HMD Light: Sharing In-VR Experience via Head-Mounted Projector for Asymmetric Interaction

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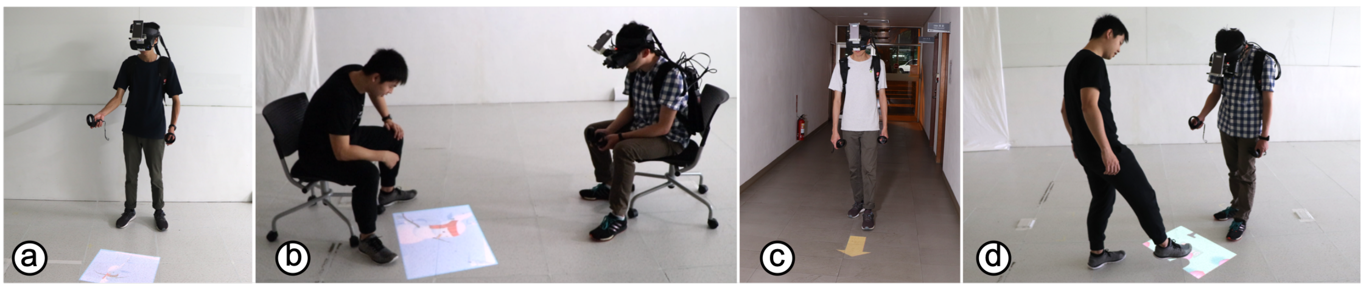

Figure 1. ***HMD Light*** **resolves the VR-external user communication gap and advances inter-user interaction by (a) revealing the VR user's virtual experience in the physical environment. By sharing the VR user's experience,** ***HMD Light*** **allows the co-located external users to (b) join a VR scene design discussion, (c) understand a VR user's approaching walking direction and (d) participate in a VR game.**

ABSTRACT
We present *HMD Light*, a proof-of-concept Head-Mounted Display (HMD) implementation that reveals the Virtual Reality (VR) user's experience in the physical environment to facilitate communication between VR and external users in a mobile VR context. While previous work externalized the VR user's experience through an on-HMD display, *HMD Light* places the display into the physical environment to enable larger display and interaction area. This work explores the interaction design space of *HMD Light* and presents four applications to demonstrate its versatility. Our exploratory user study observed participant pairs experience applications with *HMD Light* and evaluated usability, accessibility and social presence between users. From the results, we distill design insights for *HMD Light* and asymmetric VR collaboration.

Author Keywords
Virtual reality; Mobile Virtual Reality; Multi-User Virtual Reality

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CCS Concepts
•Human-centered computing → Virtual reality; Collaborative interaction;

INTRODUCTION
With the rapid development of HMD technologies, today's HMD devices with inside-out tracking ability (e.g., Oculus Quest) can be untethered and self-contained, yet trackable, promoting their use in fully mobile contexts [7, 47]. This enables users to immerse themselves inside the virtual environment (VE) wherever and whenever they want. However, the high level of immersion provided by the HMD isolates the VR user from the outside world, causing communication gaps with people who cohabitate the same physical environment (external users).

Previous works have aimed to externalize the VE or the VR user's visual expression by displaying the content on the HMD's front-facing display [5,16,34,39]. This allows external users to understand and engage in a form of interaction with the VR user's experience. Though attaching the display to the HMD itself preserves interface mobility, the display content and interactable area are restricted by physical limitations of the VR user's head.

Meanwhile, several attempts have been made to display the VE by projecting top-down or surrounding views of the virtual world into a room [15, 21, 25] or a cubic CAVE system [24]. These approaches embed projectors in the environment to externalize the VE in the physical environment and provide external users with a larger and more accessible display. Nonetheless, the way these devices are installed makes them only suitable for in-situ VR experience.

In this paper, we propose *HMD Light*, a concept mobile HMD designed to reveal the VR user's virtual experience in the physical environment. In contrast to past implementations (e.g. ShareVR), *HMD Light* places control of VR content sharing in the hands of the VR user. *HMD Light* prototype attaches a portable projector to the top of the HMD with a motor. The projector display reveals the VR experience for external users in different scenarios (Figure 1). A depth camera is also added on the portable projector to detect and enable external users' touch interaction on the projected display. By allowing VR users to place an external display into the physical environment and share their VR experience, *HMD Light* thus lowers the VR—external user communication gap for mobile VR.

While we advocate the exploration of free-surface projection to prompt diverse applications, *HMD Light* initially evaluates floor projection to focus our study on how the system aids users' communication. With respect to the floor surface, we explore the interaction design space of *HMD Light* and present four example applications to show how our designed interaction factors can be utilized in different scenarios.

Contribution

The current work presents a mobile solution to facilitating asymmetric VR interaction by projecting the VR user's experience into the physical environment. Apart from the system implementation of *HMD Light*, we also design novel interaction mechanisms to facilitate projection-based interaction between VR and external users, such as contextual affordances for mutual control and understanding of projected VR content. Our exploratory user study results provide new human factors insights on how users are influenced by and how they collaborate in the asymmetric VR scenario.

RELATED WORK

HMD Light aims to reveal the VR user's experience in the physical environment for mobile VR. We review previous works related to *Mobile VR Interaction* and *Sharing VR User's Experience*. In relation to external users' interaction, we review works on *Asymmetric Interaction in VR*.Works with a similar hardware setup are described under *Wearable Projector*.

Mobile VR Interaction

Recent developments in VR HMD devices concern mobility to enable their use wherever and whenever needed. Recent work has explored various embedded input or output techniques on the HMD to enhance the VR experience without carrying external devices.

Past works have utilized different input sensing techniques to enable new types of VR interactions, such as gaze input [11, 27], voice command, or brain-computer interface [1]. To enable natural input interaction, some works explored mid-air AR interaction by detecting hand gestures in front of the HMD [8, 30, 44]. Other works explored the input space embedded on the HMD. FaceTouch [14] attaches a touch panel on the HMD's backside to enable touch interaction for mobile VR, while FaceWidget [43] augments the HMD backside with physical widgets for tangible interaction.

There are two main types of research exploring the output space: enhancement of HMD output feedback for the VR user, and addition of an output display for the external user. Some explored the design space of different types of haptic feedback on the HMD, such as thermal feedback [36, 46], skin drag feedback [42], vibration [46] and various types of force feedback on the face [6, 17, 41]. Others looked at enhancing HMD output capability for external users by adding a display to the front side of HMD [39]. For instance, Mai et.al. [33] proposed a front-facing display showing the VR user's facial expression for VR and external users' collaboration. FrontFace [5] integrates the user's viewport and eye gaze on the display to reveal the VR user's presence. FaceDisplay [16] further enables touching functions on the display to allow external users' direct-touch interaction. In line with these works that use a display to resolve the VR and external user communication gap, *HMD Light* seeks to explore the design space of placing display into the physical environment.

Sharing VR User's Experience

The above-mentioned attempts made to reveal VR user's facial expressions [5, 33] and viewport image [5, 16, 39] on the HMD add-on front-facing display hold some limitations. Since these approaches must fit within the HMD form, the display and the interaction for the external users are physically limited to the HMD's dimensions. With a larger display and interaction region, other approaches have tried to externalize the VE to the physical environment. ShareVR [15] allows the external users to join the VR experience by projecting a top-down presentation of VE onto the floor. RealityCheck [21] presents a projection mapping system to display the VR user's viewport onto real physical surfaces. Other methods allow external users to see the VR user's surrounding VE views by projecting it onto cubic CAVE system [24]. RoomAlive [25] augments a physical room with virtual content, transforming it into an immersive environment; it dynamically maps the content to the physical environment and hence enables immersive virtual interaction with physical spatial mapping. These works externalize the VE in the physical environment and hence enable external user's spatial interaction with the VE, but their methods are still unfeasible in a mobile context. *HMD Light* aims to leverage the benefit of revealing the VE in the environment and apply it to mobile VR.

Asymmetric Interaction in VR

With shared information from VR users, the external users' participation consequently enables a mode of asymmetric interaction between the VR and external users. Asymmetric interaction in VR often adopts a mix of egocentric and exocentric interactions to facilitate users with different levels of immersion to work together on the same VE. Research has been done to explore this form of collaboration using the desktop PC [4, 22] or tabletop [23, 40] paired with mixed reality users. Furthermore, techniques in augmented reality can allow VR users to provide local users guidance, as remote experts [29, 37, 38]. ShareVR [15] and MagicTorch [31] allow co-located external users to join the VR game experience with floor-based or handheld projections to access the VE. With a touch-screen mounted on the front side of the HMD, FaceDisplay [16] further explores how users perceive and understand the interaction in such a highly asymmetric scenario. In this paper, we support the external users' touch interaction towards the mobile sharing display in the physical environment and explore how users perceive and utilize the function in our provided scenario.

Wearable Projector

Past work has explored interaction with the body-mounted projector. Pico-projectors have been worn by users to provide mobile environmental display [35] and on-body touch interface [19, 20]. AMP-D [45] provides users with an ambient display on both floor and hands, to deliver public and personal information. Others have applied coupling a procam unit with HMD or user's head to Mixed Reality (MR) applications [12, 26, 28, 49]. FoveAR [2] further applied this on a see-through HMD to extend the AR FoV. *HMD Light* further extends prior works, which demonstrated benefits of head-mounted projectors for HMD-wearers, by applying such display methods to external users around the VR user.

INTERACTION DESIGN

HMD Light works to resolve the communication gap between VR and external users by revealing the VR user's experience in the physical environment. The following section explores the design space of the display and present the corresponding interface for the interaction.

Mutual Communication

To notify the VR user of the external user's existence and what they need to see, a communication channel needs to be established when external users are interested in the VR user's VR experience. Figure 7a-b shows that when a external user wants to engage in the VR activity and approaches the VR user, they will be visualized in the VR User's view, enabling both users to communicate verbally.

To enable the communication channel whilst retaining the VR user's engagement, external users will not be visualized in the VR user's view unless they desire to engage in the VR user's experience. We represent the level of desire for engagement by the external users' distance from the VR user. When external users enter the VR user's 'play area' (2m from the VR user, suggested by Oculus' official guidelines), they will be visualized in the VR user's view. Hence, the VR user can remain immersed in VR when no one is within the VR user's activity range, and still be aware of any external users' communication requests when they are approached.

The Communication Reference: viewport

Here, we introduce how to create the external user's *viewport* to the *VE*. In the *HMD Light* system, we use a HMD-mounted projector to place the display in the physical environment. The projector's projected region then provides a *Projectable Area* where VR information can be revealed (See more in *System Implementation*). To share their VR experience with external users, VR users can create a *viewport*. External users can see or interact with the shared content through this *viewport*.

To create the *viewport*, not only its position and size, but also its behavior and content type needs to be decided by the VR user or an application developer. In our implementation, we map all the functions related to the *viewport* on the Oculus rift S' left controller, to not conflict with the application (right) controller's other functions. In the following section, we will present the *viewport*'s behavior, content type and introduce how its spatial setup (position and size) is assigned.

I. Viewport's Behavior

To create a *viewport*, the first thing to decide is its behavior. The *viewport*'s behavior can be categorized into two modes: *Anchored mode* (*A-mode*) and *Tag-along mode* (*T-mode*). If the *viewport* is chosen to be in *A-mode*, it will act as a virtual object that attaches to a spot in the virtual/physical environment and will disappear from the *Projectable Area* when the VR user's movement causes the *Projectable Area* to move away from the anchored location (Figure 3b). If the *viewport* is designed to be in *T-mode*, the *viewport* will stay on the *Projectable Area* constantly, and therefore will follow the VR user's movement during the experience (Figure 4).

If the *viewport*'s communicative purpose concerns its position relative to the virtual or physical world, then *A-mode* is more suitable for this *viewport*. This behavior can be used when the *viewport* position indicates some connection between its content and virtual world landmark, or when the VR user wants to place the *viewport* based on a physical environment position, such as beside the external user. In these cases, the *viewport* is preferred to be fixed in the same position and hence suitable to be *A-mode*. A *viewport* that is designed to be displayed continually is more suitable for *T-mode*. Cases where the *viewport* is a permanent message delivery platform or when the *viewport* acts as the "window" metaphor to the virtual world to help external users discover the VE, are suitable for *T-mode*.

We imagine that the VR application developer can choose whether the *viewport*'s behavior should be decided by the users or by the program itself. If users are allowed to choose the *viewport*'s behavior, a GUI menu will appear on the controller (Figure 2a) after pressing the *viewport* creation button (Y), and the VR user can select the mode to fit their needs. In some applications, the behavior could be predefined and decided via the *HMD Light* plugin during the programming stage.

II. Viewport's Spatial Setup

After the *viewport*'s behavior is decided, the VR user begins to assign its spatial setting (position and size). A ray casted from the controller in the forward direction appears, which is used to assign the *viewport*'s position and size on the physical reality surface (Figure 2b). To aid the user in assigning the *viewport*'s position, we visualize the physical reality surface with the wireframe appearance (via plane detection provided by the stereo camera SDK). The *Projectable Area* will be visualized as a black dotted frame in the VR user's view as well for creation reference. Once the position is confirmed, the user presses the creation button again and then starts assigning the *viewport*'s size. A footprint of the *viewport*'s proposed size is visualized to assist the user to assign its size (Figure 2c). Using the same casted ray, the user can adjust the *viewport*'s size and confirm by again pressing the same button. During

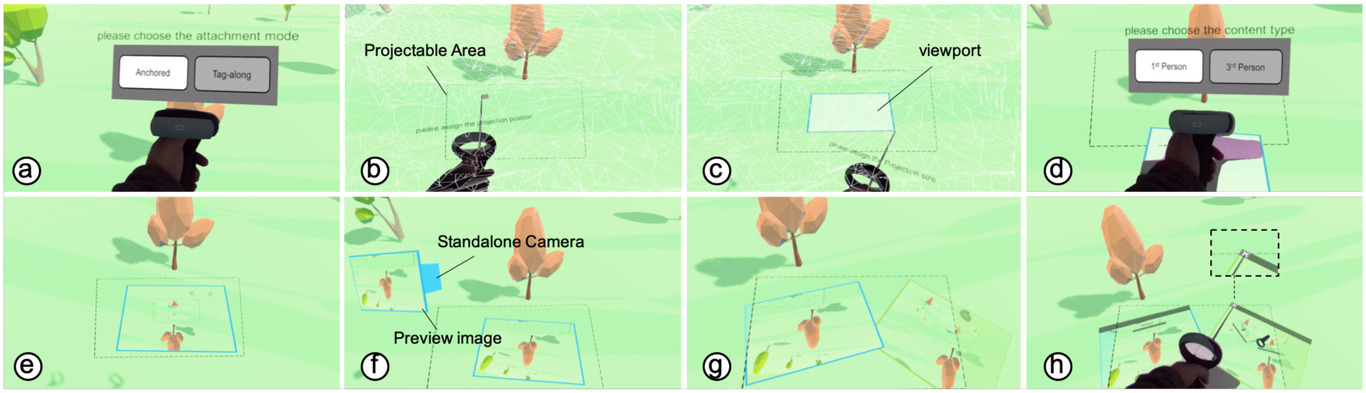

Figure 2. To create a *viewport*, the VR user will first (a) decide the *viewport's* behavior, assign the *viewport's* (b) position and (c) size and finally the (d) content type. If the user chooses the "1st Person" view, (e) the VR user's first-person view will then be visualized on the *viewport*. If the user chooses the "3rd Person" view, (f) a standalone camera will appear to help adjust the 3rd-person view. (g) Each *viewport* has a different color frame works as its ID. Finally, (h) the VR user can close the *viewport* by using the controller ray cast selecting the cross button on the UI bar.

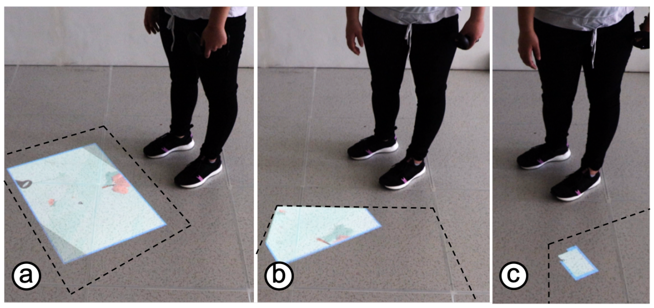

Figure 3. *Viewport* in *A-mode* (b) will disappear from the *Projectable Area* when the *Projectable Area* is moved away from the anchored location. If fully disappear from the *Projectable Area*, (c) a spatial preview window appears to indicate the *viewport*'s existence. (The black dotted frame drawn on the picture represents the *Projectable Area*.)

the creation process, the *viewport*'s rotation will face the VR user until the size is confirmed.

After assigning the *viewport's* position and size, *HMD Light* then lays the *viewport* at the assigned position in both virtual and physical environments via the HMD-attached projector. To preserve the VR user's engagement, the physical reality surface will then disappear. However, the *Projectable Area* will still be visualized in the VR user's view to inform the user about its position until no *viewports* are open.

III. Viewport's Content Type

The *viewport* content can be classified into two types: *Local view* and *Non-local view*. While *Local view* displays the VR user's first-person view, the *Non-Local view* can be divided into two types as well: *VE view* and *Non-VE view*.

The *Local view* provides the VR user's view, illustrating what the VR user is currently doing in the virtual world. Here the *viewport* works as a display, similar to the content on the monitor usually provided beside VR activity during demonstrations to help external users understand the VR experience. The *Non-Local view* provides a different view from the VR user, which can be categorized into two types: *VE view* and *Non-VE view*. *VE view* provides external users a virtual world view but from a different viewpoint, such as god-view of the VE to aid in the VR user's activity, for instance, navigation or virtual

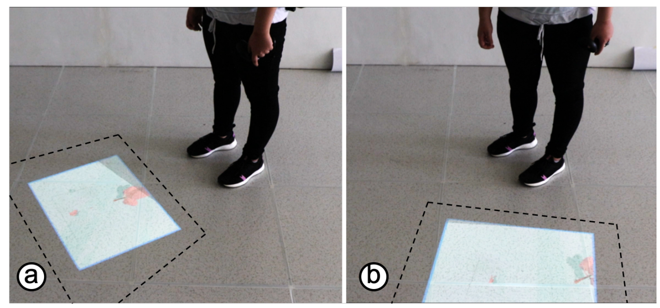

Figure 4. *Viewport* in *T-mode* will stay on the *Projectable Area* constantly, and therefore will follow the VR user's movement during the experience.

scene-building [3, 13, 23]. It can also be a "window" [16] into the virtual world, enabling external users to explore through the *viewport*. The *Non-VE view* shows external users a view not from the virtual world, such as a message from the VR user or other information designed for the external user in an asymmetric interaction.

Same as for the *viewport*'s behavior, we allow the application developer to decide whether the user can decide the *viewport*'s content type or if it should be predefined. If the user can decide the *viewport*'s content type, a GUI menu will appear on the controller after the *viewport*'s spatial setting is finished (Figure 2d). The VR user can select content type on the menu. While "1st Person" shows the VR user's first-person view on the *viewport* (*Local view*, Figure 2e), "3rd Person" creates a standalone camera model, and the *viewport*'s content will synchronize with the camera's view (*Non-Local, VE view*). The standalone camera virtual model consists of a cuboid corresponding to the *viewport* frame's color and a preview image of the camera view (Figure 2f). The VR user adjusts the camera position by grabbing and moving the cuboid. The preview image enables the VR user to check the view directly without looking back to the *viewport* itself. Also, based on the nature of the application, *viewport* content can be predefined; the developer can also assign the *viewport*'s content during the programming stage via the *HMD Light* plugin.

Since the *viewport* is mainly designed for external users, for their reading comprehension, we suggest rotating the content by 180 degrees to face the external users. This suggestion is only suitable for *viewports* that are not related to any spatial cues. That is, based on the application, a fixed rotation may affect a *viewport*'s content that relates to the VR user's or the virtual world's spatial information (such as their walking direction or a target model relative position).

IV. Viewport UI Elements

Apart from the *viewport*'s content, each *viewport* will be visualized in the VR user's view with a colored frame and an X-shape GUI button on the corner. The colored frame works as an ID, and each *viewport* is given a different color. This helps distinguish *viewports* from one another during communication if there are multiple created (Figure 2g). The X on the corner is designed for closing the *viewport* itself and is only visible to the VR user. To avoid excess visual complexity caused by the UI, it is invisible unless the VR user presses the UI button on the controller (trigger button) to enable UI mode. By pressing the same button, the VR user then can close the *viewport* with a raycast from the controller to select the cross button (Figure 2h). If the application does not allow *viewport* content to be seen by the VR user, such as in cases of asymmetric interaction affordance (see Applications *Trample Balloons* and *Keep Talking and Nobody Explodes*), the *viewport* will only be seen by the VR user with the UI elements (e.g. frame) for locational information, and with no content.

Viewport out of Projectable Area Indication

To notify the external users of the *viewport*'s existence, we indicate the "off-screen" *viewport* as a spatial preview window when the *viewport* is out of the *Projectable Area* [32] (Figure 3c). The preview window of *viewport* contains the *viewport*'s live content and same-color frame, but with the segment of the color frame closest to the *viewport*'s location flickering. This indicates the absence of the *viewport*, as well as what direction it is in, and helps external users to distinguish preview windows from *viewport*s. The preview window's size ratio is the same as the corresponding *viewport's* while its width is 0.1 times of the *Projectable Area's* width. The preview window's position encodes the direction from the center of the *Projectable Area* to the *viewport*'s position. It is aligned with the connection of the *Projectable Area*'s center and the *viewport* and floats on the periphery of the *Projectable Area*. The preview window and its content tells external users that the *viewport* still exists, and reveals a rough idea of its location and content. This provides them the opportunity to get an idea of the *viewport* and communicate their needs regarding the "disappearing" *viewport*.

Since all *viewports* are visible to the VR user, applying the same "off-screen" visual technique in the VR user's view might cause higher visual complexity and the VR users' confusion. In the VR user's view, any part of the *viewport* that escapes the *Projectable Area* will be visualized with a semi-transparent mask (Figure 2g). This allows the VR user to be aware of whether the *viewport* is fully covered by the *Projectable Area*.

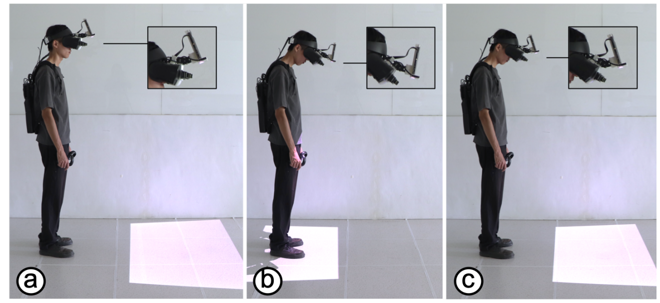

Figure 5. During the VR experience, (b) the *Projectable Area* may move towards the VR user's body due to the VR user's head movement. (c) We utilize a projection motor to offset the user's head movement and center the *viewport* in the *Projectable Area*.

Projectable Area Behavior

During the VR experience, the *Projectable Area* will be visualized in the VR user's view, represented by a black dotted frame. The *Projectable Area* visualization will appear whenever a *viewport* is created and disappear when there is no *viewport* in the VE. The *Projectable Area* visualization helps the VR user to locate its position in physical space without taking off the HMD and works as a reference for managing the layout of the *viewports*.

However, the *Projectable Area* may become unstable or even move towards the VR user's body due to the VR user's head movement. For instance, when discussing *viewport* content with external users, VR users might tilt their head downwards to look at the *viewport*, which may result in the *Projectable Area* moving towards the VR user's body (Figure 5a-b). This may lower the *viewport*'s accessibility to the external user. To stabilize the *viewport*'s visual positioning, the *Projectable Area* is designed to trace and center on the *viewport* to the best of its ability, aiming to visualize the *viewport* in the center of the *Projectable Area* even with unstable head movement.

To stabilize the *Projectable Area*, we use a projection motor mounted to the HMD's top (see more detail in *System Implementation*) to rotate the projector and allow the *Projectable Area* to offset the user's head movement. Once a *viewport* is located in the region that can be projected (*Projectable Area Set*, calculated by the set of possible *Projectable Areas* and projection motor's angle), the *Projectable Area* will focus on it (move to center around the *viewport*). If multiple *viewports* are within range of the *Projectable Area Set*, the *Projectable Area* will move to encompass all of them if it can. If this is not possible, it will focus on the most-recently created *viewport*; we reason that this is most likely to be the one most relevant to the VR and external users' current interaction.

Once the *viewport* is focused-on and traced by the *Projectable Area*, the *viewport* will be visualized in the center of the *Projectable Area*. During the VR experience, the *Projectable Area* will self-adjust to offset movement caused by the VR user's head vertical rotation. (We will discuss horizontal rotation in Limitations and Future Work.) This offsetting results in the *Projectable Area* remaining in the same position even if the VR user looks downwards or nods their head (Figure 5c). For *Projectable Area* movement caused by the VR user's vertical movement, this offset compensation for the VR user's vertical

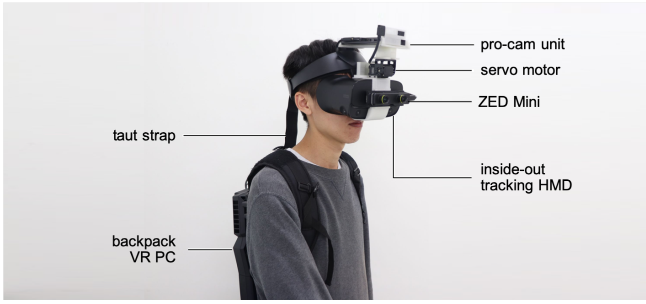

Figure 6. *HMD Light* consists of an Oculus Rift S, a pro-cam unit, a servo motor connects the pro-cam unit to the HMD and a stereo camera attaches to the front side of the HMD. A micro controller is placed behind the servo motor to control the motor's angle. To reduce the weight imposed on the user's head, we connect a taut strap between the HMD belt and the backpack VR PC to help distribute the HMD weight.

movement will only be applied to the *viewport* when it is chosen to be in *A-mode* since in *T-mode* it constantly follows the VR user. As a result, as long as the *viewport* in *A-mode* stays within range of the *Projectable Area Set*, the *viewport* will be visualized in the same position even if VR user is walking forwards or backwards.

SYSTEM IMPLEMENTATION

We designed *HMD Light* for mobile VR interaction, wherein the VR user is immersed either in a stationary location (e.g. a room), or a dynamic scenario [7, 47]. *HMD Light* aims to facilitate at-will display placement in the environment and enhance external users' interaction on the display for mutual interaction while preserving interface mobility.

Hardware Configuration

HMD Light prototype combines an Oculus Rift S, a "pro-cam" unit (projector bound to depth camera), a servo motor connecting the pro-cam to the HMD, and a stereo camera on the front of the HMD (Figure 6). A Sony MP-CL1A portable laser projector (resolution: 1920x1080) displays the VR experience and a PMD Camboard pico flexx depth camera (resolution: 224x171, 45 fps in short-range, 5 fps in long-range) to detect the external user's interaction on the display.

The portable projector and depth camera are bound using 3D-printed cases to form a pro-cam unit. This pro-cam unit is then attached to the HMD via a servo motor, which is controlled by a micro controller (Adafruit Feather M0). The servo motor provides the pro-cam unit with 100° of rotation (software limits this to 80° to avoid projector and HMD collision), so *HMD Light* can adjust the pro-cam unit to display in different locations based on users' needs. This servo motor also helps to compensate for the *Projectable Area* offset caused by users' head movement and provide a stabilized *viewport*. To reconstruct the projectable plane surface in the VR user's view and visualize external users in the VR scene based on their distance from the VR user, we use a stereo-camera kit, ZED Mini (720p video resolution) added onto the HMD. The whole system runs on a backpack VR PC (MSI 7RE, GTX1070, 16G) worn by the user. The overall weight of *HMD Light* is approximately 1.15 kg. To reduce the weight imposed on the user's head, we connect a taut strap between the HMD belt and the backpack VR PC to help distribute the HMD weight.

During the VR experience, *Projectable Area* status such as position and range can help the VR user to manage the state of *viewports* in the physical environment without taking off the HMD. To reconstruct and calculate the projector's *Projectable Area* with the current motor state in the VR scene, we calibrated every component in the *HMD Light* system to align to the same 3D coordinate system.

(Please find system calibration process in the supplementary).

Detecting External User's Input

HMD Light facilitates the external users' interaction toward the shared display by detecting their foot touch position. To detect foot touch position, we use the depth camera to distinguish users' feet from the environment and identify touch position on the projected surface. Based on the depth image, we first estimate the plane surface in the environment using the random sample consensus (RANSAC) algorithm [9] with the depth value, to subtract the effect of the depth value noise and find the best fitting plane. After finding the plane surface, the *Projectable Area* (defined by the projector) is then applied onto the estimated plane as a mask so that foot detection will only be available in the *Projectable Area*. Next, we identify the foot pixels from the depth image by filtering out pixels that are not in the range of 3-10 cm above the estimated plane (approximate foot location). The foot touch position is then determined by the biggest blob left in the *Projectable Area* region. We implement the foot detection program in Python, and the result is sent to Unity via TCP socket transmission.

APPLICATION

In the following section, we present four different applications (*VR Scene Design*, *VR User Direction Indicator*, *Trample Balloons* and *Keep Talking and Nobody Explodes*) to demonstrate *HMD Light* applicability with different design factors.

VR Scene Design

In this application, we show how *HMD Light* can be utilized in a scene design application to facilitate VR user and external users' discussion. Here, we present a simulated scenario to illustrate this application (Figure 7).

The VR user is sitting on a chair, immersed in creating and designing a VR world. As the VR user decorates a snowman model, his colleague (external user) passes by and finds him immersed in VR. He then approaches and asks the VR user what he is doing (Figure 7a). From the VR user's view, the external user appears in the VR scene and expresses interest in his current VR experience (Figure 7b). The VR user then uses *HMD Light* to create a *viewport* showing the external user his view in VR. In this application, the VR user can decide the *viewport*'s behavior and content type. To show the VR scene to the external user, he creates a *T-mode viewport* and assigns its content type to be his 1st person view. The external user can now see the VE from the VR user's view in the *viewport* (Figure 7c-d).

After reviewing the scene design, the external user tells the VR user that he has some suggestions on the snowman's decoration. The external user then pulls over a chair to sit in front

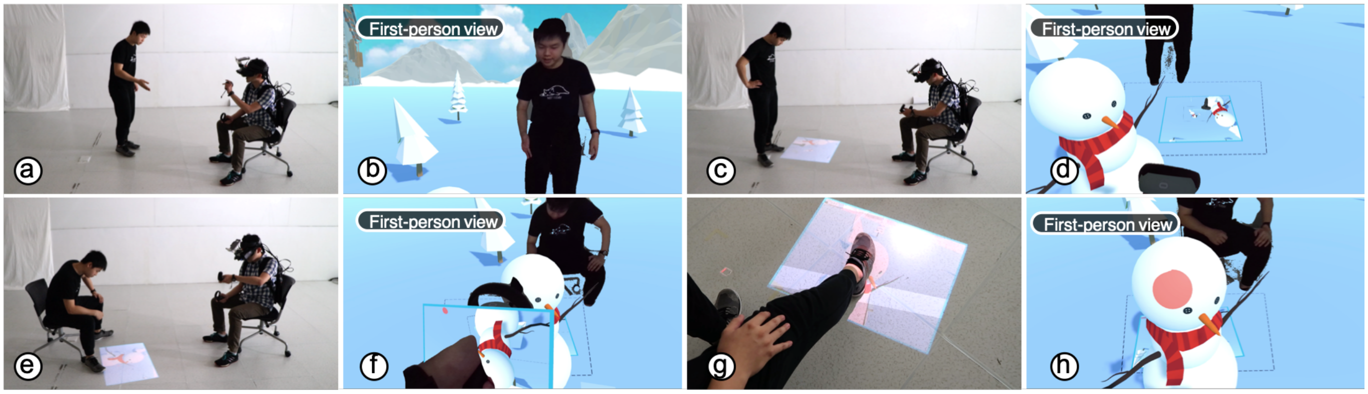

Figure 7. (ab) HMD Light visualizes the VR user's colleague (external user) when he approaches the VR user. (cd) The VR user creates a *viewport* showing the external user his view in VR. To provide a stabilized view for external user, (ef) the VR user then creates a *viewport* to capture the snowman's appearance from a downwards angle. (g) The external user uses his foot to touch the snowman's head on the *viewport* to convey the precise location. (h) An indicator appearing as a red highlight then shows up on the snowman model's head to indicate the external user's location of reference.

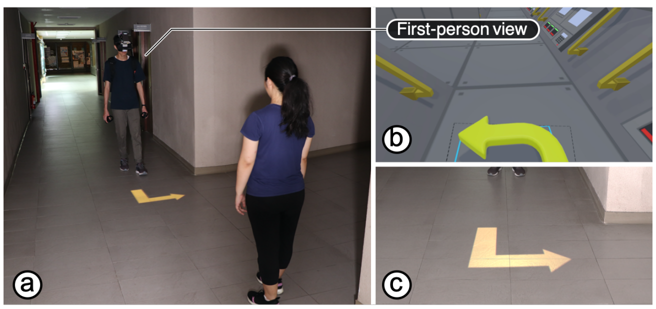

Figure 8. While the (b) VR user doing real-world walking following the pre-programmed path, (c) *HMD Light* visualizes the planned direction in front of the VR user to inform the external users of the VR user's walking direction.

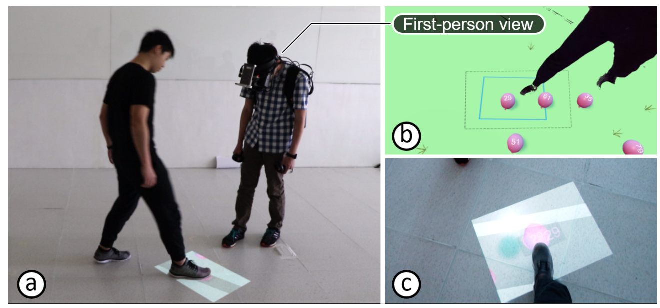

Figure 9. *Trample Balloons* requires the (b) VR user to find out the target balloon and make it appear on the *viewport* while (c) the external user provides the target serial number and trample it by stomping on it.

of the VR user. To provide a more stable view and better locational referencing of the snowman, the VR user then closes the current *viewport* and creates a new one for the external user. He creates a *viewport* in *A-mode* and sets it in front of the seated external user. The content type is set as 3rd person, and camera placed above the model to capture its appearance from a downwards angle (Figure 7e-f). The external user then gives his suggestion based on the view of the full snowman model. To reference the precise location, he uses his foot to touch the snowman's head on the *viewport*. An indicator appearing as a red highlight appears on the snowman model's head to indicate the external user's location of reference (Figure 7g-h). With the indicator, the external user suggests adding a scarf around the snowman's head. After the VR user adds it, the external user leaves and the VR user closes the *viewport*.

Here, *HMD Light* facilitates the VR and external users' communication in a 3D scene design application. Since *HMD Light's* function is to support the users' collaboration here, the application is designed to allow users freedom to decide the *viewport*'s behavior and content type. This way, users can decide based on their situation and requirement. To facilitate users' communication, we set the external users' interaction affordance as a controllable visual indicator for their pointing reference during collaboration.

VR User Direction Indicator

We extend a recent research concept [7,47] to this application by considering the experience of surrounding external users. Here, the VR User will walk to a specific destination in the real world while fully immersed in a virtual spaceship indoor scene (Figure 8a). A pre-programmed path will guide the VR user to a spot in the VE based on the user's destination. When the user reaches the virtual destination, they will concurrently arrive at a corresponding real-world destination. During the walking experience, *HMD Light* projects the display in front of the VR user and shows the walking path calculated by the program, represented with an arrow (Figure 8b). This display aims to inform nearby external users of the VR user's walking direction and of whether their walking direction may collide with the VR user's.

In this application, *HMD Light* acts as an indicator in a dynamic scenario to show VR User's walking direction to external Users. The projected display becomes a message-delivering platform from the VR user. To always visualize the VR user's walking direction, the *viewport* is pre-defined as *T-mode*, while its non-VE content is the planned direction provided by the application itself.

Trample Balloons

Trample Balloons is a collaboration game that requires both the VR user and the external user to cooperate to win. The users are placed in the VE with multiple balloons placing on the floor surrounding them. Each balloon has a number on it, and the users have to cooperate to trample the balloons with the right numbers. In this game, the *viewport* functions as a "window" metaphor to the virtual world. While the external user can only see and explore the virtual world through the *viewport*, the VR user can control the *viewport* position by moving or rotating themselves to visualize the balloon on the *viewport* (Figure 9a). However, only the external user can see the target number on the *viewport* and trample it by stomping (Figure 9b). Hence, during the game, the external user should tell the VR user the target number to help them find the target balloon. When that is found, the external user has to step on and smash it. The goal of this game is to trample all of the balloons in the shortest time.

In this application, *HMD Light* enables asymmetric active interaction between VR and external users. While the external user is responsible for giving the number information and trample balloons, the VR user should find the balloon and move to make it appear on the *viewport*. This makes the application very active since the external user has to follow the *viewport* while the VR user is moving around.

To make this *viewport* display a "window" into the virtual world, its content is produced by placing an orthographic view virtual camera on the top of the *viewport*. The virtual camera captures a top-down view of the virtual world with the field-of-view being the *viewport* size. Also, the *viewport*'s behavior is pre-defined to be *T-mode* so that information is always available to the external user.

Keep Talking and Nobody Explodes

Keep Talking and Nobody Explodes is an adaptation of a popular communication-centric VR game [10]. The VR user is located in front of a time bomb and has to defuse the bomb in time by solving all the puzzles on it (Figure 10a). The external user plays the role of expert, as they can see the solution manual displayed on the *viewport* but cannot see the bomb (Figure 10b). During the game, the VR user verbally describes the bomb appearance to the external user, while the external user verbally provides the correct solution based on the VR user's description and the manual on the *viewport*. The goal of this game is to defuse the bomb in time.

Here, *HMD Light* acts as a display to provide strategy information (the manual) to the external user. This enables both users to collaborate asymmetrically through communication. Unlike the commercial version which requires additional devices for the manual, *HMD Light* displays it into the environment with the HMD built-in projector. This enables the whole experience to be single-device portable.

The *viewport*'s non-VE content references the original game content (the manual). To make the manual always viewable by the external user, its behavior is set as *T-mode*. Since the *viewport* in *T-mode* may "destabilize" the display due to the VR user's head jitter, this adds another game factor that requires the VR user to stay calm for the external user's reading comprehension.

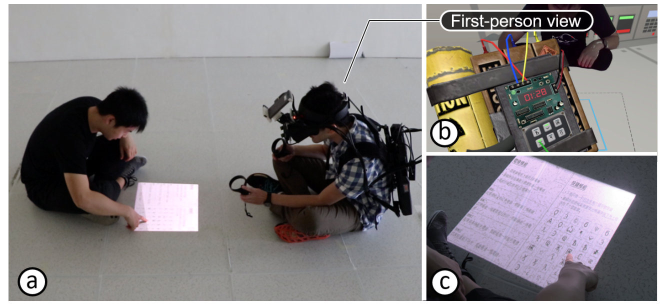

Figure 10. *Keep Talking and Nobody Explodes* is a communication-centric VR game that requires the (b) VR user to defuse the bomb in time by solving all the puzzles on it and (c) the external user provide the solutions from the solution manual displayed on the *viewport*.

USER EVALUATION

To evaluate *HMD Light* interface usability and explore how users perceive interaction via *HMD Light*, we conducted an exploratory user study. We investigated how users interact with *HMD Light* and how the interface supports users' communication. We also evaluate the interface's usability and its effect on VR and external users' social presence during the interaction.

We deployed *HMD Light* in our study with three applications involving VR and external users' collaboration, that is, *VR Scene Design*, *Trample Balloons* and *Keep Talking and Nobody Explodes*. We had participants experience these applications with *HMD Light* followed by questionnaires and an interview for us to gather their feedback on *HMD Light's* interface.

Study Design and Procedure

Our study structure generally followed a within-subjects design with an independent variable, Role, with two conditions, VR user and external user. Participants experienced three applications as the VR and external user to gather each individual's feedback from both perspectives.

Our study took place in a university meeting room containing a 6 x 3.6 m VR playground. Participants were recruited and paired by the experimenter to avoid any communication bias caused by over familiarity between participants. They were first introduced to the study purpose and the *HMD Light* system, then provided with a simple scenario to learn and practice the interface functions. The training ended when the participants felt they could understand and engage in the interaction without the experimenter's help. Afterwards, participants experienced the applications in this order: *VR scene Design, Trample Balloons* and *Keep Talking and Nobody Explodes*.

VR Scene Design

This application started with the experimenter demonstrating the application and its 3D design functions to the VR user participant. After familiarizing with the 3D design interface, they began the application. To encourage VR and external users' collaboration and communication in this task, the VR user was asked to decorate a snowman in the VR scene based on the external user's design idea. The external user was instructed to tell the VR user their design and confirm the VR user's work via the *HMD Light* interface. VR users were provided with a blank snowman model and told to decorate it with our prepared 3D models (e.g. hat, carrot, button, scarf and twig) based on the external user's design. This experience started with the VR user creating a *viewport* and ended when the external user agreed on the created snowman.

Trample Balloons and Keep Talking and Nobody Explodes

In both applications, the experimenter first explained the application's rules and goals (see details in *Application*). Participants were instructed to complete a round of the game as the VR or external user, based on the condition. Both application sessions started with the VR user creating a *viewport* for the external user and ended when the game was over.

Questionnaire and Interview

Participants experienced the three applications in one of the roles, then filled out a post-task questionnaire on topics of system usability (accessibility for the external user) and social presence [18] in four dimensions (Co-presence, Attentional Allocation (AA), Perceived Message Understanding (PMU), Perceived Behavioral Interdependence (BI)) rated on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). They were then interviewed separately with open-ended role-specific questions to gather feedback on system pros/cons, and how they felt during the interaction (Find questionnaire and interview questions in supplementary).

After the first application round, the participants switched roles and went through the above again. At the end, a post-study focus group interview was conducted to get their feedback on communication obstacles during the experience and overall opinions about the *HMD Light* interaction.

Participants

We recruited 12 participants (age 19-34, 6 female) from our local university. All participants reported having used VR devices at least once and four participants had over six months of VR development experience.

Results

We present questionnaire and interview results organized by category. For questionnaires we report the means and standard deviations (from users' ratings within conditions), and any noticeable differences in dimension ratings between user roles (t-values for rating differences between roles are calculated in a paired-samples manner to account for within-user differences).

HMD Light Interface

Usability rating means were (M=5.72, SD=0.92) for VR users and (M=5.4, SD=0.96) for external users.

Most users enjoyed the interface and remarked that they found the novel way of interaction to be fun and engaging. Some even remarked that the experience was surprisingly smooth, given the asymmetry (P2, P5).

Much effort was spent on deciding which *viewport*'s behavior mode and content type best showed they wanted to their partner. Some VR users let the external user choose the *viewport*'s behavior, as the view was intended for them (P9, P10). VR users reported not knowing without feedback if they successfully showed external users what they intended, which caused problems with mutual grounding on the object of discussion (P2, P6). External users wanted to see or alter the *viewport* creation process, such as changing anchor position (P5) or creating it themselves (P6, P9). P9 noted, *"The* viewport *was on the outside and for me, but I didn't have control over it."* Users discussed creating or tweaking the *viewport* (P1, P5, P8, P9), but external users could not see the creation and mid-action VR users could not attend to the *viewport*.

Most VR users chose *T-mode* for convenience, as it did not disappear as easily from the *Projectable Area* as *A-mode*. P11 mentioned *"*T-mode *was easier since I don't have to keep facing the exact same spot for my partner to see the* viewport.*"* But users admitted that the movement of *T-mode* was messier and *A-mode* was preferable for when they wanted to put the view next to a specific object (e.g. the snowman) (P1, P6) and for discussing the view, due to its visual stability (P2).

Comments on content type reflected pros and cons for each type. P12 said, *"I was conflicted between using one or the other; 3rd person gave a clearer view of the object, but I also wanted my partner to see the dynamic activity from my view and not be stuck looking at a static one."* Most users explained that they chose 3rd person view to give a more "stable and holistic view" or to "focus on an object", while 1st person made it harder for the external user to focus on a moving object due to the VR user's viewport swaying or to see the holistic view. But many users chose 1st person to look at the same view as their partner, which was important for collaborating especially when the VR user could not pay attention to the view mid-activity (P1, P2, P7, P8).

Co-presence

The rating means for co-presence were (M=5.85, SD=0.91) for VR users and (M=6.21, SD=0.52) for external users. A paired-samples t-test showed that the difference between roles was near-marginal significance ($t(11)$=-1.42, p=0.18).

External users were all constantly aware of the VR user, who was right in front of them. But the immersed VR users all reported lower sense of presence, sometimes even forgetting the external user was in front of them (P8). Without explicit interaction VR users had no idea what external users were attending to or thinking (P9, P11, P5, P6). P6 said, *"I felt like I couldn't actively interact with the external user, apart from changing my* viewport.*"* However, visualizing the external user and their body gestures made them seem less distant (P1, P3, P7, P10). P5 stated, *"[The VR user] could clearly see me, so it wasn't as uncomfortable to talk to me."* External users wanted to know when they were visible to the VR user (P3).

Attentional Allocation

A paired-samples t-test demonstrated a significant difference between AA ratings by VR users (M=4.56, SD=0.92) and external users (M=5.2, SD=0.76); $t(11)$=-2.27, p<0.05).

VR users reported to only pay attention if external users initiated contact (P2, P10), and focused on the VR task after being told what to do (P2, P4, P5, P12). In fact, they were unable to operate on the VE and communicate with external user simultaneously (P5, P6, P7). Moreover, both user roles expressed that external users could not concurrently focus on the *viewport* details and pay attention to the VR user's person and actions

(P10, P11). P11 said, *"I felt that the external user's attention is mostly on some part of the task in the* viewport*, and not on my person."* The roles experienced asymmetrical restrictions on their attention, which resulted in their interaction taking on a pipeline structure: a series of non-overlapping actions where users could not act and communicate simultaneously. Many users reported examples of this; *"I needed to wait until the VR user was done with their action to do or say anything else."* (P5) and *"If the non-VR user says something, I want to finish what I'm doing before responding."* (P8)

Message Understanding

The mean of ratings for PMU was (M=5.68, SD=0.87) for VR users and (M=5.69, SD=0.82) for external users.

Target objects of conversation (e.g. location of decoration or balloon number) were clear, due to the common display (P1, P4, P5, P8, P11). Some exceptions to this included describing complex actions; P1 said, *"It was sometimes harder to understand [external user's] verbal instructions, such as for how to rotate something."* User perceptions about content included worrying if they had shown content successfully (P5) or feeling an imbalance in interaction content, as VR users were perceived to rely on more content in general (P10).

Behavioral Interdependence

BI ratings saw means of (M=5.89, SD=0.65) for VR users and (M=5.82, SD=0.88) for external users. We observed a correlation between the role means (r=0.66) with a very slight trend towards significance (p=0.19).

Most users remarked that the information relied on by each role was highly asymmetrical; VR users relied most heavily on external user instructions, but for external users it was the *viewport* view from the VR user. There were two types of perceived BI; regarding collaborative activity vs. interaction mechanics. Regarding the application activity, most VR users perceived low levels, since external users did not need to respond as much to the VR user's activities as they did to the external user's instructions. External users also felt that the activity was one-sided, mostly with the VR user relying on them (P6, P10, P11). Some external users felt rather uninvolved due to the lack of more active interaction (P2, P4, P10).

Perceived interactive interdependence was high and came from the non-overlapping knowledge (P3, P8). P7 said, *"When the content is first projected, it's hard for [external user] to tell without additional conversation if the two of us are looking at the same thing."*

DISCUSSION

We saw that *HMD Light* provided affordances which enhanced the depth of asymmetric VR interaction, such as interactive VR user-controlled sharing and VR-relevant dynamic view elements. These affordances also led users to consider new issues, such as interdependence and mediation of control.

Interdependence in Asymmetric Task Collaboration

We uncovered several insights and challenges to asymmetric interaction with high levels of collaboration—the scenario targeted by *HMD Light*. The AA and BI study results reflect the high asymmetry between roles, and its consequences. Apart from their significantly lower AA from the VR user in the questionnaire results, VR users also commented that they often did not attend to the external user. There were many VR factors which contributed to this, including the high level of immersion (causing the forgetting by P8) and feeling of being disconnected from the external user (not clearly knowing their intention, or feeling that the external user was not focused on their person). These issues can make it difficult for the VR user to assert communication.

Asymmetry in communication-necessary information relied on by users raised BI levels. Users needed information exclusive to the other role (e.g. verbal instructions, the right *viewport* content) to establish a clear channel for collaboration, but had to have explicit conversations just to "get on the same page" about how to proceed. We also saw that partners prioritized looking at the same view when choosing *viewport* types. Perceived BI was high even though users had the *viewport*, which was still only a mediation tool and could not break down all between-world boundaries. Users' BI regarding the collaboration task contrasted with perceived BI for the interaction itself, as it was actually a result of the asymmetric interaction (external users felt less involved due to mostly speaking and the active parts of the task were still VR-based).

The above issues caused the interaction to take on the structure of a pipeline with non-overlapping, asynchronous segments of communication and action. The next section discusses the factors that appear to be most important in supporting synchronous collaboration for asymmetric VR interaction.

Mediation of Information and Control

The extent and symmetry of commonly-shared information relating to user state, and balance of control appeared to most heavily influence ease of communication and attitudes towards the interaction. VR and external users expressed that they wanted to know more information, and take more actions in the interaction. VR users wanted to know external users' attention/state were when they were not explicitly interacting, and whether the *viewport* content was shown clearly. Our visualization of body gestures worked towards the former issue, by reducing the distance felt by VR users. But VR users still wanted to interact with the external user in more ways than just changing the *viewport*. Overall, VR users wanted to interact more with external users and know more of their intention and comprehension, both of which are precursors for or contributing factors to communication.

But external users, as outsiders to the VR-centric interaction, wanted to both know more information related to communicating with the VR user and also exert more control in the interaction. They wanted to know when they were visible to the VR user, see the *viewport* creation process, and see more VE content (P9 wanted to zoom in on content, and P10 suggested in-VR sound could be shared). They also felt they should have rights to control the *viewport* creation, control display content, and be more active in the interaction (not just mostly verbal). Lapses in knowledge of partner state leading to complete breaks in communication (*"I had to wait until the VR user was done"* - P5) may also contribute to external users perceiving a lack of control, and hence lower engagement with the interaction. This may show an issue regarding privacy 'transparency' derived from the ability of the VR user to share content in such a controlled and self-curated manner. The push-and-pull between information and control in asymmetric VR interactions shows that we need to work towards affordance symmetry; there is a need to provide information for initiating communication as well as maintaining it, and control that corresponds to interface function and maintains mutual engagement in the interaction.

DESIGN IMPLICATIONS

We present design implications for *HMD Light* and asymmetric VR collaboration based on the study. Asymmetric collaboration magnifies the priority of user state information (what users know or attend to) for establishing communication; interface design should aim to provide these details when possible (e.g. notifying external user when they are visible to the VR user, or showing external user's gaze information to the VR user). This is especially important for the VR user, who is more deeply immersed in the non-interactive VR space. However, due to privacy or social familiarity, we should facilitate VR users' ownership of rights over what information to share, and also make the privacy level chosen by the VR user clear to the external user.

Shared user information media (the *viewport* in our case) should be commonly available in all forms (visually and interactively) to both VR and external users, and not just focus on the sharing function; if we provide a constantly-visible *viewport* preview for the VR user and *viewport* editing control to the external user, facilitating this overlap in control and information can mitigate the previously-mentioned communication pipeline by allowing VR and external users to collaborate in more depth on the shared medium.

We found that VR asymmetry still makes it easy for both roles to feel disconnected or uninvolved in reciprocative collaboration, due to the hard boundary between virtual and physical world; VR users are immersed, and external users have limited ways of reaching them. It is then especially important in this case to design for inter-user social rapport.

LIMITATIONS AND FUTURE WORK

Display Accessibility

Currently, the projection motor helps stabilize the *viewport*, but its low-frequency stepping causes the projector to shake and the display blurs during *Projectable Area* offsetting, resulting in the participants having to wait or ask the VR user to stop moving (P5, P10, P11). We can address this by upgrading the hardware configuration or replacing the motor with a programmable stabilizer to smooth the projector movement.

Mounting the projector on the HMD preserves interface mobility, but this causes the *viewport*'s visibility to be highly influenced by VR user head movement, especially for *A-mode viewports*. Adding a second servo motor can provide a horizontal axis of stabilization and allow the *viewport* to still be visible when within the motors' rotation range. Another solution is decoupling the projector and HMD; Placing it on other body parts, such as the shoulder [19] or waist, allows the display to not be influenced by VR user head movement.

Free-surface Interaction

In this work, the floor is our target display surface, but other possible surfaces can be explored as well. By rotating the projection motor, *HMD Light* can display to different locations, and hence reveal the VR experience for diverse purposes. For instance, projection on the table creates a tabletop surface, and on the wall generates an interactive public display. With the pro-cam unit, this system has the potential to deploy the display on arbitrary surfaces, so further study is required to explore more location-based applications.

Power Dynamic Between VR and External Users

While *HMD Light* strengthens the communication channel between VR and external users, it may affect the VR users' immersive experience due to the external users' presence in their view. This places power in the hands of external users, as their appearance may detract from VR users' immersivity in a way that VR users have less control over. This power dynamic between VR and external users is an interesting topic that has also been discussed in prior work [5, 48]. Our work mainly focuses on the collaboration scenario and hence assumes that both users are willing to be very mutually engaged. When considering practical scenarios in the future, the VR users' presence should be taken care not to be affected easily by external users' presence. For instance, instead of visualizing external users immediately after their approach, a commitment process should be initiated to get VR users' permission, where the VR users should be notified and be able to ignore external users' requests. Only when the VR users accept external users' request, will the communication channel be established.

Privacy Control

Unlike prior works [15] where external users controlled the viewport, we have VR users control the shared content. Although handing viewport control to external users caters the interface in their favor, in a more generalized scenario this may cause VR users' privacy issues. The topic of balancing external users' control against VR users' privacy requires further study, and we hope this work drives discussion on this when considering interaction between VR and external users.

CONCLUSION

In this work, we presented *HMD Light*, a mobile HMD that reveals VR users' VR experience in the physical environment. *HMD Light* aims to resolve the communication gap between VR and external users and advance inter-user interaction. We explored the design space of *HMD Light's* display, presented four different applications, and conducted an exploratory study to evaluate *HMD Light's* usability and its facilitation of VR and external users' collaboration in asymmetric interaction setup. From the results, we find design insights on how to mediate information and control to promote better social rapport and communication efficiency between VR and non-VR users. With the advent of mobile VR interwoven into our lives, we hope that this work can further drive the discussion of the interaction design between VR and external users.

ACKNOWLEDGEMENT

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