one (Discrete, Single Step) or many discrete refinement operations (Discrete, Iterative).

An example of a Continuous Progressive Refinement in Screen-Space is Zoom [15] where a zoom operation is performed on a specific region of the environment. This metaphor is expanded on the Continuous Zoom [16] technique, where the scene is zoomed in until the target is large enough for selection. Another work that uses the continuous progressive refinement strategy is the Intent-Driven Selection (IDS) [17]. This arms-length technique uses scalable spheres, which are continuously refined until the desired object is selected.

Other examples of continuous techniques are those based on ray-casting [18] and cone-casting [19]. Lock Ray and Depth Ray [18], improve ray-casting selection by using forward and backward hand movements to disambiguate between the intersected objects. In Lock Ray these operations are performed in sequence, while in Depth Ray they are performed simultaneously. The shadow cone-casting [19] uses a cone for selection of multiple objects, but for disambiguation the origin of the cone must be moved, while maintaining the desired objects inside the cone. The disambiguation is based on proximity to the origin of the cone.

Flashlight [20] also uses a cone to select the group of objects, but uses a single step discrete automatic refinement based on the object proximity to the origin of the cone. The Aperture and Orientation technique [21] improves the Flashlight by using a re-scalable cone originated at the eye of the user as a bounding volume and uses the proximity to cone origin and selectable objects' rotation as disambiguation parameters. The EiHCam [22] uses an extra-camera attached to a tracked tablet in an immersive environment,which is represented by a truncated-pyramid in the VE, which can be scaled with a pinch-gesture. The disambiguation is done by a single discrete step, using the rendered image of the virtual camera with a screen-space metaphor on the tablet screen. The Disambiguation Canvas [23] uses a mobile device to select objects in highly cluttered scenes. This process is composed by sphere-casting using the device sensors and the second using a representation of the touch screen in the IVE to select multiple objects in a single discrete step.

The SQUAD technique [4] on the other hand uses several discrete steps to iteratively select an object within a group of interest. This technique uses a first phase where users cast a sphere to specify a volume containing the target object. Users may then disambiguate the selection in one or more phases using a menu that distributes the objects in four groups based on their characteristics. The Discrete Zoom [16] works similarly to the Continuous Zoom, but uses instead several discrete operations. These operations consist in dividing the screen in four quadrants and expanding the selected quadrant until the object of interest is large enough for selection. The Expand technique uses a similar approach to SQUAD but using virtual grids which are iteratively rearranged until the desired object is selected. Regarding efficiency, Continuous Zoom [16] technique provided better selection times when compared to Discrete Zoom, SQUAD and ray-casting. Both Zoom and Expand techniques [15] also perform better than the standard ray-casting and SQUAD techniques, but focus on dense environments. The Expand technique also provided better selection times than the Zoom.

Despite the various studies on object selection, objects further away than room-sized distances still pose some challenges. Progressive Refinement techniques often favor closer objects either rearranging them [4,15] or automatically refining selection based on proximity [18,21], which might not be feasible for selecting far-away objects. Also, these category of techniques employ menus [4] or FoV-diminishing metaphors [16], and were developed for non-immersive and non-stereoscopic scenarios. Thus, they may not be suited for VR as menus might disrupt immersion and “small FOVs may lead to cybersickness” [24]. In this matter, there are few works that employ progressive refinement in VR, but they resort to additional interactive surfaces which may also lead to reduced immersion [25]. The Disambiguation Canvas solves this by representing the touches on a mobile phone screen on the Immersive Virtual Environment [23] to disambiguate between objects. However, they do not support selection of far-away objects. In this work we propose a new technique that uses natural pointing gestures for selecting out-of-reach objects in VR, resorting to an Iterative Progressive Refinement approach.

3. PRECIOUS

In order to support an Iterative Progressive Refinement strategy in VR for out-of-reach object selection, we developed PRECIOUS (Progressive REfinement using Cone-casting in Immersive virtual environments for OUt-of-reach object Selection), illustrated in Fig. 2. It offers Infinite Reach, using an egocentric virtual pointer metaphor [3]. We use a cone as a selection volume, casted from users' hand. While pointing, users can make the cone aperture wider or smaller, and change the cone's reach. Objects that fall inside the cone will be selected. Users are then moved closer to the selected objects for a more accurate selection. As such, this can be considered as a possible VR implementation of Discrete Zoom [16], although we modify users' position instead of the FoV. This process is repeated until a single object is selected or, if users desire, can be stopped at any time to select a group of objects, supporting both Single and Multiple Cardinality.

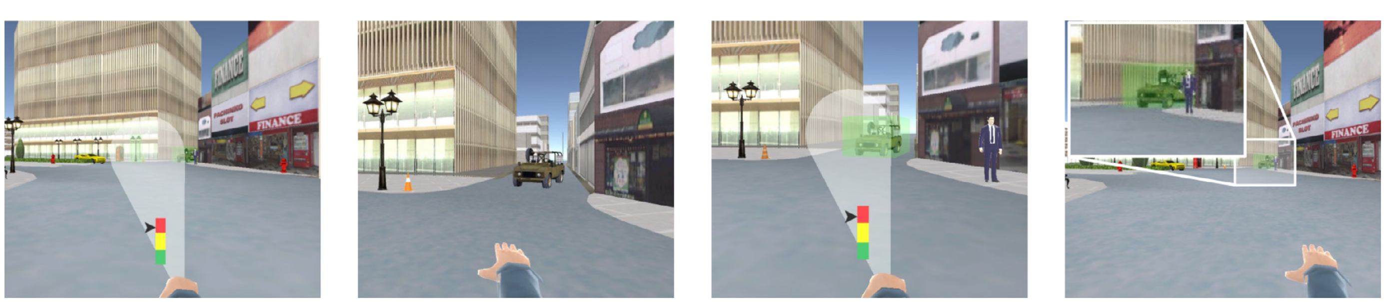
To help users better understand which objects are inside the cone volume, our approach highlights them showing their bounding boxes as semi-transparent green cubes. In the following sections we detail how the selection process can be performed with PRECIOUS. We first describe how the cone can be manipulated, then we specify how the progressive refinement works, and how users can select multiple objects simultaneously.

3.1. Selection volume manipulation

To define the selection volume, we resorted to a flashlight metaphor [20]. We cast a cone from users' dominant hand, which is used as a selection volume. The orientation of the hand defines the direction of the cone. We also offer two modifications users can perform on the cone: the first is to control its aperture and the second is to change its reach.

3.1.1. Aperture

While the Aperture Selection technique [21] allows users to change cone's aperture by moving their hand backwards and forwards, we use instead the rotation of the users wrist (Fig. 3). This is because the origin of PRECIOUS' cone is placed in users hand and not in users' eye point. The initial aperture is 11 degrees. When the wrist is rotated clockwise, the aperture of the cone increases until the opening angle reaches 15 degrees. Analogously, if rotated in the opposite direction, the aperture will decrease until a 7 degrees angle is achieved.



(a) (b) (c) (d)

Fig. 2. PRECIOUS technique: (a) selection cone intersecting various objects, (b) refinement phase, moving the user closer to the objects, (c) single object selection, (d) returning to the original position with the object selected.

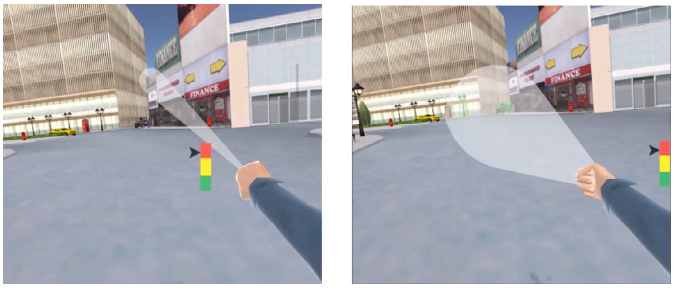


Fig. 3. Controlling the aperture of the cone.

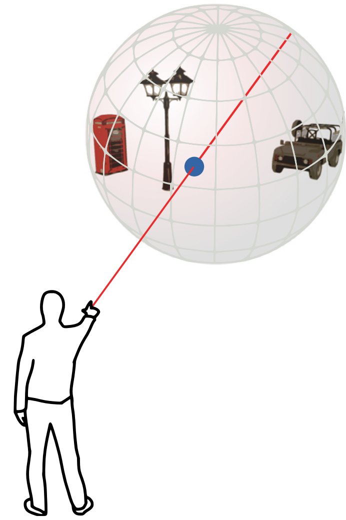


Fig. 5. Refinement process: the blue dot represents where the ray intersects the sphere, and defines next user position. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

3.1.2. Reach

To manipulate cone's reach, we adopted a similar approach to the used on Stretch Go-Go [14] to control users' virtual hand. As such, we define three spherical regions around the user (Fig. 4), but we center them in the hip side corresponding to the dominant hand. When users extend their hand into the outermost region (more than 50 cm from the shoulder), the cone will stretch in the pointed direction at a rate of 5 m/s. Placing the hand in the innermost region (less than 30 cm), will make the cone decrease in size with the same speed. While the hand is placed in the middle region (from 30 to 50 cm), the cone's reach remains unchanged.

To help users understand in which region their hand current is, we show a widget when the cone is active. The widget shows the three regions with an arrow pointing towards the one currently active, also depicted in Fig. 3. Differently from Stretch Go-Go, we use a diegetic UI showing this widget near the users' hand. This way the widget is always visible when users are controlling the cone.

3.2. Progressive Refinement

The usage of a selection volume instead of a ray can lead to several objects being intersected by it. When this happen, a disambiguation mechanism is triggered. To give users total control over the selection, we follow an Iterative Progressive Refinement approach. In our approach, we drew inspiration from previous zoom techniques [16], but instead of changing the camera's field-of-view, we move users closer to selected objects in the virtual world.

To calculate the new users' position (Figure 5), we surround all selected objects with a sphere. This sphere is then intersected with a ray casted from users' hand similarly to the cone. The intersection point gives the position where users will be moved to. To move users we perform an instantaneous teleport action (also known as infinite velocity), which showed better results regarding user disorientation and discomfort than other animated techniques [26]. The process is repeated until two or less objects are selected.

When two objects are very close to each other, it might be difficult to manipulate the selection cone in such a way that it only intersects a single object. To prevent user frustration we made these final stages of the refinement process easier. Following a canvas disambiguation [23] approach, we place them side-by-side in front of the user, while hiding the remaining objects in the scene (Figure 6).

The object that is closer to the user is displayed first, on the left. Although an higher number of objects could be used to trigger this final step, we opted to perform it only when the cone intersects two, so that user immersion is disrupted as little as possible.

After a single object is selected, the refinement process is over and users are placed back in their starting position. The object remains selected and it is ready to have further actions applied to it.

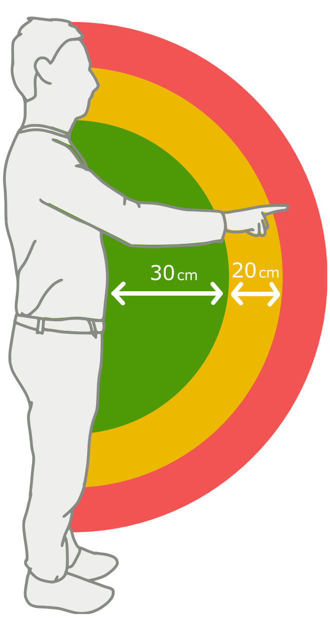


Fig. 4. Distances regions for cone's reach control.

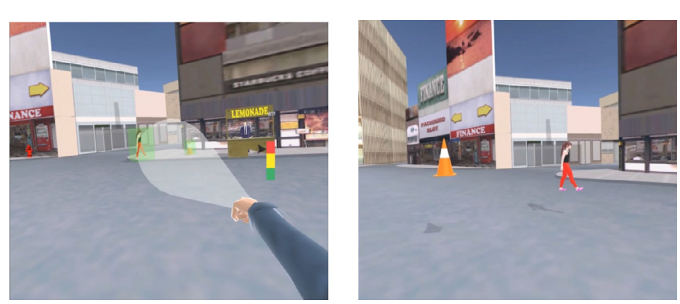


Fig. 6. Double selection process.

3.3. Multiple Object Selection

Although initially conceived for single object selection, PRECIOUS also allows multiple object selection. While pointing with the cone, several objects might be intersected. In such cases, users can either start the refinement process described above, or they can select all objects at once. In the latter case, the refinement process is promptly concluded, users return to their original position and objects are kept selected.

4. Prototype

To validate the adequacy of PRECIOUS for selecting out-of-reach objects in immersive virtual environments, we developed a prototype. In this section we will describe both the hardware components that comprise it, and the properties of the virtual environment used.

4.1. Hardware

The setup used for our prototype is composed of several components. To gather user input, we used non-invasive and affordable tracking hardware. We track users full body using three Microsoft Kinect V2 depth cameras. We also apply a double exponential smoothing filter [27] to reduce noise effects from received data.

For increased hand tracking, we use a custom Arduino based device that includes an IMU and Bluetooth LE modules. The device is placed in the users hand with an acrylic clip, that assures it does not fall when the hand is opened. It tracks 3 DOF orientation and features a pressure pad, which is used to detect if the hand is opened or closed. We start an object selection action when we detect pressure being applied. This allows users to use a natural pointing gesture, as depicted in Fig. 7. The pressure pad is also able to clearly distinguish two pressure levels. Using these pressure levels, we require users to close their hand with added pressure to trigger multiple object selection.

For the visualization component, we used a Samsung Gear VR headset with a Samsung Galaxy S6 smartphone. This headset tracks head orientation with 3 DOF. This data is combined with depth cameras' information to fully track users point of view with 6 DOF. Communication between tracking hardware and the headset is done using dedicated wireless connection.

4.2. Virtual environment

We developed our prototype using the Unity 3D game engine. The virtual environment is composed by an urban scenario, which has several objects placed in a familiar fashion. We took inspiration from urban planning tasks. To explore out-of-reach selections with multiple distances, we chose to overcome the size limitation of the test room by using a virtual representation of an urban environment. For this, we resorted to a virtual replica of Osaka city, Japan. Except buildings and pavement, all objects comprised in the environment were selectable. For user representation, we used a full-body avatar, which is totally animated according to tracking information.

Fig. 7. Pointing with our custom device.

5. User evaluation

To validate PRECIOUS, we compared it against two techniques from literature: Stretch Go-Go [9], which follows an arm-extension metaphor, and Flashlight [20], that uses cone-casting and an heuristic disambiguation method for single step progressive refinement. The choice of these techniques is explained because of their out-of-reach selection and infinite selection capability.

While a panoply of other techniques exist, they are not suitable for our scenario. For instance, Aperture different weights on the disambiguation process [21], which is not always appropriate, while others require additional interactive surfaces on the disambiguation phase [25]. Others such as the SQUAD [4] VR implementation and Disambiguation Canvas [23], completely change the virtual environment, which may disrupt immersion. Techniques that perform continuous progressive refinement also present additional problems. For example: Shadow-cone [19] require users to point at the desired object from different positions, but this is difficult to do when the object is very far; Zoom techniques [16], although were developed for non-immersive and non-stereo environments, could be implemented in VR, but changing the FoV might lead to user discomfort or cybersickness.

5.1. Baseline techniques

While our technique implements an iterative progressive refinement in VR, built upon Discrete Zoom [16], both Stretch Go-Go and Flashlight, the chosen baseline techniques, follow different approaches.

Stretch Go-Go was one of the first techniques developed to overcome the physical limitations of out-of-reach selection. It uses the metaphor of extending users' arm [9], with an infinite reach. While pointing, a virtual hand is continuously moved outwards when users extend their arm, or inwards when users retract it. A gauge is shown indicating the current action being applied to the virtual hand according to users' physical hand: red when moving away from users, yellow when the distance is kept unchanged, and green when getting closer to users. When objects are intersected by the virtual hand, they can be then selected.

The Flashlight technique was developed with the intention to overcome the low accuracy of ray-casting [20]. As the name suggests, it uses a flashlight metaphor, using a cone as selection volume instead of a ray. Objects that fall inside the cone are candidates for selection. Keeping its roots in ray-casting, when more than one object are hit, the closest to a ray in the center of the cone is selected. If two or more objects have the same distance to the center ray, the object with the smaller Euclidean distance is chosen. We only highlight the object that will be selected at that time. We did not allow any modifications to the cone, as previously proposed [21], since it would require additional disambiguation mechanisms, and we want users to explicitly define which object they want to select. Cone's aperture was set to 7 degrees.

5.2. Methodology

All user evaluation sessions followed the same methodology and lasted approximately 45 min. The experiment started with a brief introduction. For each technique, we explained them and played a video illustrating how they work. Participants were then

(a) Task 1 (b) Task 2 (c) Task 3 (d) Task 4

Fig. 8. Tasks performed by the participants. The square indicates the target cactus.

given a training period of three minutes to adjust themselves to the environment and to the technique about to be tested. Afterwards, participants were instructed to perform four tasks, described in the next section. After completing these tasks for each technique, participants were asked to fill out a questionnaire about their experience. The order of the techniques followed a partial random order for each participant, so that all permutations were exhausted, to avoid biased results. In the end, participants filled out a profiling questionnaire.

5.3. Tasks

Participants were requested to complete a set of four tasks for each technique, and all consisted in selecting a cactus in our virtual environment (Fig. 8). In these tasks, we had two variables for target object positioning: distance from the user and amount of surrounding objects. For tasks where the cactus was closer to the user we used distances that can be considered to be plausible in room-sized scenarios, whereas in the tasks with the object far from the user we placed it on the other side of a large avenue. Although not exploring heavily cluttered environments as other works [4,16,23], where a lot of objects are placed together in a small space, half of our tasks in included some distractors. This way, we explored both situations where cone-casting approaches could easily select the target object alone, and others where this would be considerably more difficult, requiring refinement strategies. Tasks were designed to have an increasing difficulty.

In the first task, the cactus was next to the user, with few objects surrounding it at a considerable distance. For the second, the cactus was placed far from the user, also with few objects next to it. The third task brought the cactus back to the user once again, but increased the number of surrounding objects. Finally, the fourth task,the most difficult, the cactus was placed far from the user with other objects positioned very close to it.

Every time participants selected an object that was not the cactus, we registered it as an incorrect selection. In order to avoid an excessive session duration, we restricted the duration of each task to 3 min. If participants reached the time limit they would be informed they could stop, and we registered this as an uncompleted task.

5.4. Apparatus and participants

The experiment was carried out in our laboratory, a controlled environment, using the setup previously specified. We counted with a total of 18 participants (2 female), with ages varying between 18 and 40 years old, with the majority (62%) being between 18 and 25. More than half held at least a Bachelor degree (62%). When asked regarding previous experience in Virtual Reality, 39% reported having none. Only 28% admitted never interacted before with a mid-air gesture-based system, such as the Microsoft Kinect or the Wii Remote.

5.5. Results

During the experiment we gathered user performance data, using system logs for each task, and user preference data through questionnaires. Logs registered information regarding the completion time and the number of incorrect selections. Additionally, we calculated techniques' success rate for each task. Using the Shapiro–Wilk test, we assessed 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. Additionally, for data with such distribution, we used the Friedman non-parametric test with Wilcoxon Signed-Ranks post-hoc tests. Both with ANOVA and Friedman tests, post-hoc tests used the Bonferroni correction (corrected sig. = sig x 3).

5.5.1. Task performance

We measured the total time that participants took on each task, as well as the number of incorrect selections made. Time was registered in seconds and is depicted in Fig. 9. We also registered the number of incorrect selections, presented in Table 1. The success rate of the techniques was also analyzed.

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). We used a Paired *T*-Test for the fourth task times because there was not sufficient data from Stretch Go-Go to perform a Friedman test (only 4 participants finished the task, being too small of a sample to be tested).

When comparing the completion times in the first task, post-hoc test showed that the Flashlight approach (avg=10 s) was faster than both PRECIOUS (avg=22s, Z=−2.430, p=.045) and Stretch Go-Go (avg=44s, Z=−3.479, p=.003) and PRECIOUS to be faster than Stretch Go-Go (Z=-3.574, $p<$ .0005). In this task, all techniques achieved a 100% success rate.

For the second task, Flashlight (avg=6s) was also faster than other two approaches, PRECIOUS (avg=11 s, p=.098) and Stretch Go-Go (avg=76 s, p=.007). PRECIOUS had significantly better completion times when compared to Stretch Go-Go (p=.009). This tasks reveals the flaws associated to the Stretch Go-Go technique, as the object was positioned further away from the user and the success rate dropped to 61%, while others remained with 100%.

In the third task, Flashlight (avg=6s) was again faster than PRECIOUS (avg=13s, Z=−3.030, p=.006) and Stretch Go-Go (avg=28s, Z=-3.296, p=.003). In this task, PRECIOUS also showed better results when compared to Stretch Go-Go (Z=−2.480, p=0.039). As expected, when the object is moved closer to the user the success rate of Stretch Go-Go increased to 83%, but remaining different from the other techniques' 100%.

In the final task, Stretch Go-Go had a success rate of only 22%, making it a sample too small to be analyzed. The others continued with a perfect success rate score. This task revealed the

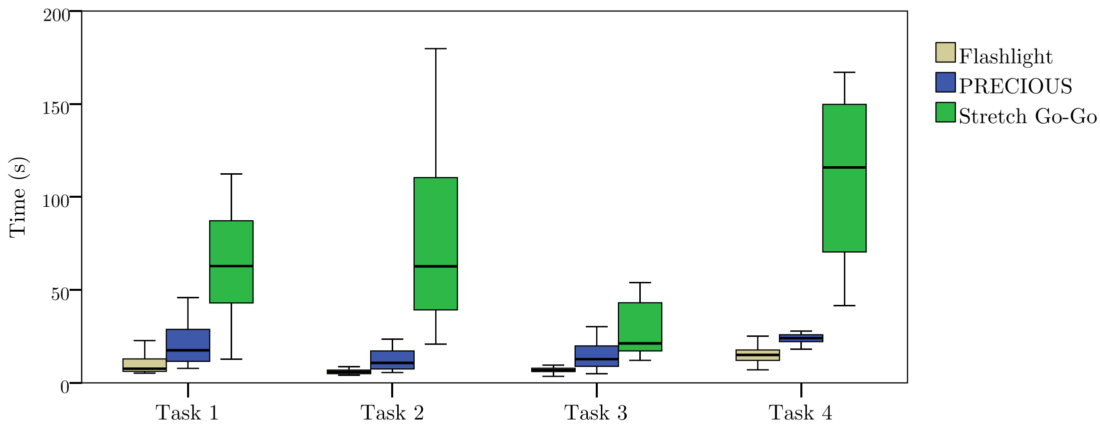


Fig. 9. Tasks' completion time. The graphic presents the median, 1st and 3rd inter-quartile ranges (boxes) and 95% confidence interval (whiskers).

Flashlight (avg=15 s) approach to be once again faster than PRECIOUS (avg=24 s). This was the only task in which significant differences in incorrect selections occurred, with Flashlight causing more errors than PRECIOUS ($Z=-3.21$, $p=.003$).

5.5.2. User Preferences

Questionnaires asked participants about their experience with each technique. They had questions regarding the difficulty of the techniques, the fun factor, if they felt tired and if there was any discomfort. Additionally they were asked about the control of the cone in the Flashlight and PRECIOUS and the virtual hand in Stretch Go-Go. We used a Likert Scale from to 1 to 5 (5 being the most favourable value), and answers are depicted in Table 2.

When analysing participants' answers, 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 ($\chi^2(2)=18.582$, $p< .0005$) and discomfort ($\chi^2(2)=22.189$, $p< .0005$) felt. Participants strongly agreed that Stretch Go-Go was the hardest to use (Flashlight: $Z=-3{,}673$, $p< .0005$, PRECIOUS: $Z=-3{,}556$, $p< .0005$), less fun (Flashlight: $Z=-3{,}660$, $p< .0005$, PRECIOUS: $Z=-3.572$, $p< .0005$), most tiring (PRECIOUS: $Z=-3.441$, $p=.003$) and most discomforting (Flashlight: Z=-3.342, $p=.003$, PRECIOUS: $Z=-3.475$, $p=.003$).

Regarding the difficulty of using the cone in the Flashlight technique, participants responded positively ($\bar{x}=4$, IQR=1). When questioned about the easiness of controlling the virtual hand, participants' answers justified previous results ($\bar{x}=1.5$, IQR=2). Regarding PRECIOUS' selection process, participants classified the control of the cone's aperture to be moderately easy ($\bar{x}=3$, IQR=1), and its reach was classified as being easy to manipulate ($\bar{x}=4$, IQR=2). The teleport technique used to move users was received very positively ($\bar{x}=5$, IQR=0).

5.6. Discussion

From our results, it is clear that Stretch Go-Go is an ineffective approach when objects are far away from users' reach. As participants pointed out, two characteristics of the technique contributed to this: when moving the virtual hand away from the user it becomes smaller until eventually is barely visible, and as it has a small selection volume, accurately place it so it intersects the desired object can take too long. The final task made this more evident, as the object is placed further away from the user and controlling the virtual hand becomes even more demanding. The impact of both these problems could be reduced by using an increased selection volume, however that would require additional disambiguation mechanisms.

Flashlight was revealed as the fastest technique in all tasks. Nevertheless, it is more prone to errors when the difficulty of the selection task increases, with half of participants committing at least two errors in the final task (max=12 errors). Depending in the application context, performing unwanted selections can have a severe impact on the outcome, by applying actions to a wrong object.

PRECIOUS, on the other hand, offers a low error selection approach (only 6 users made an incorrect selection in the last task) with a small increase in task duration. We observed that most participants did not change cone's aperture, finding the initial aperture adequate for all tasks. Participants also mentioned that they would prefer cone's reach to begin as far as Flashlight's, reducing it when only needed. Indeed, the starting short reach of PRECIOUS' cone required participants to increase it in all tasks, being the major reason why PRECIOUS was slower than Flashlight.

6. Conclusions and Future Work

The task of selecting an object is present in our everyday life. From desktop interfaces to immersive virtual environments, there is a need to select an object before interacting with it in any way. When considering the current approaches for object selection in virtual reality, few tackle the problem of selecting objects at great distances. The most common approaches of ray-casting and arm-extension severely suffer from jitter problems when the intended object is too far from users' position. Volume selection techniques, on the other hand, can deal more effectively with this problem, but when several objects are close together unwanted selections may occur.

To combat this, we proposed PRECIOUS, a combination of iterative progressive refinement and cone casting that allows users to select objects at various distances. We allow selection of more

Table 1
Number of incorrect selections: Median (IQR).

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

Table 2
User preferences: Median (IQR). * indicates statistical significance.

	Stretch Go-Go	Flashlight	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)

than one object using the cone volume, and then refining the selection with those fewer objects. A formal user evaluation was then conducted, where PRECIOUS was compared with two other out-of-reach selection techniques. With the results from this evaluation we found that Stretch Go-Go is an impractical technique when selecting objects that are very distant. The Flashlight technique can provide faster completion times on standard selection tasks, but when there are objects close to the desired one it is prone to incorrect selections. Regarding PRECIOUS, we can state that although it was not the fastest, the lack of errors and uniform completion times across all scenarios tested make it a suitable out-of-reach selection technique.

As future work, we believe that an increased starting cone's reach in PRECIOUS can significantly reduce selection times. It would be interesting to assess if that modification is enough to achieve times similar to Flashlight, while keeping the very low number of incorrect selections. Extending PRECIOUS to be better suited for heavily cluttered environments, using different or additional refinement mechanisms, it is also worth of attention. For instance, a better approach to the final refinement step could take into account the actual position of objects, and use some heuristics to determine whether a disambiguation grid should be used, instead of always showing it when two objects are selected. Finally, combining our selection with a manipulation approach for out-of-reach can create an all around technique capable of interacting with objects at any distance in VR.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.cag.2017.06.003.

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