Slice of Light: Transparent and Integrative Transition Among Realities in a Multi-HMD-User Environment

Chiu-Hsuan Wang   **Chia-En Tsai**   **Seraphina Yong** *   **Liwei Chan**
Department of Computer Science, National Chiao Tung University, Hsinchu, Taiwan
*NTU IoX Center, National Taiwan University, Taipei, Taiwan
{chwang821014, tsaice05, liweichan}@cs.nctu.edu.tw   *seraphinayong@ntu.edu.tw

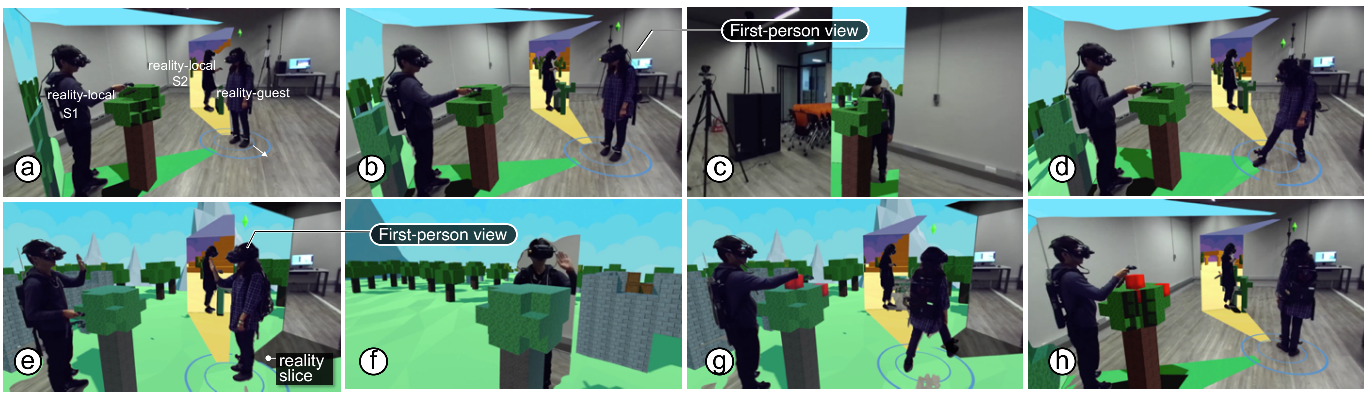

Figure 1. (abc) Slice of Light allows the reality-guest (indicated by a green crystal) to access a sliced preview of HMD users' realities with free walking. (d) She can cross into an HMD user's virtual reality with a natural interaction by stepping on the corresponding slice of light. This enables her to have a face-to-face conversation with the HMD user. (gh) Stepping on the reality slice, she transitions back to the physical environment (continued in Figure 4)

ABSTRACT
This work presents *Slice of Light*, a visualization design created to enhance transparency and integrative transition between realities of Head-Mounted Display (HMD) users sharing the same physical environment. Targeted at reality-guests, *Slice of Light's* design enables guests to view other HMD users' interactions contextualized in their own virtual environments while allowing the guests to navigate among these virtual environments. In this paper, we detail our visualization design and the implementation. We demonstrate *Slice of Light* with a block-world construction scenario that involves a multi-HMD-user environment. VR developer and HCI expert participants were recruited to evaluate the scenario, and responded positively to *Slice of Light*. We discuss their feedback, our design insights, and the limitations of this work.

UIST '20, October 20–23, 2020, Virtual Event, USA

ACM ISBN 978-1-4503-7514-6/20/10 ...$15.00.
DOI: http://dx.doi.org/10.1145/3379337.3415868

Author Keywords
Virtual reality; Multi-realities environment; Spatial augmented reality; Transition interface

CCS Concepts
•**Human-centered computing** → **Mixed / augmented reality;** *Virtual reality; Collaborative interaction;*

INTRODUCTION
The high levels of immersion and visual seclusion provided by HMDs isolate users in virtual environments. To solve the issue of communication gap with the outside world, past research externalized the virtual environment using spatial augmented reality [1, 7, 8, 17]. Externalizing the virtual environment lowers the communication barrier and enables non-VR users to collaborate with VR users. However, these approaches have focused mainly on a rudimentary collaborative configuration which only involves one co-located HMD user.

This work seeks to extend the affordances of communication interaction to more complex scenarios which involve multiple co-located HMD users. This can occur in several ways. For instance, in a VR classroom, students may use VR to explore the provided material or build their artworks. The instructor then needs to actively supervise the different students' learning progress simultaneously or in a heavily interchanging manner.

Or, in a VR content exploration setting, to explore all available applications, users may normally need to traverse through all the environments physically to get further information. In either scenario, current technology does not provide the users with an integrated interface to view across disparate VR activities. This work seeks the utilization of spatial augmented reality to support users in making sense of and navigating among multiple co-located remote realities.

We refer to this kind of environment as a *multi-realities* environment. Here, a *reality* refers to a virtual reality or physical reality. Therefore, we define *multi-realities* environment as a physical environment situating multiple HMD users, each presumably immersed in his or her own virtual reality environment. That being said, in a physical environment with two HMD users, the environment involves three realities: the two virtual realities and the physical reality.

While previous works mainly focused on the interaction between HMD users and non-HMD users [2, 7, 8], we present a similar concept which is based on the same view but considers the interactive scenario where all users are equipped with HMDs. We present the operationalization of the role of an HMD user as a *reality-local* or *reality-guest*. HMD users have the role of a local when fully immersed in a reality, either virtual or physical. As a guest, they are offered the ability to view across and transition between the multiple realities of other HMD users. Our work enables this ability by proposing a visualization design that provides reality-guests with an integrated presentation of multiple realities for their global understanding and smooth transition across these realities.

Slice of Light

We present *Slice of Light*, a visualization design created to enhance transparency and integrative transitioning among realities of HMD users sharing the same physical environment. *Slice of Light* offers each HMD user acting in the role of a guest a visualization constructed by piecing together disconnected remote realities pertaining to all the other HMD users into the reality-guest's own reality.

Figure 1a illustrates the visualization. Each piece resembles a slice of light extending from a HMD user's reality, shining into the reality-guest's reality. This allows a reality-guest to view all other HMD users' interactions contextualized in their own reality. The slice of light also acts as an entryway into the remote reality from which it comes, allowing the reality-guest to transition into it by stepping on the corresponding slice of light with their feet (Figure 1d-e).

Before walking through *Slice of Light* with a scenario, we first define the terms used in our design. *Reality* refers to either a virtual environment or the physical environment. Below, we will define some characterizations of HMD users, namely *presence* and *role*. An HMD user can only have *presence* inside one reality at a time, in which their *role* can take the form of a local or a guest.

Walkthrough: Block-World Construction

Here, we illustrate *Slice of Light* with an education scenario in a VR classroom. The scenario simulates an instructor (a guest) who oversees students' (locals') work progress in their own virtual environments and provides them guidance when needed. The experience involves block-world construction. Two students, S1 and S2, whose presence is set in the virtual environments, VE1 and VE2, and who play the role of locals, create block-based designs. Initially, the instructor's presence is attached to the physical environment as a guest's, indicated by a green crystal above her head. In her view (Figure 1a), two slices of light coming from behind the students in her perspective are laid out in front of her feet. Through the slices, she sees the students' virtual environments and the tasks in their operation. Meanwhile, the majority of the instructor's view is the physical environment, so she can still easily navigate and be aware of other non-HMD students in the same physical environment (Figure 1c). Because the slices of light always orient to her steps, she can walk around a student to observe their work and virtual environment from different perspectives (Figure 1a-b). When she steps on a slice of light with a stride gesture, she steps into the reality of the light, VE1 (Figure 1d-e). While her presence switches into VE1, the slice starts to widen, circling her as the guest until she is fully encompassed. Then, the VE1 scene becomes the new majority of her view, with one slice extending from S2 at VE2 and another new slice, the so-called *reality slice*, extending from the physical reality from where she made the transition, allowing her to transition back to the physical environment when necessary.

Sharing the same presence, the instructor can now see the wider context of S1's interaction in VE1 and talk with S1, but her actions do not directly influence VE1 due to her role as a guest (Figure 1f). Meanwhile, S1 can also see the instructor's appearance in his reality, VE1, and can talk with the instructor. The instructor teaches S1 to add an apple to the tree S1 creates. She then walks back to the physical reality by stepping on the reality slice. Because they are now in different realities, the instructor disappears from S1's view (Figure 1g-h). The walkthrough continues in our section BLOCK-WORLD CONSTRUCTION.

Contribution

This work contributes a visualization interface, *Slice of Light*, to drive the discussion on communication barriers in a multi-HMD-user, multi-realities environment. We suggest framing the communication by referring to reality- locals and guests. We demonstrate *Slice of Light* to provide reality-guests with an integrated presentation for their global understanding and integrative transition across the multiple realities. By facilitating users' transitioning in multiple realities, we enable a new type of mental model structure that promotes users to think and act based on a multi-realities experience.

RELATED WORK

The goal of *Slice of Light* is to provide the reality-guest with an interface that enhances transparent and integrative transitioning among multiple realities in the same physical environment. Hence, Slice of Light involves visualizing HMD user realities and blending them together in physical reality. We review works related to blending multiple realities, bridging HMD users and non-HMD users, and visualizing HMD users' experience.

Mixing Multiple Realities

Mixed-realities techniques have been referred to as mixing of physical and virtual reality, for applications of either augmented reality or augmented virtuality. Spatial augmented reality overlaying virtual elements on the physical elements or environments has been extensively explored for information visualization [32, 28] and entertainment [17, 16, 15]. With the rise of VR technology, more recent research has been focused on augmented virtuality, mixing physical elements into VR for the enhancement of user experience in a virtual environment (VE). For instance, A Dose of Reality [22] suggested that inclusion of physical elements can enhance usability for HMD users immersed in a VE and investigated how a range of blends affects HMD users' process of accessing physical elements. RealityCheck [10] proposed ways to situate physical elements in a VE while considering dynamic adjustment of their appearance for coherent presentation. Contextualized videos [34] embedded live video feeds in the corresponding VE to connect two realities. Roo demonstrated a proof-of-concept system, one reality [30], which sought to show distinct benefits in levels of virtuality on physical interaction. These works focused on pair-wise blending of one reality into another. In comparison, *Slice of Light* explores the extended issue of mixing multiple realities, referring to the physical reality and realities of multiple HMD users in the same physical space.

Recently, Worlds-in-Wedges [23] presented a 3D user interface that supports comparative immersive visualization by presenting the virtual space in volumetric wedges and embedding them with world-in-miniature (WIM) and portal interaction techniques. Similar to Worlds-in-Wedges, *Slice of Light* also introduces a visualization design that presents multiple realities in wedge-shape. But targeting a different scenario, we design *Slice of Light* to manage a multi-HMD-user environment. Therefore, we consider multi-user interactions and different role-switching techniques while designing this interface.

Bridging HMD Users and Co-located Non-HMD Users

Including non-HMD users to assist in HMD users' interaction has been found beneficial in collaborative gaming [8, 19, 7], guidance [31, 24, 13], in-situ design [1, 11], and even provision of haptic feedback [3, 4, 1]. In previous works, asymmetric designs were widely employed to enable the access of non-HMD users to HMD users' interactions in aspects complementary to the HMD users' primary experience, such as via different viewing perspectives [17, 13] or representations [24], playing different interaction roles [1], or supporting different interaction modalities [3, 4]. Non-HMD users in these cases played an active role in assisting in HMD users' performance.

Another body of research emphasized seeing non-HMD users as reality-guests due to the concern of HMD users lacking awareness of the outside world, which could negatively impact the reality-guests' experience. HMD users can silently switch back and forth between virtual and real environments, while reality-guests have no clue about the current presence of the HMD users. FrontFace [2] suggested an add-on display on the HMD to reveal more information for guests. ShareSpace [35] considered the shared use of physical space between HMD users and guests and suggested tangible tools that they could both grab when in negotiation.

As in prior studies [2, 8], this work seeks to resolve lost communication between guests and HMD users. However, unlike prior studies, which considered a guest to be a non-HMD user, *Slice of Light* addresses *reality-guests*, giving guests the ability to access an HMD user's virtual environment directly through their dual-functioning HMD.

Presentation of HMD Users' Experience

Several attempts have been made to display HMD users' visual experience to guests in an integrated, coherent manner. At a minimum level, for instance, HMD users' facial expressions [20, 2] or viewport image [29, 2, 8] are shown on the HMD's add-on front-facing screen. For guests to see the HMD users' VE, previous works have explored projecting a top-down presentation of the VE on the floor [7]. Furthermore, an HMD user's surrounding views are revealed via projections on four sides of a cubic CAVE system [14] in which the HMD user is situated. Guests can walk around the cubic system to browse the HMD user's experience. The above methods do not require a display from the guests but are subject to a flattened presentation of a VE, owing to inherent limits of 2D display. Using mobile screens allows guests to access a 3D perspective of the HMD user's VE by pointing the screen at the HMD user [8]. Moreover, guests can access an augmented perspective without obstruction by using a pair of augmented reality glasses [17]. Previous work exploring spatial augmented reality has dedicated to representing a single HMD user's reality. In this work, *Slice of Light* was designed to spatially present realities of multiple HMD users. Because each reality, either virtual or physical, is a complete 3D environment, the unique challenge *Slice of Light* deals with is the presentation of them in a single view while still preserving the contexts of all HMD users' interaction.

INTERACTION DESIGN

To design the interface for navigating co-located multi-realities, we briefly explore envisioned use cases and challenges of this interface and derive our design requirements from these presented cases.

Envisioned Use Cases and Challenges

When managing a multi-HMD-user environment, a HMD user may need to easily view all realities' content, location, and owners with minimal effort. For example, in a multiple-student VR-based training course, the instructor would likely need to simultaneously monitor all students' learning progress to manage students' need for assistance. Without sufficient cues and contextualized presentation of the co-located HMD users' reality content, they may lack a sense of what and where reality content and users are, reducing efficiency in managing and interacting with students across these realities.

When HMD users consider a remote reality, they may need to preview before transitioning into it. Apart from basic transitioning into realities, the interface should facilitate gradual or step-by-step informational "testing the waters" instead of requiring users to prematurely immerse into a VR experience.

Lastly, after transitioning into a reality, the now-immersed HMD users may want to perform activities that fully engage in it, or collaborate with other reality users. For instance, in a VR workspace setting, a designer may transition into co-workers' realities and work with them to complete a larger project, e.g. a video game with many VR scenes. Since these co-located HMD users may exist across separate realities, we should enable balanced action-taking between reality-immersed users and users travelling across realities; these two types of users are likely engaged in different modes of interaction, such as concentrating on a task vs. exploration.

Design Requirement

Based on the use cases we envision, we list the design requirements that we account for in our proposed visualization design for HMD users. (1) Transparency: The design should be able to display multiple HMD users' presence (e.g., the realities in which they are situated) and allow them to view across and locate them with minimal effort. (2) Transition between realities: The design should support a user's transition into other HMD users' realities, in order to facilitate more engaged interaction. (3) Facilitate role switching: The design should allow HMD users to switch roles between local or guest, and communicate user roles to users through the design. Since guests have heightened ability of transitioning, the design should be considerate of the balance of interaction capability between locals and guests.

In this paper, to avoid users' memorization and conflict of gestures or controller functions with VR applications, the *Slice of Light* interface is designed with natural interaction in mind. Thus, while many possible designs can represent the realities, we pick the slice shape for a natural interface as the shape's meaning "part of a whole" affords a more natural association to "part of a virtual world", and hence the affordance to transition to other realities. A stride gesture is chosen to produce the transition, as it represents "stepping into" another reality. In the following section, we provide details on how *Slice of Light* meets these design requirements (DR).

Visual Representation

In a guest's view, there is a slice of light extending from behind each HMD user towards the guest. This slice of light in the shape of a 3D wedge resembles a sliced duplicate of the HMD user's reality in the guest's current reality. A thin cutout projection of the virtual environment in the guest's perspective is displayed on the inner surface of the 3D wedge (Figure 2). The volume of the 3D wedge contains 3D elements that fall inside the range of the slice of light. This allows the wedge to present not only the background environment of the reality in which the HMD user is situated but also the foreground interaction of the HMD user. As a result, the slices of light from all HMD users blend into the guest's current reality to form an integrative presentation of where these HMD users are situated and how they behave (*DR: Transparency*). These slices of light are laid out in the guest's current reality such that the guest can view every reality alongside his or her own reality at once (*DR: Transparency*).

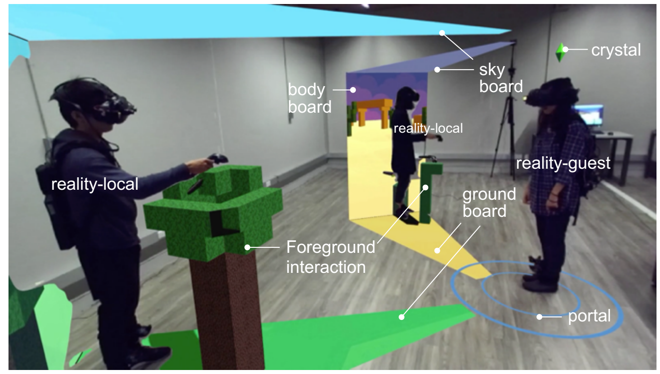

Figure 2. ***Slice of Light*** **presents to a guest the interaction context of an HMD user by displaying a sliced duplicate of the experience including the background scene and the foreground interaction.**

HMD Users' Spatial Cues

Slices of light arrive by the feet of a guest within range of the *Portal*, a ring-shaped widget on the ground that follows the guest (Figure 2). These slice interfaces on the Portal encode the HMD users' orientations and distances relative to the guest, using their angles in relation to the Portal and how close they are to the inner ring of the Portal, resembling the offscreen indicator design [9] (*DR: Transparency*). Because we also need to map physical distance to a short portion of the ring, our design favors the display of HMD users in close range by applying an exponential mapping function set to compress far ones. HMD users beyond a distance of, say, 5m from the guest are excluded from the visualization to avoid visual clutter. This cutout threshold is dependent on applications.

Transition Function

The Portal implements the transition function, which allows a guest to enter an HMD user's reality by stepping on the corresponding slice of light on the Portal. We determined the inner radius of the Portal such that the guest would not inadvertently step on the ring region in free walking navigation. On the flip side, to reach the Portal region, the guest needs to take a greater stride.

Once the guest places one foot on a slice of light, the light promptly expands two times wider for visual feedback (Figure 3). Retracting the step cancels the intent, which also reverts the expansion. When the guest completes the stride gesture with their second foot, a transition to the corresponding reality is activated. The sliced light starts to expand horizontally until it fully immerses the guest. Then, slices of light from other HMD users update in the new view and the interaction continues (*DR: Transition between realities*).

When a guest who is based in physical reality steps into a virtual reality, a slice of light, called the *reality slice*, extending from the physical reality at where the guest made the transition is added to the guest's current reality (Figure 1e). This slice of light keeps the door open for the guest to walk back into the physical environment.

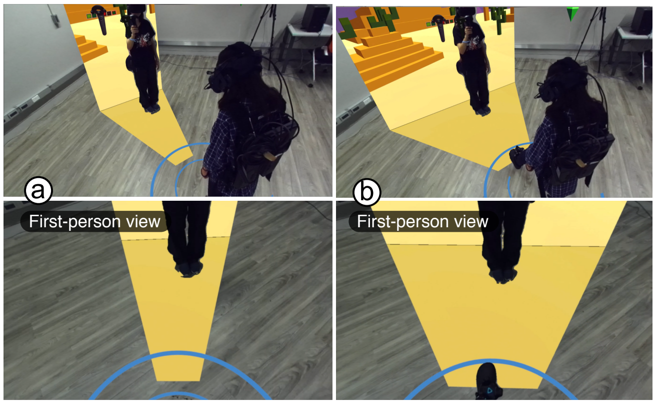

Figure 3. A slice of light widens when the user steps on it with one foot.

Mediating Locals and Guests

Aside from the function which allows HMD users to switch between a local or guest role, we devise access control of guests to a local's reality as per below, to maintain equality in interaction between them.

HMD users, no matter their role as a local or guest, have open communication channels when sharing the same reality, which means they are visible to and can talk to each other. This enables guests to fully communicate with locals, such as providing guidance with natural voice or gestures, similar to behaving as a spectator. However, only if guests switch to the role of a local can they become an influencer so their actions have direct influence on the reality, e.g., to modify the reality. To identify guests from locals in each other's view, a green crystal appears above the guest's head, suggesting their heightened ability (*DR: Facilitate role switching*). With a two-step design which requires guests to turn into a local to gain the influence on a reality, we aim to maintain locals' awareness of other users' significance to the reality.

Furthermore, locals are no different from typical HMD users immersed in a virtual environment. When two locals share the same reality in their presence, it is equivalent to virtually co-located collaboration.

BLOCK-WORLD CONSTRUCTION (CONTINUED)

We have presented the design and basic interaction offered by the *Slice of Light* interface. We now demonstrate the interface with the continued multi-realities scenario.

Continuing the *Walkthrough* (pg. 2), the instructor situated in the physical reality now turns to S2. Through S2's slice of light, the instructor has a first impression of S2's virtual environment, a desert. The instructor previews S2's work by stepping one foot into S2's slice. She then brings forward the second foot, and the transition takes her into VE2 (Figure 4a-b). Likewise, the majority of her view is of VE2 (Figure 4c), augmented with a slice from VE1 at S1's location and a reality slice from the location in physical reality from which she made the transition.

At this moment in time, S1 has completed his work in VE1. S1 turns on the *Slice of Light* function, switching to the role of a guest. Then, three slices appear in his reality. Two slices are from the instructor and S2, both situated in VE2. The third slice is a reality slice at the place where S1 first entered a virtual reality from the physical reality (Figure 4e). S1 walks toward S2 and takes the stride into VE2 on the way (Figure 4d-f). Now, the instructor, S1, and S2 are all situated in the same reality, VE2, so they can see each other in their views. Green crystals appear over the instructor and S1, indicating their role as guests (Figure 4f-g).

S1 initially informs the instructor of his completion and then walks to stand in front of S2. Talking with S2 about how to provide assistance, S1 then switches his role to a local, which dismisses the green crystal. S1 then can start to help grow the cactus (Figure 4h). The instructor strides back to the physical reality (Figure 4i-j) and looks back at S1 and S2 before leaving the room (Figure 4kl).

SYSTEM IMPLEMENTATION

Figure 5 displays the equipment of our HMD users. We used an HTC VIVE Pro HMD for its built-in front-facing stereos. However, the HTC VIVE Pro cameras limit the video resolutions to 480p, which profoundly degrades user experience for mixed-realities presentation. Instead, we used an add-on stereo-camera kit, ZED [1], which can support 720p video resolution at 60 Hz, as well as functions such as depth-sensing, spatial mapping, and easy integration into the stream environment in Unity. To track users' foot positions, we attached Vive trackers to the shoes. A physical switch added to the HMD provides an easy-to-access interface for swapping between the roles of guest and local (*DR: Facilitate role switching*). The system ran on a backpack VR PC (MSI 7RE, GTX1070, 16G) worn by each user. All HMDs used the same set of lighthouse-tracking systems, so all HMD users shared integrated tracking coordinates.

To compose a *Slice of Light* view, we need to blend all HMD users' realities into the guest's reality. Instead of rendering all the virtual environments simultaneously in one local reality [23], we streamed the rendered data from each HMD user to the guest's reality in real-time. This enables the flexibility to apply the system to any VR application as a portal interface without the need for major modifications or other VR applications.

Blending all the realities requires access to these realities on the fly, which can cause severe network latency without careful design. We implemented a private network platform whose framework resembles a multi-user chatroom for a multi-HMD-user environment. Once HMD users log on to the platform, each pair of HMD users can use a two-way transmission channel using WebRTC to exchange media data such as video streams, tracking data (e.g., HMD positions), and interaction data.

Formatting a Slice of Light

After the *slice of light* function is turned on, the guest program constantly collects the following information from each HMD user to gather the materials required for the composition of the interface: (1) the HMD user's position and orientation, (2)

[1] https://www.stereolabs.com/

Figure 4. The walkthrough continued from Figure 1: (abc) She walks into VE2, the reality of the HMD user, S2. (de) Later, the HMD user S1 switches to the guest role and joins VE2. (f) S1 talks to S2, asking to help. (g) Both S1 and S2 are in the view of the guest. (h) To interact in VE2, S1 switches to the local role and starts building the scene with S2. (ih) The guest walks back to the physical environment by walking across the reality slice. (kl) She looks back to see that they are working well.

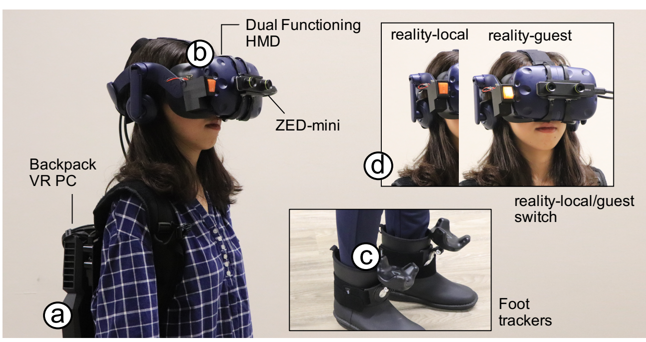

Figure 5. The HMD user wears a backpack VR PC, (b) a dual-functioning HMD whose video-see-through augmented reality is enabled with a ZED stereo mini, (c) foot trackers, and (d) an add-on switch on the HMD to swap between the local and guest roles.

the guest's view of the HMD user's reality, and (3) the 3D elements that fall within the slice volume in the HMD user's reality.

Figure 6 depicts the procedure for acquiring (2). The guest first sends his or her viewport information (e.g., HMD position/orientation), which the HMD user uses to set a virtual camera in his or her reality. Then, the HMD user sends the camera's viewport image back. The viewport extends 140 degrees vertically and 45 degrees horizontally, and the texture resolution is set to 2000 x 6000 (width x height) to maintain display quality. The 140-degree height was devised to include the ground and the sky, while the 45-degree width is to accommodate enough content elements needed for presenting the visual effect of stepping into a slice of light. Texture resolution was carefully tested to strike a balance between visual quality and transmission latency over a wireless network on WiFi 5GHz. In our implementation, this resolution allowed 45 fps with approximate latency at 90 ms over streaming on three HMD users.

The guest program uses the image to prepare the visuals of a slice of light. First, we position the image in the guest's reality to resemble how it is captured. Because the image contains a field of view of 45 x 140 degrees, the actual display size to maintain the field of view depends on how far away it is viewed by the guest. In our design, the slice of light is positioned 50 cm behind the HMD user from the guest's perspective, facing the guest. Accordingly, the display size is calculated and a textured board using the image is created and positioned at the same height of the guest's viewport.

Sky Board, Body Board, and Ground Board

Referring to Figure 6a, we cut off from two sides of the board depending on the width needed for a visual effect. In a default state, we used a width of 1.2 m to form a background board behind the HMD user. When the guest steps on a slice with one foot, we set the background board to be two times wider, with a maximum width of 2.4 m. Then, we divide the board into three segments: the sky, the body, and the ground boards at 2 m height and 0 m height on the ground level, respectively. Keeping them hinge-linked, we folded the sky and the ground boards 90 degrees toward the guest.

Shaping Spatial Traits

We squeezed the sky and ground boards on the side of the guest to be half their original width such that they form a wedge shape pointing at the guest. We added folding lines between the connecting boards and darkened the sky and ground boards to simulate shading from the folding structure, which also enhances their geometric traits. Then, we stretched the ground board until it reached the Portal region by the guest's feet, as displayed in Figure 7a. In the implementation, the Portal region is set to a radius between 35 cm and 70 cm, centering on the guest head position. The extension end of a ground board is mapped to this range using its physical distance to the guest. To avoid potential clutter, HMD users beyond 5 m from the guest are excluded in the interface. According to [21], the average stride length is 75 cm (2.4 ft), measured from heel to heel in continuous walking. Our design, made for walking navigation indoors and targeting users from Asia in our institute, is comparably short. We piloted the threshold at 35 cm with our users, with the intent to reduce their effort in making the stride gesture.

To deal with visual confusion which may occur when two slices overlap, we also prioritize presentation of slices according to their distance from the guest, so that closer slices that are usually more important to the guest are positioned above the far slices, as displayed in Figure 8.

Foreground 3D Elements

A slice of light composed of a sky, body, and ground boards set behind an HMD user only displays a flattened version of the HMD user's reality. Board images alone cannot capture the HMD user's foreground interaction in the three dimensional space, which is important for making sense of the observed HMD user's interaction. For this purpose, the guest program also continuously collects the status of 3D elements in the observed HMD user's reality that fall within the range of the slice of light.

It is worth noting that our approach to capture the slice's content via streaming a virtual camera's image is generalizable. However, streaming 3D elements is tricky because recreating their appearance in the guest's reality will have to track down to the elements' materials, their reflection factors, the environment lighting, and so on. Our demonstration on block-world construction is simple enough, so we only stream their geographic information. In the future, a more developed framework accounting for this rendering issue is needed.

Placing HMD Users between Boards and Foregrounds

For the spatial representation to be correct, the guest should see an HMD user contained by a slice of light, which means, from the perspective of the guest, the HMD user would be presented within the volume formed by the boards and behind the foreground elements. This requires extracting the appearance of the HMD user based on RGBD images provided by the guest's front-facing ZED mini stereo camera.

To implement the effect, we use the techniques of stencil buffer[2] and multi-pass[3] in Unity Shader. We place filtering boards, whose geometric properties are identical to the default boards of the slice of light, behind the HMD user and assign it a unique stencil value ID. Because the HMD user should be well covered by the filtering boards, this allows us to extract only those pixels in the ZED's RGBD images that fall within the range of the filtering boards (e.g., the slice of light) very efficiently, processed in Shader.

[2]https://docs.unity3d.com/Manual/SL-Stencil.html
[3]https://docs.unity3d.com/Manual/SL-Pass.html

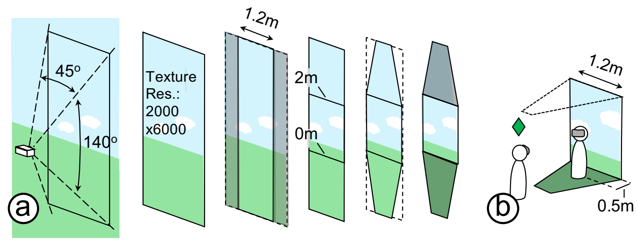

Figure 6. (a) The preparation of the sky board, body board, and ground board that constitute the slice of light interface. (b) The slice of light is placed 50 cm behind the HMD user in the view of the guest.

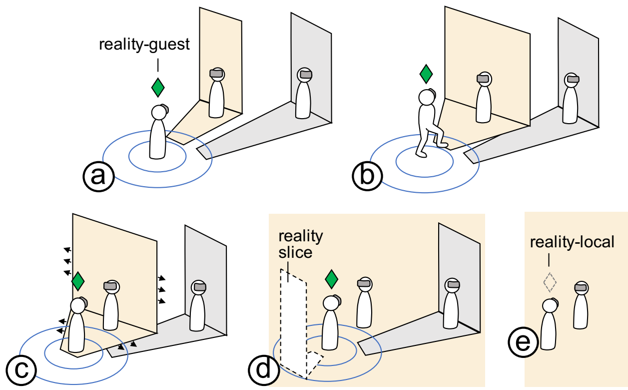

Figure 7. (a) Slices of light extend to a guest by the *Portal* region, the closer to the guest, the further from the inner region. (b) A slice of light widens to give a preview when stepped on with one foot and (c) continuously expands to fill up the guest's view when stepped on with both feet. (d) Partially immersed in the virtual environment, the guest can still keep track of important contexts in other virtual environments and the physical environment via slices of light. (e) Switching to the role of a local, he or she has influence on the virtual environment.

Stepping into a Slice of Light

We attached a Vive tracker on each ankle of the HMD user to detect if they step into the ground board of a slice. When the HMD user steps in with one foot, the slice expands promptly to two times as wide (Figure 7a-b).

When the HMD user steps in with both feet, the slice will continuously expand to fill (Figure 7c). To provide this expansion effect, we temporarily upscale the board's field of view to 140 degrees wide and request a resolution of 3500 x 3500 to maintain the same transmission burden. This new board image with a 140 (H) x 140 (V) field of view can simulate an expansion to cover the HMD user's viewport. Meanwhile, the system of the HMD user preloads the reality to enter (Figure 7d). The HMD user transitions into the new reality, followed by updates of slices of light to reflect new proximities. Because the HMD user is in the role of a guest, we disable his or her direct interaction on the reality. When the HMD user becomes a local by flipping the switch on the HMD, we dismiss the slice of light visual interface and activate their interaction to influence the reality (Figure 7e).

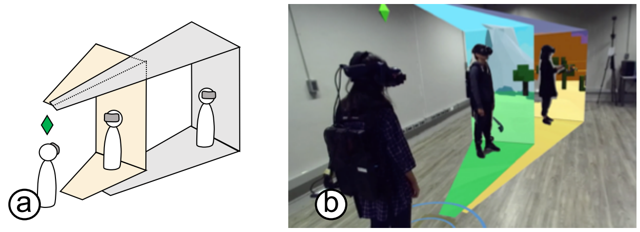

Figure 8. Overlap handling.

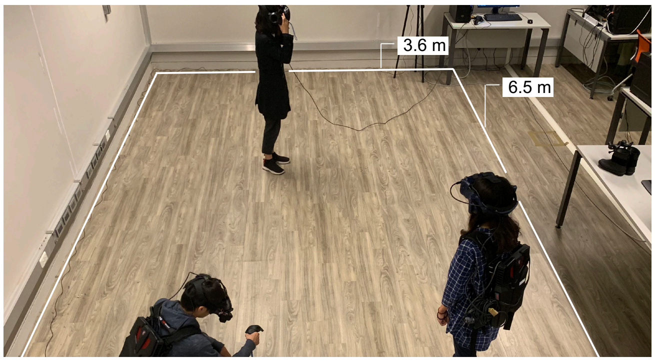

Figure 9. The environmental setup of the user study.

Reality Slice: Back to the Physical Environment

When an HMD user transitions to a virtual reality from the physical reality, we leave a slice of light, called the *reality slice*, as an entry back to the physical reality 1 m behind where the user made the transition (Figure Figure 7d). Similarly, the reality slice is implemented with stencil buffer and multi-pass in Unity Shader.

EXPERT STUDY

We conducted an expert study to gain feedback on the effectiveness and usability of the *Slice of Light* interface. We were interested in whether *Slice of Light* could help users communicate interactions in a *multi-realities* environment.

Participants

We recruited six interdisciplinary experts (age: 24-45, 1 female) from our local university. They were composed of four experts in VR interaction design (one graduate assistant and three research associates) and two HCI experts (research associates).

Task and Procedure

The expert study consisted of the following stages, starting from introduction of the interface, experiencing each of the provided applications, and ending with an interview.

Introduction and Training (20-30 minutes)

Participants were first given an introduction to the *Slice of Light* system and the study. To familiarize them with the system, they were provided with a simple scenario to learn and practice each function. The experimenter described the interactions verbally. The training persisted until all participants could understand and engage in the interaction without any help.

Scenario: Multi-User Block-World Construction (20 minutes)

The experimenter explained to participants a narrative modified from the block-construction Walkthrough. They were asked to complete the given tasks: 1) Enter the first HMD user's virtual environment (S1, VE1) and provide suggestions to S1 regarding the construction. 2) Enter the second HMD user's virtual environment (S2, VE2) and build the world with S2. 3) Instruct S1 to complete the construction when S1 joins later. 4) Go back to the physical reality.

Questionnaire and Interview (20-30 minutes)

The study concluded with a post-task questionnaire and a semi-structured interview. The questionnaire collected participants' feedback on the system's effectiveness and usability, as well as the comprehension and intuitivity of each part of *Slice of Light* (slice, transition, role switching), rated on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). The experts were then interviewed with open-ended questions to further gain their feedback on how the system helped their communications in a multi-realities environment and how the design could be applied in the future.

Results and Discussion

All participants completed the tasks and responded positively to *Slice of Light*, considering it easy to use (Mean = 5.8, SD = 0.9) and easy to learn (Mean = 6.5, SD = 0.8) in both scenarios. Regarding the block-world construction, they agreed it helped to learn other HMD users' virtual environments (Mean = 6.3, SD = 0.6) and supervise them for communication (Mean = 6, SD = 0.6). We present a detailed analysis of each function and participants' suggestions to improve and explore in the future.

Transparency

Participants positively considered the visual design of *Slice of Light* as easy to understand (Mean = 6.7, SD = 0.5) and helpful for understanding other HMD users' virtual environments (Mean = 6.5, SD = 0.5). They reported that *"[Slice] is effective to make sense of HMD users' status"*; *"slices of light nicely embodies [HMD] users' virtual environment, their interaction and movement using limited space."*

Some room for improvement has been suggested by the participants. Visual clutter is a concern when more slices are involved. P2 suggested to visually emphasize only the slice under the user's focus (e.g., head cursor) while tuning down other slices by, for example, decreasing their contrast or brightness. They also mentioned that when slices are close enough, gaps between them might be confused as slices that do not actually exist. It seems that modulating the visual saliency of slices to differentiate them from the guest's current reality is beneficial for the above concerns.

Foreground Elements

Furthermore, participants recognized that foreground objects allowed them to preview the interaction an HMD user was performing (Mean = 6.5, SD = 0.5). Their remarks included, P1: *"foreground interaction seems to have more important information than the background scene to learn an HMD user's task"*; P4: *"Though foreground elements may not be full observable due to the cutout by the slice, I felt the partial information is sufficient to draw the guest's interests to look* *closer and make sense of the user's interaction."* P1 pointed it out as a concern and suggested rendering all foreground elements involved in the user's interaction or widening the slice to cover the full foreground. However, P1 also mentioned it has to account for the scale of the foreground elements. Therefore, the current design approach may still be a better balance.

Spatial Cues
Participants recognized that the spatial cues embedded in the design of the Portal helped in understanding surrounding HMD users' relative positions and distance (Mean = 5.3, SD = 0.8). However, they pointed out that the action of tilting the head down to view the interface on the floor was ergonomically difficult. They stated, *"a glance of the slices is sufficient to grasp spatial information; even if it is to find out an HMD user in the behind, I prefer turning back instead of looking down on the Portal."*

Transition Interaction
Participants reported that the transition interaction of *Slice of Light* is intuitive (Mean = 6.3, SD = 1). Their remarks included, *"It makes teleportation easy because it only asks to step into it."* However, echoing the same ergonomics concern due to the fact that the strike gesture involves hitting an interface on the floor, P2 said, *"once learnt the interaction, I started to try to step in a slice without looking at it on the floor to reduce the effort; however, not only the blind operation may make it undershoot or overshoot the interface, I found it may cause a worry of feet bumping into obstacles that can cause injury."* This highlights that the foot interface needs to be customized for participants' stride size to better support their blind operation, and the slice of light should warn of potential hazards due to obstacles (e.g., by applying color shading). Moreover, because the stride gesture was designed with natural interaction in mind, it might be more appropriate to apply in a spacious environment. Future work can consider more space-efficient gestures, such as foot tapping or using voice commands.

Local and Guest
Participants stated that switching roles on the HMD using a physical button is easy (Mean = 6.5, SD = 0.5) and understandable (Mean = 5.7, SD = 1.5). They liked the control set directly on the HMD, resembling the idea of literally switching perspectives. All participants considered the use of the crystal to indicate an HMD user's guest role to be easy to understand (Mean = 4.8, SD = 1.5). P5 pointed out the crystal may not easily observable, and suggested to apply transparency directly on the appearance of the guests. Additionally, P4 mentioned a moment of shock when a user suddenly appeared in his reality since he did not see the user appearing behind him and only found out about it later. P4 suggested to provide on-screen notifications of the arriving users.

Our design asks guests to turn into a local to gain direct influence on a reality. While participants generally agreed the design was easy to understand, P2 and P4 pointed out we can further speed up cooperation by letting guests directly influence without switching roles, considering the strong intention of stride-gesture they had to have made. We agreed with their opinion but we wish to emphasize that *Slice of Light* is devised to facilitate equality between locals and guests via explicit communication. Locals should be notified if a guest in the same reality turned into a local, so they would know of a new influencer who can now also modify the reality.

DESIGN INSIGHTS
Based on the participants' reviews and suggestions, we deliver insights about how to better design an interface that helps users manage and transition among multiple realities. The scope of these design insights include the interface's visual design, transition interaction style, and mediation between the *reality-local* and *reality-guest*.

Transparency vs. Visual Clutter
When presenting HMD users' experience, occlusion and visual clutter are inevitable if more HMD users appear in guests' view. Here, we suggest some solution directions worth exploring, but careful evaluations are needed in future work. (1) Visual scaling: Regarding occlusion, which may be caused by multiple HMD users appearing in the guest's line of view, the scale of the visual design can be adjusted based on the distance from a 'target' user if an occlusion is detected by the system. This helps to better facilitate accessibility to the context from a HMD user who may be behind another HMD user. (2) Access control: To avoid visual cluttering, one can apply access control options to enable with priority the presentation of HMD users who are of particular interest. The access control can be dependent on distance range, application type, or predefined groups. For instance, new students can be visualized in a group since they need more assistance than senior students. (3) Interactive control: Apart from applying access control, elements of the visual context can be displayed or dismissed via gaze or hand gestures. As none of the above can fully resolve the issue of visual complexity on their own, they should be considered in tandem, and further study is required to assess and refine these proposed functionalities.

Space-Efficient Transition Interaction
In this work, we proposed foot gestures to interact with the *Slice of Light* interface. Foot gestures provide natural interaction, such as in our case with the interface on the ground, which improves interaction learnability. However, this may cause fatigue in the case of frequent crossing between realities and can be error-prone without customization of individual differences such as stride length. Also, sufficient space is needed, or a collision might happen when performing stride gestures. Other gestures such as foot-tapping or other hands-free navigation gestures [18, 33] for the ground interface might be considered for their efficiency in terms of space and effort. Or, a GUI menu using hand controllers to select may be the most ergonomically-efficient option, but requires the additional resource of external devices and more evaluation to create a usable GUI design.

Guest Efficiency vs. Local Awareness
Owing to the guests' heightened ability to access and influence a local's reality, it is important to communicate their participation to the locals, so as to maintain equality between them. For

instance, guests may enter a reality unnoticed by the locals. To ensure locals' awareness, the system can communicate with explicit on-screen notifications of e.g., someone just joined as a guest or turned into a local, beside the passive crystal indicators on guests' head. Our two-step design which adds leveled accessibility on guests may slow their direct cooperation to locals, but is meant for locals' leveled awareness. In a use case asking for more efficient communication, one can further heighten guests to have direct influence, but further study should be conducted to learn the potential impacts of this on locals.

LIMITATION AND FUTURE WORK

While *Slice of Light* can provide users with an integrative interface for transitioning between realities while navigating in a multi-HMD-user environment, some limitations relating to the users' experience can still be improved upon. Additionally, while we focus in this work on deploying *Slice of Light* in a co-located multi-HMD-user environment, the flexibility of *Slice of Light's* interface concept allows it to be applied to other scenarios as well. Here, we explore and list some directions in which the *Slice of Light* interface can be improved and describe how it can be deployed to other applications.

Transition Notification and Permission

In this work, we allow HMD users to transition between realities without enforcing permissions, in order to demonstrate the interface's feature at a more fundamental stage. During our study, participants suggested that it may be better to notify VR locals when guests are about to transition into their local realities, as well as when a guest turns into a local. Message notifications [6, 12] are a possible approach for delivering these messages in VR. Or, other interruption methods and approaches to notification timing [5, 26] can be discussed in the future to provide locals a better user experience. Furthermore, due to privacy concerns of VR locals, locals may be enabled to enforce permissions that facilitate securing of private reality content when guests would like to transition into their realities. This can be done by adding a commitment process for guests to obtain locals' permission after they send a 'visitation' request to the locals.

Privacy Management

Because *Slice of Light* reveals one's interaction context, the privacy issue needs to be considered, and customization of the level of reveal is needed. We have assumed a collaborative environment, such as our scenario involving an instructor and students, to best demonstrate the benefits of *Slice of Light*. For various privacy concerns, one could apply strategies such as (1) semantic abstraction: display application name or type, not the actual visuals, or (2) visual manipulation: blur, darken, or mask out content, which also hints at the user's privacy concerns. We look forward to more research into this space.

Including Non-HMD Guests

While this work referred to guests as specifically HMD-wearing guests, our design does not conflict with previous works for non-HMD guests using an add-on display on the HMD [2, 8], floor projection [7], or mobile augmented reality [35]. When considering colocated non-HMD users as active guests to HMD users' interactions, HMD users might wish to include them in their reality for collaboration. We believe complicated environments like this involving HMD and non-HMD users, and locals and guests, will soon arrive following the advent of mobile VR. Extensive studies are needed to develop an inclusive design for fluent asymmetric communication.

Remote User Collaboration

In this work, while we assumed all the HMD users share the same physical environment in our scenario, *Slice of Light* is also flexible enough to apply to remote user setups as well. In a mixture setup of VR and AR users cooperation, with the adding of a 3D avatar to represent each remote user, *Slice of Light* can act as an interface that links together the remote users' environment. This enables the users to collaborate face-to-face via the avatars and the slice of light itself serves as a portal to transport between user environments. Moreover, with the physical environment being fully captured, *Slice of Light* can also be applied to a telepresence interface that serves primarily to connect different locations as well [25, 27]. Further study is needed to realize the remote user setup, but we believe the core interaction component of *Slice of Light* can promote considerations of mixed reality collaboration.

System and Network Latency

It is suggested to keep at least 90 fps performance to maintain user experience and avoid VR sickness. However, the data transmission among HMD users necessary for the formation of slices of light can cause significant latency due to networking. In our implementation, we downgraded the transmitted resolution in favor of low latency. Still, our implementation only afforded smooth experience up to three users. Future studies may want to suggest the lowest network requirement against numbers of users. In addition, future work can adjust the display quality of slices of light according to user attention, such as suspending those slices outside of the user viewport and reducing the resolution of slices not under user gaze.

CONCLUSION

This work presented *Slice of Light*, a visualization interface using spatial augmented reality to communicate the immersive experiences of multiple colocated HMD users for reality-guests. We devised the design for transparency and smooth transition, enabling reality-guests to view the other HMD users' interactions contextualized in their own virtual environments while navigating among these virtual environments. With the advent of mobile VR interwoven into our daily working and living spaces, it is important to improve comprehension among HMD workers in the same physical space to streamline their collaboration. We hope this work offers an example to drive the discussion.

ACKNOWLEDGEMENT

This research was supported in part by the Ministry of Science and Technology of Taiwan (MOST109-2628-E-009-010-MY3, 109-2223-E-007-001-MY3, 109-2218-E-011-011, 108-2633-E-002-001, 106-2923-E-002-013-MY3). We also thank the reviewers for their thoughtful comments.

REFERENCES

[1] Sang-Gyun An, Yongkwan Kim, Joon Hyub Lee, and Seok-Hyung Bae. 2017. Collaborative Experience Prototyping of Automotive Interior in VR with 3D Sketching and Haptic Helpers. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17)*. ACM, New York, NY, USA, 183–192. DOI: http://dx.doi.org/10.1145/3122986.3123002

[2] Liwei Chan and Kouta Minamizawa. 2017. FrontFace: Facilitating Communication Between HMD Users and Outsiders Using Front-facing-screen HMDs. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '17)*. ACM, New York, NY, USA, Article 22, 5 pages. DOI: http://dx.doi.org/10.1145/3098279.3098548

[3] Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic Turk: A Motion Platform Based on People. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 3463–3472. DOI: http://dx.doi.org/10.1145/2556288.2557101

[4] Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: Physical Virtual Reality Based on People. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 417–426. DOI: http://dx.doi.org/10.1145/2807442.2807463

[5] Ceenu George, Philipp Janssen, David Heuss, and Florian Alt. 2019. Should I Interrupt or Not? Understanding Interruptions in Head-Mounted Display Settings. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 497–510. DOI: http://dx.doi.org/10.1145/3322276.3322363

[6] S. Ghosh, L. Winston, N. Panchal, P. Kimura-Thollander, J. Hotnog, D. Cheong, G. Reyes, and G. D. Abowd. 2018. NotifiVR: Exploring Interruptions and Notifications in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (April 2018), 1447–1456. DOI: http://dx.doi.org/10.1109/TVCG.2018.2793698

[7] Jan Gugenheimer, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. 2017. ShareVR: Enabling Co-Located Experiences for Virtual Reality Between HMD and Non-HMD Users. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 4021–4033. DOI: http://dx.doi.org/10.1145/3025453.3025683

[8] Jan Gugenheimer, Evgeny Stemasov, Harpreet Sareen, and Enrico Rukzio. 2018. FaceDisplay: Towards Asymmetric Multi-User Interaction for Nomadic Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 54, 13 pages. DOI: http://dx.doi.org/10.1145/3173574.3173628

[9] Sean Gustafson, Patrick Baudisch, Carl Gutwin, and Pourang Irani. 2008. Wedge: Clutter-free Visualization of Off-screen Locations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 787–796. DOI: http://dx.doi.org/10.1145/1357054.1357179

[10] Jeremy Hartmann, Christian Holz, Eyal Ofek, and Andrew D. Wilson. 2019. RealityCheck: Blending Virtual Environments with Situated Physical Reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 347, 12 pages. DOI: http://dx.doi.org/10.1145/3290605.3300577

[11] R. Holm, E. Stauder, R. Wagner, M. Priglinger, and J. Volkert. 2002. A combined immersive and desktop authoring tool for virtual environments. In *Proceedings IEEE Virtual Reality 2002*. 93–100. DOI: http://dx.doi.org/10.1109/VR.2002.996511

[12] Ching-Yu Hsieh, Yi-Shyuan Chiang, Hung-Yu Chiu, and Yung-Ju Chang. 2020. Bridging the Virtual and Real Worlds: A Preliminary Study of Messaging Notifications in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. DOI: http://dx.doi.org/10.1145/3313831.3376228

[13] Hikaru Ibayashi, Yuta Sugiura, Daisuke Sakamoto, Natsuki Miyata, Mitsunori Tada, Takashi Okuma, Takeshi Kurata, Masaaki Mochimaru, and Takeo Igarashi. 2015. Dollhouse VR: A Multi-view, Multi-user Collaborative Design Workspace with VR Technology. In *SIGGRAPH Asia 2015 Emerging Technologies (SA '15)*. ACM, New York, NY, USA, Article 8, 2 pages. DOI:http://dx.doi.org/10.1145/2818466.2818480

[14] Akira Ishii, Masaya Tsuruta, Ippei Suzuki, Shuta Nakamae, Junichi Suzuki, and Yoichi Ochiai. 2019. Let Your World Open: CAVE-based Visualization Methods of Public Virtual Reality Towards a Shareable VR Experience. In *Proceedings of the 10th Augmented Human International Conference 2019 (AH2019)*. ACM, New York, NY, USA, Article 33, 8 pages. DOI: http://dx.doi.org/10.1145/3311823.3311860

[15] Brett Jones, Rajinder Sodhi, Michael Murdock, Ravish Mehra, Hrvoje Benko, Andrew Wilson, Eyal Ofek, Blair MacIntyre, Nikunj Raghuvanshi, and Lior Shapira. 2014. RoomAlive: Magical Experiences Enabled by Scalable, Adaptive Projector-camera Units. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 637–644. DOI: http://dx.doi.org/10.1145/2642918.2647383

[16] Brett R. Jones, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2013. IllumiRoom: Peripheral Projected Illusions for Interactive Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 869–878. DOI: http://dx.doi.org/10.1145/2470654.2466112

[17] K. Kiyokawa, H. Takemura, and N. Yokoya. 1999. A collaboration support technique by integrating a shared virtual reality and a shared augmented reality. In *IEEE SMC'99 Conference Proceedings. 1999 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No.99CH37028)*, Vol. 6. 48–53 vol.6. DOI:http://dx.doi.org/10.1109/ICSMC.1999.816444

[18] Joseph J. LaViola, Daniel Acevedo Feliz, Daniel F. Keefe, and Robert C. Zeleznik. 2001. Hands-Free Multi-Scale Navigation in Virtual Environments. In *Proceedings of the 2001 Symposium on Interactive 3D Graphics (I3D '01)*. Association for Computing Machinery, New York, NY, USA, 9–15. DOI: http://dx.doi.org/10.1145/364338.364339

[19] Jiabao Li, Honghao Deng, and Panagiotis Michalatos. 2017. MagicTorch: A Context-aware Projection System for Asymmetrical VR Games. In *Extended Abstracts Publication of the Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '17 Extended Abstracts)*. ACM, New York, NY, USA, 431–436. DOI: http://dx.doi.org/10.1145/3130859.3131341

[20] Christian Mai, Lukas Rambold, and Mohamed Khamis. 2017. TransparentHMD: Revealing the HMD User's Face to Bystanders. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia (MUM '17)*. ACM, New York, NY, USA, 515–520. DOI: http://dx.doi.org/10.1145/3152832.3157813

[21] Philip E. Martin and Anthony P. Marsh. 1992. Step length and frequency effects on ground reaction forces during walking. *Journal of Biomechanics* 25, 10 (1992), 1237 – 1239. DOI:http://dx.doi.org/https://doi.org/10.1016/0021-9290(92)90081-B

[22] Mark McGill, Daniel Boland, Roderick Murray-Smith, and Stephen Brewster. 2015. A Dose of Reality: Overcoming Usability Challenges in VR Head-Mounted Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2143–2152. DOI:http://dx.doi.org/10.1145/2702123.2702382

[23] J. W. Nam, K. McCullough, J. Tveite, M. M. Espinosa, C. H. Perry, B. T. Wilson, and D. F. Keefe. 2019. Worlds-in-Wedges: Combining Worlds-in-Miniature and Portals to Support Comparative Immersive Visualization of Forestry Data. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 747–755. DOI: http://dx.doi.org/10.1109/VR.2019.8797871

[24] Cuong Nguyen, Stephen DiVerdi, Aaron Hertzmann, and Feng Liu. 2017. CollaVR: Collaborative In-Headset Review for VR Video. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 267–277. DOI: http://dx.doi.org/10.1145/3126594.3126659

[25] Sergio Orts-Escolano, Christoph Rhemann, Sean Fanello, Wayne Chang, Adarsh Kowdle, Yury Degtyarev, David Kim, Philip L. Davidson, Sameh Khamis, Mingsong Dou, Vladimir Tankovich, Charles Loop, Qin Cai, Philip A. Chou, Sarah Mennicken, Julien Valentin, Vivek Pradeep, Shenlong Wang, Sing Bing Kang, Pushmeet Kohli, Yuliya Lutchyn, Cem Keskin, and Shahram Izadi. 2016. Holoportation: Virtual 3D Teleportation in Real-time. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 741–754. DOI: http://dx.doi.org/10.1145/2984511.2984517

[26] Joseph O'Hagan, Julie R. Williamson, and Mohamed Khamis. 2020. Bystander Interruption of VR Users. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays (PerDis '20)*. Association for Computing Machinery, New York, NY, USA, 19–27. DOI:http://dx.doi.org/10.1145/3393712.3395339

[27] Tomislav Pejsa, Julian Kantor, Hrvoje Benko, Eyal Ofek, and Andrew Wilson. 2016. Room2Room: Enabling Life-Size Telepresence in a Projected Augmented Reality Environment. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing (CSCW '16)*. ACM, New York, NY, USA, 1716–1725. DOI: http://dx.doi.org/10.1145/2818048.2819965

[28] Ben Piper, Carlo Ratti, and Hiroshi Ishii. 2002. Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02)*. ACM, New York, NY, USA, 355–362. DOI: http://dx.doi.org/10.1145/503376.503439

[29] D. Pohl and C. F. de Tejada Quemada. 2016. See what I see: Concepts to improve the social acceptance of HMDs. In *2016 IEEE Virtual Reality (VR)*. 267–268. DOI:http://dx.doi.org/10.1109/VR.2016.7504756

[30] Joan Sol Roo and Martin Hachet. 2017. One Reality: Augmenting How the Physical World is Experienced by Combining Multiple Mixed Reality Modalities. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 787–795. DOI: http://dx.doi.org/10.1145/3126594.3126638

[31] A. Stafford, W. Piekarski, and B. H. Thomas. 2006. Implementation of god-like interaction techniques for supporting collaboration between outdoor AR and indoor tabletop users. In *2006 IEEE/ACM International Symposium on Mixed and Augmented Reality*. 165–172. DOI:http://dx.doi.org/10.1109/ISMAR.2006.297809

[32] John Underkoffler and Hiroshi Ishii. 1999. Urp: A Luminous-tangible Workbench for Urban Planning and Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '99)*. ACM, New York, NY, USA, 386–393. DOI: http://dx.doi.org/10.1145/302979.303114

[33] Julius von Willich, Martin Schmitz, Florian Müller, Daniel Schmitt, and Max Mühlhäuser. 2020. Podoportation: Foot-Based Locomotion in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. DOI: http://dx.doi.org/10.1145/3313831.3376626

[34] Yi Wang, David M. Krum, Enylton M. Coelho, and Doug A. Bowman. 2007. Contextualized Videos: Combining Videos with Environment Models to Support Situational Understanding. *IEEE Transactions on Visualization and Computer Graphics* 13, 6 (Nov. 2007), 1568–1575. DOI: http://dx.doi.org/10.1109/TVCG.2007.70544

[35] Keng-Ta Yang, Chiu-Hsuan Wang, and Liwei Chan. 2018. ShareSpace: Facilitating Shared Use of the Physical Space by Both VR Head-Mounted Display and External Users. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. ACM, New York, NY, USA, 499–509. DOI: http://dx.doi.org/10.1145/3242587.3242630