We developed a new technique for out-of-reach selection in VR, PRECIOUS: Progressive REFINement using Cone-casting in Immersive virtual environments for OUT-of-reach object Selection, depicted in Figure 1. It offers an infinite reach, and resorts to a flashlight metaphor [8] with a cone as a selection volume, casted from users’ hand. The orientation of users’ hand defines the direction of the cone. While pointing, users can make the cone aperture wider or smaller, and change the cone’s reach. Differently from the Aperture Selection technique [5], we change cone’s aperture using users’ wrist rotation. 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. To manipulate cone’s reach we adopted a similar approach to the used on Stretch Go-Go [2] to control users’ virtual hand. As such, we define three spherical regions around the user, 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 is active, we place a widget next to users’ hands when the cone is active, which shows the three regions with an arrow pointing towards the one currently active.

The usage of a selection volume instead of a ray can lead to undesired selections. This can be overcome by using a Progressive Refinement strategy [7]. For instance, Flashlight [8], a variant of ray-casting, uses a cone instead of a ray to select a group of objects, and uses an automatic refinement based on the object proximity to the center line of the cone to choose a single object. Grossman and Balakrishnan [6] improved ray-casting by using forward and backward hand movements to disambiguate between the intersected objects. Zoom-based techniques have also been proposed [1, 3], which employ a Progressive Refinement strategy by diminishing the field-of-view until the desired object appears large enough to be selected. However, these techniques were developed for non-immersive and non-stereoscopic scenarios, and may not be suited for Virtual Reality (VR) as they might led to user discomfort or cybersickness. There are few works that employ Progressive Refinement in VR, but they require additional interactive surfaces to disambiguate selection [10], or completely change the virtual environment [4], which may disrupt immersion.
selected or, if users desire, can be stopped at any time to select a group of objects, supporting also the selection of multiple objects. When the refinement process is over, users are placed back in their starting position. 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 approach [4], we place them side-by-side in front of the user, while hiding the remaining objects in the scene. 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.

3 USER EVALUATION

To validate PRECIOUS (PRE), we compared it against two techniques from literature: Stretch Go-Go [11] (SGG) and Flashlight [8] (FL). We counted with a total of 18 participants (2 female).

Our prototype was developed in Unity3D and run in a Samsung Gear VR headset with a Samsung Galaxy S6 smartphone. Users’ full body was tracked using three Microsoft Kinect V2 depth cameras. We used a custom device that tracks 3 DOF hand orientation with an IMU and features a pressure pad to detect if the hand is opened or closed. An object selection action is started when some pressure is detected. When users close their hand with added pressure, a multiple object selection is triggered.

Participants were requested to complete a set of four tasks for each technique, and all consisted in selecting a cactus in a virtual representation of an urban environment. In these tasks, we varied the distance of the cactus from the user and the amount of objects surrounding it (Task 1: near and alone, Task 2: far and alone, Task 3: near with objects close, Task 4: far with objects close). For tasks where the cactus was near we used distances plausible in roomsized scenarios, whereas in the others we placed it on the other side of a large avenue. Every time participants selected an object other than the cactus, we registered it as an incorrect selection. If users reached 3 minutes in any task, we informed them to stop, and made a single error in the last task) with a small increase in task duration. This makes it a suitable technique to select objects out-of-reach. Moreover, we believe that an increased starting cone’s reach in PRECIOUS can significantly reduce its selection times.

4 CONCLUSIONS

In this work we proposed PRECIOUS, a new technique for out-ofreach object selection in VR, which employs a progressive refinement strategy. We evaluated it against Stretch Go-Go and Flashlight. With the results of our evaluation we found that Stretch Go-Go is impractical for objects that are further away than the size of a room. Flashlight provided the fastest completion times, but when the environment is not sparse it is prone to incorrect selections (half of participants committed at least 2 errors in the final task, max=12). Depending in the application context, unwanted selections can have a severe impact on the outcome, by applying actions to a wrong object. PRECIOUS, on the other hand, offers an almost error free selection approach (except for 6 participants that made a single error in the last task) with a small increase in task duration. This makes it a suitable technique to select objects out-of-reach.

Table 1: Participants’ preferences: x(IQR). * indicates statistical significance.

<table>
<thead>
<tr>
<th></th>
<th>SGG</th>
<th>FL</th>
<th>PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easiness *</td>
<td>1(1)</td>
<td>4.5(1)</td>
<td>4(1)</td>
</tr>
<tr>
<td>Satisfaction *</td>
<td>2(1)</td>
<td>5(1)</td>
<td>4(1)</td>
</tr>
<tr>
<td>Physical discomfort *</td>
<td>2.5(2)</td>
<td>5(1)</td>
<td>5(1)</td>
</tr>
<tr>
<td>Visual discomfort *</td>
<td>3(1)</td>
<td>5(1)</td>
<td>5(1)</td>
</tr>
</tbody>
</table>

p<.0005 felt. Participants strongly agreed that SGG was the hardest to use (FL: Z=-3.673, p<.0005, PRE: Z=-3.556, p<.0005), less fun (FL: Z=-3.660, p<.0005, PRE: Z=-3.572, p<.0005), most tiring (PRE: Z=-3.441, p<.0003) and most discomforting (FL: Z=-3.342, p<.003, PRE: Z=-3.475, p<.003). Statistically significant differences between PRE and FL were not found.

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