vMirror: Enhancing the Interaction with Occluded or Distant Objects in VR with Virtual Mirrors

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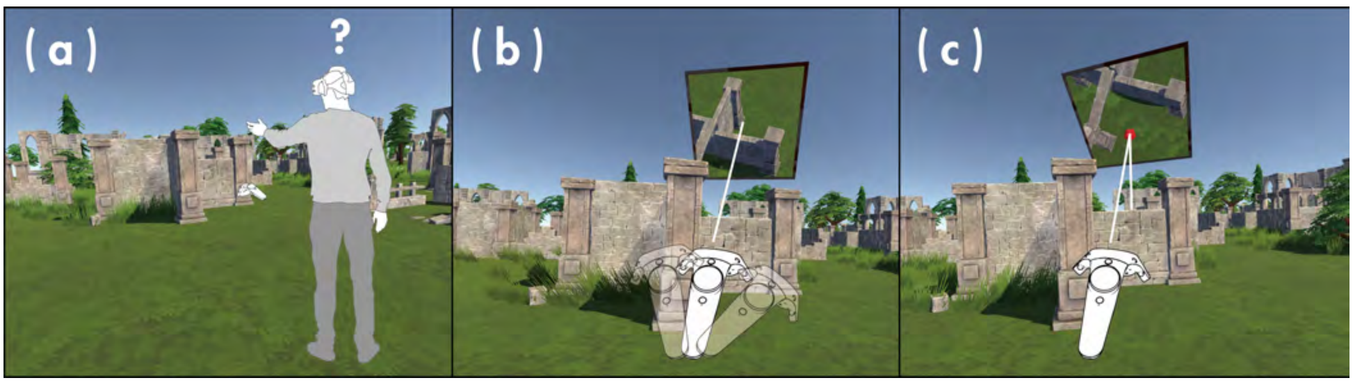

Figure 1: Users can select occluded objects by semi-automatically creating a mirror and manually adjusting it.

ABSTRACT

Interacting with out of reach or occluded VR objects can be cumbersome. Although users can change their position and orientation, such as via teleporting, to help observe and select, doing so frequently may cause loss of spatial orientation or motion sickness. We present vMirror, an interactive widget leveraging reflection of mirrors to observe and select distant or occluded objects. We first designed interaction techniques for placing mirrors and interacting with objects through mirrors. We then conducted a formative study to explore a semi-automated mirror placement method with manual adjustments. Next, we conducted a target-selection experiment to measure the effect of the mirror's orientation on users' performance. Results showed that vMirror can be as efficient as direct target selection for most mirror orientations. We further compared vMirror with teleport technique in a virtual treasure hunt game and measured participants' task performance and subjective experiences. Finally, we discuss vMirorr user experience and present future directions.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

Virtual mirror; vMirror; Virtual Reality; VR; target selection; occlusion; out of reach; DOF; raycasting

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1 INTRODUCTION

Head-worn Virtual Reality (VR) has become prominent in recent years, endowing a host of applications in education, entertainment, skill training, creation, and so on. Though VR devices are visually immersive, there exist much greater varieties in terms of input techniques and user interactions [20]. For instance, raycasting remains the dominant input method with current VR devices [2], but users often encounter complicated situations where objects are partially or fully occluded when selecting far field targets [3]. Moreover, manipulating an object out of the arm's reach can be challenging as it lacks input degrees of freedom (DOFs) at the depth (i.e., along the ray) [2]. Although users may change their positions to alleviate the issues, frequently doing so can be tedious and impractical for selection-intensive applications [2], and may increase the spatial disorientation and induce motion sickness [38].

Disambiguation mechanisms have been proposed to compensate for the occlusion and lack of DOFs issues. Making extra selections (e.g., via a added menu) is a staightfoward way but could be costly [3], Other approaches help refine the selection while manipulating the ray via increasing the amount of its DOFs. For instance, with DepthRay [14] or RayCursor [3], a user may specify the ray, and its depth simultaneously. Aside from manual disambiguation mechanisms, heuristic and behavioral techniques were employed to automatically rank and predict potential selections. However, such techniques were not always accurate [2]. In spite of the performance, most proposed techniques require target objects to be visible, while in actual cases, tasks could first involve discovering occluded targets. Although a variety of occlusion strategies exist (e.g., using multiple views of the scene, turning occluded object visible or environment semi-transparent, presenting miniature replicas) [10], many can be cognitively demanding and potentially increase selection time [2].

We present *vMirror*, an interactive widget that leverages the metaphor of mirror to help resolve occlusion and DOF issues for raycasting. Mirrors are widely used, e.g., for personal grooming, decoration, architecture, viewing the area behind and on the sides while driving, and viewing around and behind obstructions by technicians and dentists. We took an initial step to apply such a metaphor into VR, where a user can easily see (i.e., discover), select (i.e., access) and even manipulate an obstructed object from its reflection (Figure 1). Essentially, vMirror enables additional views in VR, integrated in the same scene in a focus + context way [10]. Unlike using multi-projection cameras, vMirror uses the metaphor of mirror to help improve the affordance of the technique and ease the learning process. More importantly, it provides compound ray-based input capabilities, and can be used naturally and intuitively in scenarios such as examining hidden contents and grasping unreachable objects without requiring users to change their position.

To help determine design parameters of the technique, including the mirror's physical properties and placement, we first conducted a formative study and asked participants to build target structures with toy blocks using vMirror. Participants used a manual approach and a semi-automatic approach to place vMirror, respectively. While they had varied preferences for vMirror placement methods, they favored the technique overall because it helped to ease the observations and selections. We conducted the second study to understand how vMirror placed at different orientations of a target would impact the selection time. The results quantified the target selection performance in six orientations using vMirror. In the third study, we further investigated how vMirror would assist users with a navigation and target selection task in VR. We designed and compared the *Teleport + vMirror* technique with the traditional *Teleport* technique in a target searching task in VR scenes of two sizes. Results show that *Teleport + vMirror* was significantly faster than *Teleport* and needed significantly fewer times of teleport and orientation change. Moreover,it induced significantly less motion sickness to participants than *Teleport*. Finally, we discuss vMirror's user experiences and highlight potential future directions. In sum, we make the following contributions:

- An interactive widget—vMirror—using mirror to alleviate occlusion and DOF issues with raycasting techniques in VR;
- Two studies that refined the design choices of vMirror and evaluated its impact on target selection;
- One comparative study that showed vMirror was able to significantly improve Teleport technique in a VR target searching task through both quantitative and qualitative measures.

2 RELATED WORK

Our work is inspired by previous research on extending interaction range, occluded objects selection in VR, and distant objects selections in VR.

2.1 Extending Interaction Views

To search for objects outside of their current FOV in VR environments, users have to turn their head around or teleport themselves. Recent research has explored techniques to migitate the FOV limitation. For instance, Outside-in is a technique that visualizes a projection-corrected picture of an out of view object into the current FOV [21]. Slice of Light technique enables guests to view other HMD users' interactions contextualized in their own virtual environments [36]. The Worlds-In-Miniature technique (WIM) [32] provides a second (often "bird's eye") POV from which to examine the scene. Users can view and pick objects by turning a model in his or her hand. However, WIM provides a miniaturized overview of the entire scene with limited detail and viewing angle. In contrast, vMirror supports discovering and interacting with occluded objects in the user's vicinity.

In a more general context, mirror has been often used to extend the FOV for vision based interactions. For example, SurroundSee uses an omni-directional mirror attached to the mobile device's front facing camera to recognize the device's peripheral environment [40]. Prism mirror, clipped to a corner of a smartphone, was used to achieve a stereo vision of the scene above the phone's touchscreen surface [41]. For example, PenSight uses a fisheye camera mounted on the top of a digital pen to capture the user's hand gestures to enhance interactions [24]. Furthermore, human cornea has also been leveraged as mirror to enable interactions, which is known as corneal imaging [27, 30]. Anamorphicons leverages a cylindrical mirror to reflect images from a flat screen and thus can display the undistorted reflected image of the distorted image on the flat screen [39]. Researchers also utilized mirror in AR/VR to augment the direct view of a surgeon [6] or extend the user's spatial perception ability [15]. Inspired by the idea of using mirror to extend the FOV and some portal-based interaction techniques [13, 19, 23], we design and evaluate an interactive mirror widget—vMirror to enhance the interaction with occluded and distanced objects in VR.

2.2 Occluded Objects Selection in VR

Occlusion is a common challenge for target selection in VR and has received considerable research effort. For example, BalloonProbe reduces the occlusion of a cluster of VR objects by allowing the user to place a balloon into the cluster, which displaces the objects to the surface of the balloon along its radius direction [9, 10].Ray enhancement techniques, such as DepthRay [14] and RayCursor [3], use a depth marker attached at a fixed position on the ray or controlled by the touchpad to select the object closest to the depth marker. Sidnmark et al. recently proposed the “outline pursuits” technique allowing for using gaze to trace the moving outline of a partially occluded VR object to select it [31]. These techniques, however, are suitable for partially-occluded objects selection. Wang et al. proposed a rendering technique to detect potential occluded views and render the occluded view that the user chooses to reveal [37]. However, as there could be many potentially occluded views from the user’s POV, it is unclear how the user would traverse the possible views and choose one efficiently. In contrast, vMirror allows for selecting partially-occluded objects as well as directly observing/discovering and selecting fully-occluded objects by intuitively placing a mirror.

2.3 Distant Objects Selection in VR

Two common categories of techniques have been investigated for distant objects selection in VR. The first category is extending the user’s virtual arm [12, 17, 29]. For example, Go-go technique provides a non-linear mapping of the control–display ratio (CD ratio) between the motor space and control space [29]. The second category is using virtual pointing techniques, such as raycasting [25]. Unlike virtual hand techniques, virtual pointing techniques allow the user to select out-of-reach objects and require less physical movement. However, selecting small or distant objects through virtual pointing remains a difficult task due to the limitation of human motor control (e.g., jitters) [1, 5] or the noise from the tracking device [22]. To address this limitation of virtual pointing techniques (e.g., raycasting), researchers proposed techniques to increase the size of the selection tool [11, 28] or stabilize human input by using a low-pass filter [7, 35]. However, such techniques require disambiguation mechanisms to infer the target object [2, 8], which may not be accurate, or need to tune parameters for the filter. In contrast, vMirror allows the user to place a mirror to bring closer the image of a distant object and thus makes it easier to select. This process does not require any inference on the system side or any parameter tuning on the user side.

3 DESIGN CONSIDERATIONS

In VR, occlusion is a common challenge for the discovery of target objects and makes the selection and manipulation of these objects difficult. Changing the user’s point of view (POV), such as via rotating head or teleporting, might alleviate this issue but doing so frequently could cause the user to lose orientation and induce motion sickness [38]. Moreover, teleporting actions adds burden to the user if she has to resume to her original POV afterward. vMirror was designed to avoid such POV change. Generally speaking, by placing a mirror in the vicinity of a partially occluded object, the user could select and access it in a much easier way through its reflective images in the mirror. vMirror was further extended for object discovering and manipulating. Aside from augmenting interactions in VR, vMirror aimed to be intuitive and natural to use via relying on a human’s inherent skills to handle a familiar tool in the real world. We adopted the following considerations when designing vMirror.

3.1 Principle of the Plane Mirror Reflection

vMirror follows the principle of the common known plane mirror reflection. The object and its reflected image in the mirror are symmetric to the mirror plane. The original ray from the object and its reflected ray from the mirror are symmetric to the normal of the mirror plane. We chose not to adopt other types or shapes of mirror (e.g., convex, concave, non-linear) to avoid potential visual confusions and operating complexity.

3.2 Single vs. Multiple Mirrors

It is intuitive to consider multiple mirrors to allow for more flexibility in interaction. However, multiple mirrors placed in a close vicinity can result in multi-path reflection among them. Although such multi-path reflection may offer potential benefits, such as periscope, it can also result in infinite reflection and create severe overlaps among reflected images. Consequently, observing and selecting objects through their reflected images becomes harder. As a result, vMirror focuses on single-mirror interaction.

3.3 Eye-and-Hand Misalignment

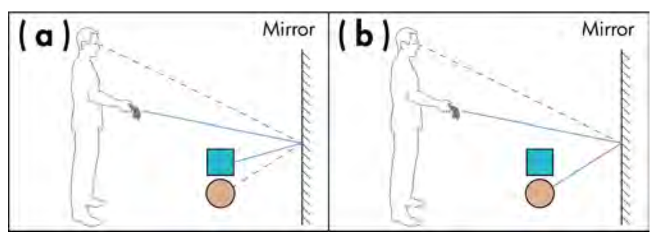

Figure 2: (a) A wrong object is selected if the ray from the handheld controller also follows the reflection principle; (b) vMirror allows for pointing the ray at the observed reflected image to select the corresponding object.

The eye-and-hand misalignment is a common issue for raycasting based selection. Specifically, due to inter-object occlusion, some objects can appear occluded from the hand but not from the eye and vice versa [2]. In the case of selecting from mirror relections, the eye-and-hand misalignment issue happens when the ray originated from the hand gets reflected in the same way as other virtual objects do. As Figure 2(a) illustrates, the user observes the ball relection in the mirror and points the ray at it, but the reflected ray would actually select the cube instead following the reflection principle, causing confusions. To resolve this eye-and-hand misalignment, the ray from the controller was set to follow the same reflection as the ray from the user's eyes. In this way, vMirror allows users to select the target that they observe in the mirror by pointing the ray directly at the target's reflected image (Figure 2(b)).

3.4 Mirror Placement

It is critical to provide appropriate and easy ways for users to change the position and angle of the mirror. Here both manual and semi-automatic were considered. In the manual mode, users use the touchpad on the controller to change the position, angle, or scale of the Mirror. Users use a side button on the controller to change either the position, angle, or scale. The left, right, up, and down buttons on the touch panel move the mirror in the corresponding direction. The up and down buttons rotate the mirror around its horizontal x-axis while the left and right buttons rotate it around its vertical y-axis. Similarly, the up and down buttons scale the mirror in the vertical direction while the left and right buttons scale the mirror in the horizontal direction.

In the semi-automatic mode, users first select an initial position in the space to locate the mirror center. Then, vMirror computes the angle formed by the ray between the user and the mirror's center and the ray between the target object and the mirror's center. Finally, vMirror uses the bisector of the angle, which is the normal of the mirror plane, to compute the angle of the mirror. The mirror's orientation gets adjusted accordingly.

3.5 Mirror Edges

vMirror visualizes the frame of the mirror to enhance its visual perception and visually distinguish the reflected images from the original objects in it from other VR objects. We investigated common materials used in many 3D games, such as The Sims[1] and GTA[2], and found that wood and metal were most visually salient materials for the frame of the mirror. Furthermore, we adopted dark colors, such as brown and gray, to enhance the visual perception of the frame of the mirror.

The virtual mirror was implemented in Unity by creating a camera and dynamically updating the material of a rendered plane object (i.e., the mirror) with the camera's view. The position of the camera is set to be always symmetrical with the position of the scene's main camera along the plane/mirror.

4 STUDY 1 - FORMATIVE STUDY OF VMIRROR DESIGN

We conducted a first user study to evaluate the initial design of vMirror and gather user feedback for further improvement.

4.1 Study Design and Procedure

As shown in Figure 3, participants were asked to reconstruct the structure on the right side by picking and piling up colored bricks from the left side. The task consisted of 16 bricks to be picked one by one. One advantage of vMirror is to minimize frequent view angle switching. To assess this function, participants were asked

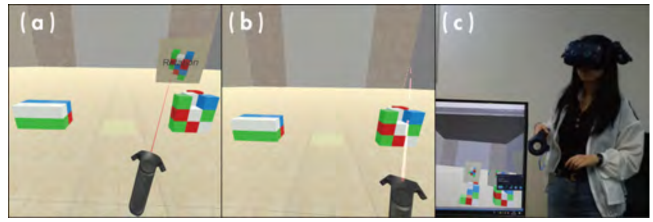

Figure 3: Study 1 task scene: a user can place the mirror via (a) the manual approach or (b) the semi-automatic. approach.

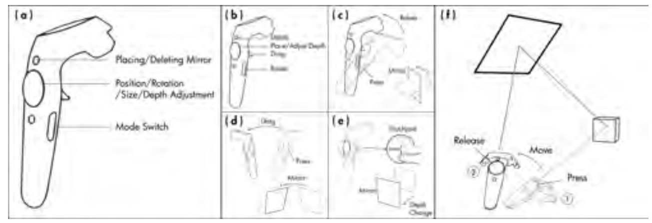

Figure 4: Mirror interaction via controller: (a) The initial design adjusts the mirror by pressing buttons; (b-e) The improved design adjusts the mirror through gesture; (f) The improved semi-automatic mirror placement method.

to stand at a fixed position and were not allowed to walk around. They performed the task by placing vMirror around the objects for viewing and interacting with occluded items.

Participants tested two methods for placing the mirror, the order of which was counterbalanced. One method is to manually place the mirror, in which case participants press a button to create a mirror with the ray crossing its center with a default distance of 5 meters from the user. The mirror has a default size of 1.5 x 1.5 meters and is oriented to face the user. A mode switch can be triggered between placing the mirror and operating on objects through the mirror. A long press while pointing at a mirror removes it. The properties of the mirror, including the orientation, position, size and distance from the user, can be adjusted via the touchpad on the VR controller. Additionally, a side button is used to switch between these properties (Figure 4.a). The second method of placing the mirror is the semi-automatic approach. Participants use a standard teleport technique, akin to the way used in SteamVR[3], to select an object center, then choose a direction and press the menu button to press the mirror. The distance between the mirror and the user is set to 5m by default. vMirror system calculates the best orientation to create the mirror by taking into account of the position of the user and the object center. The semi-automatic approach should enable the participant to see the object from the mirror according to the law of reflection.

Participants were first informed the purpose of the study and instructed to familiarise themselves with operations of vMirror. They practiced moving the bricks, placing vMirror, and operating with it. They were given on average 5 minutes to get familiar with the manual and semi-automatic ways to place vMirrors before the formal study (Figure 3.c). During the formal study, they were told to freely play and no specific rules were set up. After the

[1]https://www.ea.com/games/the-sims?isLocalized=true
[2]https://www.rockstargames.com/V
[3]https://store.steampowered.com/steamvr

participants completed the tasks, we interviewed them and collected their feedback and opinions on the design.

4.2 Participants

Twelve12participants (7 female and 5 males, average age 30.14 (SD = 4.91)) were recruited from a local research institute for the study. All were right handed. Each participant was rewarded with $10 USD for their participation. Three of them had VR experiences before.

4.3 Apparatus

The system was implemented with Unity and run on HTC VIVE Pro [4], which was driven by a Windows 10 desktop (CPU: i7-6700, 16GB, GPU: Geforce GTX 1080). A lighthouse positioning system was used in HTC Vive to track the head-mounted display and the two handheld controllers [26].

4.4 Results

4.4.1 User preference. Overall, vMirror received positive feedback from the participants. All felt that using mirror(s) facilitated observation and selection, and they also felt the method was intuitive and easy to learn: *"It fits my life experience."-P4*; *"It was hard at the beginning, but once I got used to it, everything went smoothly"-P6.*

4.4.2 Mirror placement. The participants had different preferences for semi-automatic or manual placement of the mirror. Seven (7) participants preferred semi-automatic placement because it required less operations, and matched their needs; The rest of the participants preferred manual placement because it was more flexible. They felt the semi-automatic placement did not give the desired placement, so that they still had to manually adjust the mirror afterwards.

Some participants preferred placing the mirror on the side of the target, while others preferred placing it above the target with a tilt angle. The participants also had various strategies to place mirrors. Some always started with placing mirrors at a location and then adjust it frequently while others only created mirrors when objects were occluded. They tended to place the mirror once and avoid adjusting it frequently afterwards.

Some participants mentioned the distance to the mirror was an important factor to consider. While a closer mirror allowed for observing objects with bigger reflected images, a farther mirror allowed for viewing more contents. In contrast, some participants cared more about the angle of the mirror, which would affect the distortion of the reflection image. Furthermore, it is critical to decide the center position of the mirror. If the initial placement of the mirror is reasonably close to participants' expectation, they often do not mind a few extra steps of manual operations.

4.5 Improved Mirror Placement Design

Based on the participants' feedback, we adopted the semi-automatic mirror generation to allow users to manually adjust it. We replaced the previous button-based interface with motion gestures to enable manual adjustment of the mirror position.

[4]https://www.vive.com/eu/product/vive-pro/

As shown in Figure 4.f, the user creates a mirror by pressing the touchpad while pointing to a target location where she wants to see from the mirror. According to the law of light reflection, to ensure that the user can see the target, the normal vector of the mirror should be the bisector of the angle between the user and the target to the mirror. Before releasing the touchpad (while pressing), the user can rotate and swing the controller to change the mirror orientation and position. Once releasing the button, the mirror is placed in the environment. After being placed, the mirror can still be manually adjusted. We provide three ways to manually adjust the mirror as shown in Figure 4.b-e. The rotation of the mirror can be adjusted by pressing the touchpad and rotating or swinging the controller(c). A mirror can also be directly dragged to follow the hand movement, by dragging the device while pressing a side button (d) The distance from the mirror to the user (i.e., depth) can be adjusted by swiping on the touchpad without pressing (e).

We invited five of the previous participants to evaluate the improved mirror placement method. They all agreed that both the mirror placement and the adjustment methods were better than the earlier version. They felt the improved mirror placement approach was more intuitive and easier to learn.

5 STUDY 2 - EVALUATING TARGET SELECTION WITH VMIRROR

The results of Study 1 revealed differences in user experiences and preferences when the mirror was placed at different positions and angles. This suggests that the placement of the mirror might affect users' performance when interacting with objects through their reflected images. Thus, we designed and conducted Study 2 to examine the target selection performance with mirrors positioned at representative locations and angles. The goal was to understand how the positions and angles of mirror affects the performance. Moreover, as mirror reflection could distort our targets and potentially decrease the performance. We were interested in how much performance it might cost to perform selections via a reflected view. Therefore we added a comparison to direct object selection.

5.1 Experiment Design

We adopted the standard ISO 9241-9 reciprocal selection test [33] to evaluate the performance of vMirror, when positioned at different locations and angles, for selecting occluded items, compared to direct target selection with the same raycasting device.

The experiment consisted two sessions, one was target selection with vMirror, and the other one was direct target selection. The session with vMirror was a [6 x 3 x 2] within-subject design with three factors:

- MirrorPosition: we chose six angles of placing the mirror surrounding and facing the user, two on the top, two on the left and two on the right, as shown in Figure 5.a.
- TargetSize: *Small* (W1), *Large* (W2).
- TargetDistance: *Short* (D1), *Medium* (D2) and *Long* (D3).

The experiment task featured 13 balls of various sizes (TargetSize) placed on a circle with various radius (TargetDistance). An obstacle object was placed in front of the target, occluding the user's direct sight to the target. Before each selection, the first target appeared in blue color at a random spot on an invisible circular path. After successful selection, each of the next 12 consecutive targets appeared at the opposite position on the circular path in farthest distance from the previous target. They appeared one after another successful selection, in red before the selection and turns green after. Each selection was triggered by pressing a button on the input device while keeping the ray intersecting with the target. No audio feedback was provided. The TargetSize were chosen to be 0.054 m for *Small* as the diameter of the target balls and 0.09 m for *Large*. The TargetDistance was the distance between two ball targets for each selection, chosen as 0.42 m for *Short*, 0.90 m for *Medium* and 1.14 m for *Long*. Our choices of TargetSize and TargetDistance produced six Fitts' IDs (2.50, 3.13, 3.46, 3.77, 4.14, 4.47) which were identical to the ones in [33]. In the direct selection (DirectSelect) session, the obstacle was removed, and users were asked to select the targets without mirrors. The same TargetSize and TargetDistancefactors were used as the vMirror session, only without the MirrorPosition factor.

The following factors were kept constant. The distance from the user to the mirror was 2 m and from the user to the object was 1.2 m. These choices were made considering the need of viewing all the targets in one mirror and keeping the distance between the reflected targets and the participants within a reasonable range between 3.26 m and 4.18 m. The choice of this distance range referenced previous VR target selection experiment [34]. We chose a fixed set of mirror placements while ensuring that the participants could view all the targets at their natural positions. The obstacle object size was set to 1m x 1m x 0.01m, about 1m distance to the user.

5.2 Procedure

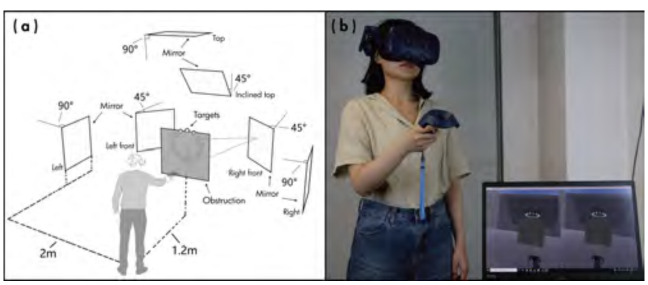

Figure 5: Study 2 setup: A participant selects occluded targets via reflection in the mirror that is placed at different angles and positions.

The experiment began with a training session where participants were briefed the experimental task and procedure and practiced the technique until feeling comfortable to start. The orders of vMirror and DirectSelectsessions were counterbalanced among participants. For each trial, participants performed 12 target selection across the circle in consequence with a random starting point, similar to [33]. Figure 5.a shows the study setup. Participants moved to the next MirrorPosition after finishing 12 selections. The trials were blocked by MirrorPosition to avoid frequent change of viewing perspectives. The order of MirrorPosition was counterbalanced across participants. The order of TargetSize and TargetDistance was presented randomly. After completing all the trials, participants filled a Likert scale questionnaire to evaluate

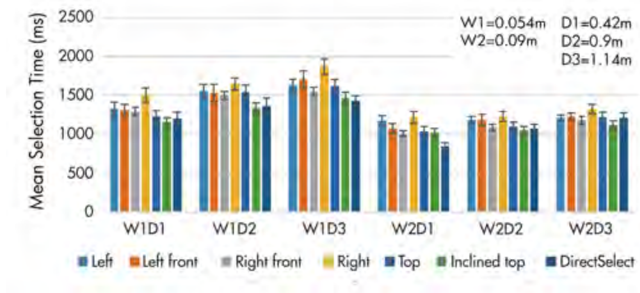

Figure 6: Selection time grouped by TargetSize **x** TargetDistance**. Each color represents a** MirrorPosition**.**

their preferences, mental loads, physical loads, and the reflection image distortion effect due to the mirrors in different directions. The experiment lasted about fifty minutes.

5.3 Participants

The participants were the same as Study 1 (Figure 5).b.

5.4 Data collection

We collected 1512 measured trials ((6 MirrorPosition × 2 TargetSize × 3 TargetDistance × 3 replications + 1 DirectSelect x 2 TargetSize × 3 TargetDistance × 3 replications) x 12 participants)). We measured Selection Time, *ST*, which is the time for each selection from the target appearing to the selection being validated (there are 12 selections in each trial). We calculated the Error Rate, *ErrorRate*, by counting the number of attempts for each selection. Subjective feedback and preferences of the participants were collected via the questionnaire.

5.5 Results

We considered single target selections that exceeded 10 attempts or 20 seconds as outliers, which counts for 0.4% of all the selections. A Shapiro-Wilk normality test showed that data were normally distributed at the 5% level.

5.5.1 Selection Time. Figure 6 shows the target selection time for conditions with different mirror placements. We performed a full factorial ANOVA test with Bonferroni correction on *ST*. There were significant effects of MirrorPosition ($F_{5,60} = 6.16, p < 0.0001$), of TargetDistance ($F_{2,24} = 202.41, p < 0.0001$) and of TargetSize ($F_{1,12} = 178.74, p < 0.0001$) on *ST*. Interaction effects were found between TargetSize and TargetDistance ($F_{2,24} = 24.19, p < 0.0001$) as well as between TargetSize and MirrorPosition ($F_{5,60} = 2.66, p = 0.032$). Tukey HSD post-hoc pair-wise comparison showed significant difference between *InclinedTop* and *Left* ($p = 0.022$) and *InclinedTop* and *Right* ($p = 0.003$). As shown in Figure 6, participants were significantly faster when the mirror was placed at *InclinedTop*, compared to *Left* (11.7% faster in average) and *Right* (18.4% faster in average).

We performed T-test pair-wise comparison between DirectSelect and each of the MirrorPosition for *ST*. Only marginally significant difference was found between DirectSelect and *Right* ($p = 0.01$). This indicates that target selection via vMirror can be as

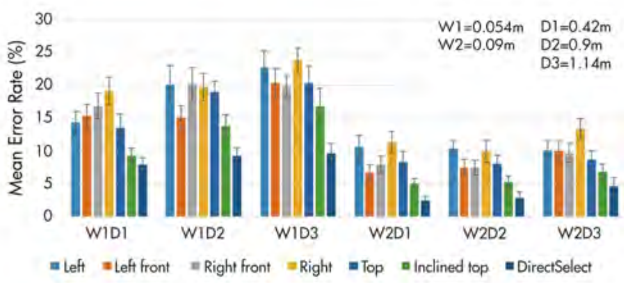

Figure 7: Error rates grouped by TargetSize **x** TargetDistance**. Each color represents a** MirrorPosition**.**

efficient as direct selection except when the mirror is placed at the least convenient position. This is promising considering that the objects look smaller and tilted after reflection compared to being seen directly.

5.5.2 Error Rate. We performed a full factorial ANOVA test with Bonferroni correction on *ErrorRate* as well. There were significant effects of MirrorPosition ($F_{5,60} = 11.39, p < 0.0001$), of TargetDistance ($F_{2,24} = 15.65, p < 0.001$), and of TargetSize ($F_{1,12} = 104.85, p < 0.001$) on *ErrorRate*. An interaction effect was found between TargetSize and TargetDistance ($F_{2,24} = 9.1, p = 0.001$). Tukey HSD post-hoc pair-wise comparison showed significant difference between *InclinedTop* and four other MirrorPosition respectively (*Left* (p = 0.01), *Right* (p = 0.009), *LeftFront* (p = 0.047), *RightFront* (p = 0.037)). Other pair-wise comparisons were not significant. As shown in Figure 7, participants made significantly fewer errors when the mirror was placed at *InclinedTop*, compared to *Left* (37.8% less in average), *Right* (43.7% less), *LeftFront* (25.4% less) and *RightFront* (31.1% less).

We also performed T-test pair-wise comparison between DirectSelect and each of the MirrorPosition for *ErrorRate*. Every pair had a significant difference ($p < 0.0001$) except between DirectSelect and *InclinedTop*. We can see that vMirror was more error-prone than DirectSelect, except when the mirror was placed at the most comfortable position - *InclinedTop*. This was consistent with what we found in the error rate comparisons between different MirrorPosition. Potential reasons for the high error rate include the tilted view seen in mirror reflection. Another reason we observed was that sometimes participants missed the target while pressing the button after aiming it, because the button press shifted the ray away from the target. The increased distance between the participant and the target after mirror reflection did incur some cost on precision with a raycasting input.

5.5.3 Subjective Feedback. Based on the participants' ratings, we found the participants did not like placing the mirror on the ceiling most. This could because they needed to look up and became fatigued easily. P3 also mentioned that she got dizzy after looking up for too long. There was little difference regarding the space or target distortion caused by the mirrors among the participants. The mental workloads of the participants were all below 2.5 (7-point), indicating that the participants did not need to spend too much cognitive effort to select the target through mirror. This is perhaps because mirror is a familiar everyday object and they could leverage their life experience to quickly comprehend it. Lastly, the highest physical workload was reached by the ceiling mirror. Fatigue caused by selecting objects through mirrors for an extended period is an issue that needs to be investigated further in the future.

5.5.4 Fitts' ID with angular measurements. We analyzed the Fitts' ID with angular width (AW) and distance (AD) [18] of the targets in two placement angles (45° and 90°) in each direction (left, right, and top). Results in each directions were the same, and the angular width, angular distance, and Fitt's $\text{ID}_{angular}$ in different conditions were shown in Table 1. The average $\text{ID}_{angular}$s in the 45° placements were consistently smaller than those in the 90° placements. This was consistent with our finding that users performed better with 45° than 90° mirrors.

	45°			90°		
	AW	AD	$\text{ID}_{angular}$	AW	AD	$\text{ID}_{angular}$
W1D1	0.95	5.51	8.37	0.74	3.83	11.46
W1D2	0.95	11.84	15.12	0.74	8.23	19.48
W1D3	0.95	15.03	17.74	0.74	10.42	22.46
W2D1	1.58	5.51	1.59	1.24	3.83	2.53
W2D2	1.58	11.84	4.00	1.24	8.23	5.81
W2D3	1.58	15.03	5.14	1.24	10.42	7.25

Table 1: Angular width (AW), angular distance (AD), and Fitt's $\text{ID}_{angular}$ in different conditions.

5.5.5 Summary. Overall, Study 2 provided strong evidence that the most efficient and least error-prone position to place the mirror was the *InclinedTop* of the user. This confirms the subjective feedback we received from Study 1. We also found that vMirror can be as efficient as direct target selection for most mirror positions despite that the targets appear smaller in reflected view. This is encouraging, as it suggests only minor cost in selection efficiency is introduced by vMirror. With a good angle this cost can even be ignored. However, mirror reflections lead to tilted and smaller targets from the user's perspective, which was found to be particularly error-prone when raycasting was used as input technique. Nevertheless, this problem could be mitigated to a large extent by placing the mirror at the *InclinedTop* position of the user. These findings provide a deeper understanding of the advantages and disadvantages of vMirror technique.

6 STUDY 3 - A COMPARATIVE STUDY WITH TELEPORT

The goal of this study was to evaluate whether vMirror could assist users with navigating in VR environments and selecting targets in a more effective manner with better subjective experiences than only using the widely adopted navigation technique in VR—*Teleport*. Therefore, we conducted a controlled lab study to compare Teleport technique with and without using vMirror.

6.1 Experimental Design

Our study followed a [2 x 2] within-subject design with two factors:

- *Input Techniques*: *Teleport*, *Teleport + vMirror*.
- *Scene Range*: *Large*, *Small*.

We implemented the *Teleport* technique using the standard SteamVR package downloaded from unity asset store[5]. We incorporated vMirror with Teleport to create the *Teleport + vMirror* technique, which uses the same button for teleporting and placing vMirror. If the user points the virtual ray from the handler to the ground and presses the button, it triggers the typically teleporting function. If the user points the ray to an object (e.g., stone, trees) in the VR scene and presses the button, it creates and places a vMirror at the pointed position.

To understand whether VR scene's size has effects on users' performance, we designed the VR scene in two sizes. The *Large* size scene was about 110 ×90 square meters, and contained 40 stone walls of various sizes. The *Small* size scene was half the size of the whole scene, with 20 stone walls of various sizes. These stone walls acted as obstacles to add difficulty to the searching task. The positions of the obstacles were randomly generated and kept the same for all participants.

The input techniques were counterbalanced across the participants, and for each input technique, the scene range were counterbalanced. Each condition of an input technique and a scene range was repeated three times. In total, there were 12 test trials (2 *Input Techniques* × 2 *Scene Range* × 3 replications) for each participant.

The task of the game was to find a red gem in the ruins of stones and trees. A bird-view of the ruins scene and the first person perspective of treasure hunting were shown in Figure 8. The boundaries were high walls and trees, and participants were only allowed to move within the rectangular area for the corresponding scene range. The maximum distance allowed by *Teleport* was 10m each time, which was a common practice for teleporting. For *Teleport + vMirror*, when the participant creates a new vMirror, the old vMirror is automatically delete to reduce the burden of doing so manually. However, the participant can keep the old vMirror by pressing the menu button. The same desktop and VR devices were used as Study 1 and Study 2.

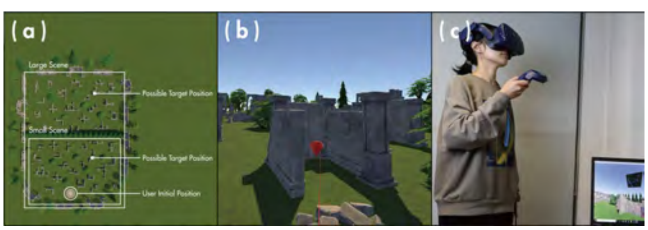

Figure 8: (a) A top view of the overall game scene; (b) The first person perspective of treasure hunting; (c) A user is performing the task.

6.2 Participants

Twelve participants (7 female and 5 males, average age = 24.18 (SD = 1.25)) were recruited from a local research institute for the study. All were right handed. Each participant was rewarded with $10 for their participation. Six of them had VR experience before.

[5]https://assetstore.unity.com

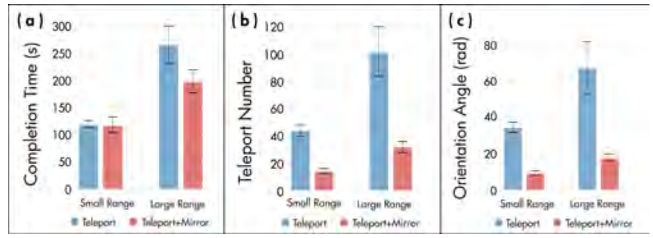

Figure 9: (a) Mean completion time, (b) mean teleport number, and (c) mean orientation angle for two techniques.

6.3 Procedure

The moderator first showed participants how to use two input techniques. Then participants were asked to practice the two input techniques until they learned how to teleport and operate vMirror techniques (Figure 8.c). At the beginning of the game, the red gem, as the search target, appeared randomly under one of the stone walls. The participant's initial position was on a circular stone, which was in the center of the scene edge. When the participant found and selected the red gem, the game ended. To ensure the game was complete in time, the maximum search time in each trial was set to be 10 and 15 minutes for the two scene ranges respectively. Participants were allowed to move in a physical space of roughly 1.5m × 1.5m. After participants completed all the trials, they were asked to fill out two standard questionnaires to assess their perceived usability of the techniques and potential VR motion sickness. One questionnaire was the universal System Usability Scale (SUS) [4], which consists of 10 items, categorized in two sub-scales (i.e., learnability and usability). Each item is rated on a 5-point Likert scale ranging from 1 to 5. The other one was the Simulator Sickness Questionnaire (SSQ) [16], which consists of 16 items, categorized in three sub-scales (i.e., nausea, oculomotor, and disorientation). Each item is rated on a 4-point Likert scale ranging form 0 to 3. The study lasted on average 40 mins per participant.

6.4 Measures

For the quantitative assessment, we measured the user's completion time, number of teleport, and change of the orientation angle. The completion time was the time between the beginning of the task and the moment the participant selected the gem or the allocated time was out. The change of the orientation angle was calculated by the sum of the angles changed after each teleport, which measures how much the participants turned their body during the experiment.

For qualitative assessment, we used the ratings of the aforementioned two questionnaires (i.e., SUS, SSQ).

6.5 Results

We performed a Shapiro-Wilks test at the 5% level on the task completion time, teleport times, and change of orientation angle respectively and found that all data followed a normal distribution. Thus, we further performed two-way repeated-measure ANOVA on the data.

6.5.1 Completion Time. Results showed a significant effect of *Input Techniques* ($F_{1,11} = 32.77, p < 0.001$) and Scene Range ($F_{1,11} = 11.32, p < 0.05$) on task completion time. The interaction effect between *Input Techniques* and *Scene Range* was close to significant ($F_{1,11} = 4.86, p = 0.05$). The *Teleport + vMirror* technique ($\mu = 157.66s, \sigma = 17.69s$) was significantly faster than *Teleport* ($\mu = 191.98s, \sigma = 18.76s$). As shown in Figure 9.a, the performance of the two techniques in the *Small* scene was very close, but *Teleport + vMirror* technique was significantly better in the *Large* scene (p < 0.05).

6.5.2 Number of Teleport. There was a significant effect of *Input Techniques* ($F_{1,11} = 46.59, p < 0.001$), Scene Range ($F_{1,11} = 15.49, p < 0.05$) and *Input Techniques* x *Scene Range* ($F_{1,11} = 7.07, p < 0.05$) on the number of teleport. The number of teleport for *Teleport + vMirror* technique ($\mu = 72.62, \sigma = 9.97$) was significantly smaller than that for *Teleport* ($\mu = 22.80, \sigma = 3.0$) (Figure 9.b). This result was expected as participants did not need to explore some areas when using vMirror, which reduced the need of random teleport.

6.5.3 Change of Orientation Angle. There was a significant effect of *Input Techniques* ($F_{1,11} = 38.65, p < 0.001$) and *Scene Range* ($F_{1,11} = 7.85, p < 0.05$) on the change of orientation angle. The interaction *Input Techniques* x *Scene Range* was not significant effect ($F_{1,11} = 3.53, p = 0.087$). The *Teleport + vMirror* technique ($\mu = 50.66rad, \sigma = 7.40rad$) significantly reduced the change of orientation angle than *Teleport* ($\mu = 13.25rad, \sigma = 1.62rad$) (Figure 9.c).

6.5.4 Usability & VR Motion Sickness. For the SUS, we performed a Wilcoxon signed-rank test on the questionnaire results. We did not find significant differences between *Teleport + vMirror* ($\mu = 74.583, \sigma = 13.81$) and *Teleport* ($\mu = 81.68, \sigma = 11.29$) (p = 0.182). Although many participants felt that it was more convenient to search for the target with vMirror, they also agreed that *Teleport* technique was simpler and more intuitive.

For the SSQ, we performed a Wilcoxon signed-rank test on the questionnaire results. The *Teleport + vMirror* ($\mu = 9.97, \sigma = 12.39$) technique received significantly lower VR motion sickness scores than *Teleport* ($\mu = 24.93, \sigma = 35.10$) (p < 0.05). By comparing the scores of *Nausea*, *Oculomotor*, and *Disorientation*, we found significant differences between two techniques on *Disorientation* (p < 0.05). This suggested that participants were less likely to get lost when using *Teleport + vMirror* ($\mu = 15.08, \sigma = 17.26$) than *Teleport* ($\mu = 39.43, \sigma = 52.02$). There were no significant effects of two techniques on *Nausea* (p = 0.109) and *Oculomotor* (p = 0.066)

6.6 Discussion

Results showed that compared to only using Teleport, *Teleport + vMirror* effectively improved search efficiency, reduced the amount of virtual movement and orientation change, and maintained a better sense of orientation and direction.

When searching in a small scene range, using vMirror did not significantly reduce the search time though the number of teleport and change of orientation were significantly reduced. This was hinted by the close to significant interaction term between *Input technique* and *Scene Size* in Section 6.5.1. One potential reason was that the cost of placing vMirror was relatively higher in a small scene compared to the cost of teleport since small scenes would require relatively fewer times of teleport to be fully explored. However, as the VR scene became larger, the benefit of vMirror took over its cost because it allowed for observing a wider range of a user's surrounding scene, which reduced the times of random teleport. In addition to saving time and movement, vMirror also reduced the feeling of disorientation.

Our observations revealed that participants adopted different search strategies. 8 out 12 participants searched along the boundaries of the map to make sure that they did not get lost. Some participants tried to create and place a mirror directly on top of the area of interest. However, they often had to move it farther away from the area of interest to observe the area through its reflection in the mirror. This, unfortunately, made the reflections of objects in the area relatively smaller and thus harder to observe. Therefore, in the future it is worth exploring ways to combine the global view interaction techniques, such as WIM [32], with vMirror, so that users can switch between a global view of a larger area and the fine-grained local view of a smaller area.

7 DISCUSSION

7.1 vMirror User Experience

Our study results show that users had different preferences in mirror placements and selecting targets through their reflections in mirrors could be as efficient as selecting them directly. However, selection via mirror had higher error rate than direct selection. This is because the targets appeared smaller and distorted in the mirror. This happened when the reflected image of an object was further away from the user than the object itself. One potential solution is to add a magnifier function to vMirror to allow users to observe enlarged images when needed.

We also found that users tended to minimize the adjustment of the mirror. In our current design, placing and tuning the mirror is accomplished with touchpad and buttons on the controller. Although this design makes it possible to use vMirror with a single hand, it also increases the effort of placing the mirror especially when the user needs to frequently change and adjust the mirror. To alleviate the issue, vMirror provides a semi-automatic way to place the mirror. However, this design received mixed feedback from users. While some appreciated the design, other felt that the approach had a learning curve and was not as flexible as the manual placement. Therefore, future work should investigate better ways to reduce the effort of placing the mirror, such as better automatic mirror placement methods or integrating vMirror with bi-manual interaction techniques.

Furthermore, in a crowded VR environment where there is little empty space, the ideal position for placing the mirror to observe the target might be occupied by other VR objects. Thus, how to interact with vMirror in a crowded VR environment remains an open question. One possible solution is to allow vMirror to penetrate VR objects. Once the collision between the vMirror and objects is detected, the system can temporarily remove the collided objects to yield space for the mirror.

7.2 vMirror Augmentations

When designing vMirror, we have followed the principles of the plane mirror reflection in the physical world to offer users a familiar metaphor to use the widget. We have also envisioned extensions that are beyond the principle in the physical world to leverage the

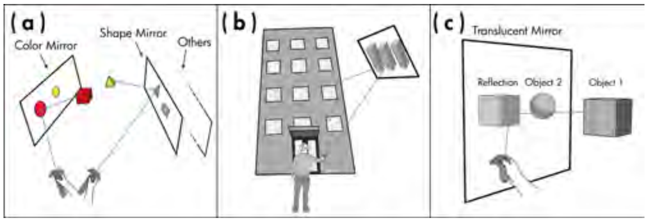

Figure 10: vMirror augmentations: (a) a property mirror reflects a property of objects; (b) a scale mirror allows for observing and selecting out-of-scale objects; (c) a translucent mirror allows for observing and selecting behind-mirror objects.

unique properties of VR. Figure 10 illustrates three types of extensions: property vMirror, scale vMirror, and translucent vMirror. The property vMirror reflects one property of objects that is of interest to facilitate observation and selection. Figure 10 (a) shows color and shape property mirrors. The scale vMirror allows users to observe objects that are far beyond their scales. Figure 10 (b) shows a scale-down mirror to observe the occluded side of a tall building. Moreover, the translucent vMirror allows users to observe both the reflected images and objects behind the mirror (Figure 10 (c)).

7.3 Future Directions

We have taken an initial step toward unveiling the potential of mirror as an interaction metaphor in VRand identified limitations and potential directions for further improvement.

7.3.1 Fully Occluded vs. Partially Occluded VR Objects. We compared vMirror with the teleport technology to evaluate whether it helped users observe fully occluded VR objects. Future work should investigate ways of using vMirror to observe partially occluded objects and compare it with other techniques, such as DepthRay [14] and RayCursor [3] techniques.

7.3.2 Automatic Mirror Placement. We adopted a semi-automatic strategy to place a mirror. Future work could explore automatic strategies to further reduce users' efforts. However, automatic strategies would require inferring the target object or area that the user wants to observe and calculating an appropriate position and angle to place the mirror with respect to the user's position and orientation. Thus, more work is needed to better infer the user's intended object.

7.3.3 Bi-Manual Mirror Interaction. In our current work, placing the mirror and selecting the target via its reflection in the mirror using raycasting was accomplished with a single hand. Future work should explore ways to combine vMirror with bi-manual operations to further improve its user experience. For example, users can use one hand to place the mirror and use another hand to select the target from the mirror.

7.3.4 Multi-Mirror Interaction. Our current work allows the user to interact with a single mirror. In some scenarios, placing more than one mirror might provide additional benefits. However, using multiple mirrors must overcome the multi-path reflection challenge, which makes observation and selection through reflection hard.

7.3.5 Other Shaped Mirrors. In addition to plane mirrors, Other shaped mirrors have other unique optical properties.

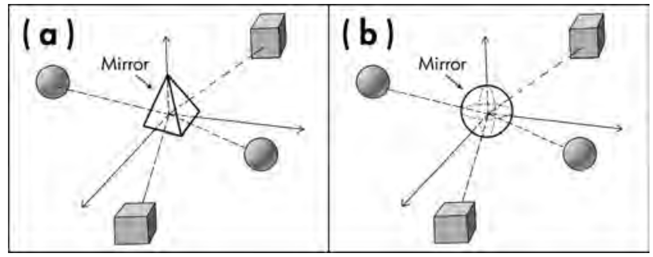

Figure 11: Other shaped mirrors: (a) multi-facet mirror; (b) spherical mirror.

Figure 11 shows two other shaped mirrors. In fact, recent research has begun to leverage different shaped physical mirrors (e.g., cylindrical mirror [39]). It is worth exploring how these unique shapes of mirrors could enrich VR interactions that a plane mirror, such as vMirror, could not.

8 CONCLUSION

We have presented vMirror, an interactive widget leveraging the principle of plane mirror reflection to facilitate occluded, distant, and out-of-view objects observation and selection in VR. Our first study showed that participants appreciated the familiar metaphor and felt that vMirror was intuitive and easy-to-learn. Participants had different preferences for the manual and the semi-automatic ways of positioning a mirror. Participants felt that the manual way gave them more flexible but was more effortful to use compared to the semi-automatic way. Moreover, participants preferred to position the mirror at different positions and angles for the same task. Consequently, we conducted the second study to investigate the performance of target selection with vMirror placed at different positions and angles. The results showed that selecting targets via vMirror could be as efficient as selecting them directly even though having higher error rates. The higher error rates were caused by objects appearing smaller and distorted in vMirror. This suggested that although vMirror allowed users to observe occluded, distant, and out-of-view objects, it might make them smaller and distorted when positioned at certain angles and positions. To better evaluate the benefits of vMirror in VR, we conducted the third study to compare *Teleport + vMirror* with the traditional *Teleport* technique in a target searching task in two sized VR scenes. Our results demonstrated that participants were able to complete the searching task significantly faster, needed significantly fewer times of teleport, and changed their orientations significantly less often when using *vMirror* than without using it. Moreover, participants also felt significantly less disoriented when using *vMirror*. Finally, we discussed potential extensions from the current work. As an initial step toward utilizing the mirror metaphor, we believe that future work could continue to explore other types of virtual mirrors, similar to vMirror, to further enhance interactions in VR.

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