ShareSpace: Facilitating Shared Use of the Physical Space by both VR Head-Mounted Display and External Users

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ABSTRACT
Currently, "walkable" virtual reality (VR) is achieved by dedicating a room-sized space for VR activities, which is not shared with non-HMD users engaged in their own activities. To achieve the goal of allowing shared use of space for all users while overcoming the obvious difficulty of integrating use with those immersed in a VR experience, we present ShareSpace, a system that allows external users to communicate their needs for physical space to those wearing an HMD and immersed in their VR experience. ShareSpace works by allowing external users to place "shields" in the virtual environment by using a set of physical shield tools. A pad visualizer helps this process by allowing external users to examine the arrangement of virtual shields. We also discuss interaction techniques that minimize the interference between the respective activities of the HMD wearers and the other users of the same physical space. To evaluate our design, a user study was conducted to collect user feedback from participants in four trial scenarios. The results indicate that our ShareSpace system allows users to perform their respective activities with improved engagement and safety. In addition, this study shows that while the HMD users did perceive a considerable degree of interference due to the internal visual indications from the ShareSpace system, they were still more engaged in their VR experience than when interrupted by direct external physical interference initiated by external users.

CCS Concepts
•**Human-centered computing** → Virtual reality; User interface toolkits;

Author Keywords
Virtual reality; Shared use of physical space; External users experience

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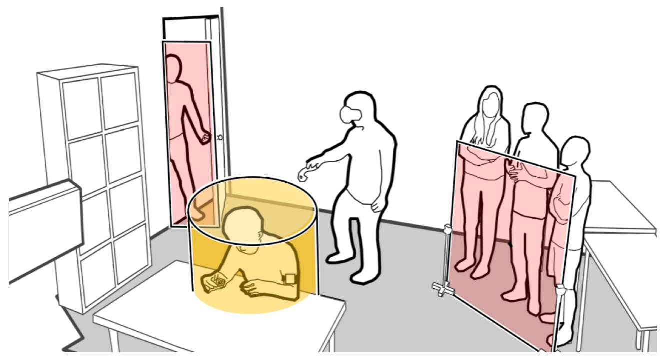

Figure 1. ShareSpace toolkit presents a set of physical shield tools that allow users to add "shields" in the virtual environment. They help avoiding physical conflict and promote the shared use of the same physical space for heterogeneous activities of both HMD and external users.

INTRODUCTION
Current walkable virtual reality (VR) [21] is best achieved with a room-sized physical space dedicated to VR activities only. In an average home, this causes extra maintenance efforts before each VR gameplay. Furthermore, this division of physical space may very likely discourage any other activities by other persons in that same room, thereby decreasing the utility rate of the physical space and decreasing the attraction to install VR systems in home due to this obvious logistical obstacle in regard to the shared use of space.

We consider that the cause of low utilization and installation rates for VR systems can be attributed to the scarcity of VR rooms that can accommodate mixed activities for both VR HMD-using and other users. In current practice, a physical space is manually maintained to serve the temporary requirements of a VR activity. For instance, HTC's Vive allows users to secure a walkable region, called "the VR zone", within a real world boundary defined during the setup of the virtual environment. The VR zone prevents HMD users from walking into possible obstacles; however, the static boundary does not reflect novel and dynamic occupations of possible external activities outside. In addition, since the VR zone is not directly observable by external users, they may feel insecure and damage may occur due to conflicts between users engaged in their respective activities.

ShareSpace
We propose the ShareSpace system, which consists of a set of shield tools, with the goal of promoting the shared use of the

same physical space for heterogeneous activities of both HMD and external users. Shield tools are physical widgets that allow external users to define virtual shields, which are incorporated into the VR zone, modifying the available space in which the HMD user can safely explore virtual environments. We also provide a shield visualizer to help the external users examine the allocation of virtual shields.

Each shield tool represents one of the two virtual shields, i.e., a circle or an edge shield. The circle shield, which appears as a cylinder in the virtual environment, is meant to protect external users. Multiple edge shields can form a complex and malleable virtual shield. As illustrated in Figure 1, the external user is protected by a circle shield while studying at his desk, whereas wall shields, formed by paired edge shields, create an extra space for a group of onlookers and guard the doorway when the door swings open.

Unlike existing technologies, which enable the cooperation of co-located HMD and non-HMD users [11, 7, 5] incorporating them into the VR activity, ShareSpace considers the non-HMD users as external users, who are not a part of the VR experience, and seeks to accommodate their respective activities using the same physical space.

ShareSpace's main contribution, along with our interaction designs as a proof-of-concept, is the concept of allowing a VR zone that accommodates both HMD and external users engaged in their own respective activities. We believe this is an important concern to increase installation rate of VR systems in average homes as well as to improve the overall safety and comfort in use of all users.

RELATED WORK

We review previous works on asymmetric interaction, communicative means between HMD and non-HMD users, and shared use of the same tracking space.

Asymmetric interaction

Asymmetric interaction in virtual reality often adopts a mix of egocentric and exocentric interactions to accommodate co-located or remote collaboration of users with multi-fidelity displays working in the same virtual environment. Previous studies have exploited this cooperation among desktop[10, 2], tabletop[20, 11] and VR users. Benko, et al., introduce a mixed-reality environment[1] for AR and VR users' local co-operation. Mini-Me[16] allows remote VR users to appear as avatars to join local AR users' work. A more recent study explores inviting non-HMD users for collaboration. ShareVR[7] allows addition of non-HMD users into the VR experience with co-located floor projection and mobile displays. MagicTorch[12] integrates handheld projections for non-HMD users to access virtual environments on physical surfaces. Allowing for mobility, FaceDisplay[8] augments a touchscreen on the back of the HMD through which non-HMD users can direct-touch the virtual environment in user viewports.

Communication between HMD and non-HMD users

Instead of emphasizing cooperation, another category of studies seeks to narrow the communication gap for external users by revealing an HMD user's interaction status with the addition of a face screen on the HMD backside. See what I see[17] displayed the user's viewport on the face screen. TransparentHMD[13] displayed a simulated face to reintroduce the HMD user's facial expression. FrontFace[3] integrated the user's face with the user viewport on the face screen and demonstrated hiding or disclosing the user viewport as an indicator to whether the HMD user was present in the virtual or reality world. They further presented ways that external users can actively initiate a communication (e.g., summon the HMD user to reality via HMD's augmented reality camera).

Unlike existing technologies or devices, which promote co-located collaborative interaction[11, 8, 7, 12] between HMD and non-HMD users, ShareSpace is designed for external users who are not part of the VR activity, and aims to offer a means to accommodate their activities using the same physical space. Like FrontFace[3] which adds a face screen on the HMD for external users to activate a communication, the ShareSpace system enables external users to communicate their needs in terms of space for their activities.

Shared Use of the Same Tracking Space

Techniques of sharing same tracking space have been explored [18, 19] to accommodate multiple local VR users experiencing the same virtual world, while avoiding collision. More recently, VirtualSpace [15] extends the concept to allow the local VR users to be engaged in their own virtual worlds. In this work, ShareSpace deals with external users and HMD users sharing the same physical space.

INTERVIEWS

To understand design considerations for ShareSpace, we note circumstances in which conflicts exist among the activities of the HMD and external users in the same physical space.

We interviewed three VR event conductors and two VR users (gamers). The two conductors had demonstrated their projects at SIGGRAPH Emerging Technology and VR Village events, and have conducted several experience sessions on the same projects in their lab for lab visitors. One conductor had conducted two semester-long VR courses; each course had 30 students and was completed with a demo showcase. The two VR users (gamers) had installed a VR environment in their living rooms. The interviewees shared the hurdles they experienced while conducting the VR sessions.

Summary of results

According to their roles, external users are considered either onlookers or outsiders. Onlookers may refer to external users who are watching the VR gameplay standing beside the VR zone or waiting for their turn. Outsiders are users irrelevant to the VR activity, i.e., they work on their own activities, such as reading a book or chatting with other outsiders.

According to the types of external activities, the demands for space are categorized as either protective or aggressive demands. In the case of protective demands, those engaged in external activities seek to be protected from the potential threats of the HMD users' activities. These protective demands have the same property as the real world boundary that the

HMD users need to be aware of during a gameplay; however, no immediate action is required. In the case of aggressive demands, those engaged in external activities are in competition for a resource (space, an access way, etc.) that may present a conflict with ongoing VR activities. For instance, external users try to access a door, while the doorway is blocked by the HMD user. Compared to protective demands, aggressive demands have higher priorities to address.

An external activity may alter its demand type according to any given current goal. Consider this scenario for instance: at home, an external user can have a protective demand while reading a book beside the VR zone. However, when the user needs to access a bookshelf blocked by the VR activity, this aggressive demand should allow him or her to seek access to that space from the HMD users.

In addition, conflicts may be caused by changes in the disposition of furnish. Movable furniture, such as chairs, may intrude into the VR zone when they are not where they were original mapped to be. Similar to external users, movable furniture beside the VR zone should be monitored to protect HMD users during gameplay. Another reason for conflict can be transformable objects. For instance, a swinging door or a drawer uses more space while opening or when pulled out, respectively. When conflicts occur during transformation, an aggressive demand can strongly lodge for the space required.

Interviewees also mentioned that the lack of visual revelation of the real world boundary affected their sense of security in relation to external users in proximity to their VR activities.

DESIGN CONSIDERATIONS
Based on the results of the interviews, the following design considerations have been conceptualized and implemented in the design of ShareSpace with its proposed toolkit.

Accessibility of the Interface
To accommodate mixed activities with sufficient flexibility, the interfaces should be easily accessible for external users to address a desirable space for their activities. When a given activity is completed, the occupied space can be released. To allow accessibility, we chose interaction using tangible interfaces. Our ideal realization of the interface is in the form of stickers that the external users can tag a space with, by directly adding it to their bodies or on furniture within the environment. Accordingly, we present shield tools that can be worn by the user and / or added to the environment.

Complex and Malleable Virtual Protection
Virtual shields should be versatile enough to address the requirements of space for various activities. In our interviews, we observed that the requirements frequently come from needing to protect external users and furniture whose disposition may be modified. The aforementioned cases need to deal with the transformation of the space used by an object according to any given associated activity (e.g., a standing or seated person, or an opened or closed swinging door, have multiple and dynamic space requirements within an environment). To maximize space utilization, the system should address these changes continuously during mixed activities.

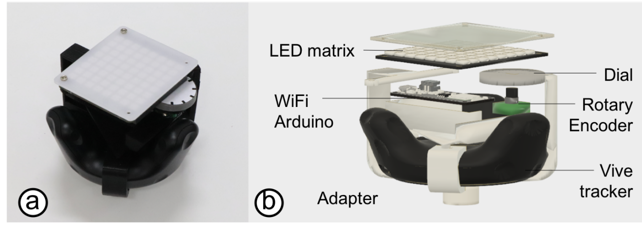

Figure 2. (a) The hardware of a shield tool. (b) The explosion view displays components it contains.

Protective and Aggressive Demands
We consider that a virtual shield should adapt to protective and aggressive demands for protection of space, which reflect how aggressive the need for space is. Thus, in the case of 'protective protection,' the HMD user must be aware of the space under protection, i.e., the HMD user can stay close to the protection as long as he or she does not affect the external users' activity. However, in the case of 'aggressive protection,' external users strongly need a space to complete their task, such as accessing a door that may be, or become, blocked by HMD users. Therefore, the HMD user should avoid coming too near the assigned aggressive protection.

Immediate Feedback and Mutual Negotiation
Shield tools are primarily designed for external users, which places the HMD users in a passive position in that they can only accept requests from the external users. To allow mutual negotiation, the system should properly inform the HMD users whenever the VR zone is modified because of the external users' activities. Further, when serious conflicts occur (e.g., HMD users are not willing to accept this change), the system should allow the HMD users to redeem their space.

SHARESPACE SYSTEM
The ShareSpace system consists of a set of shield tools and a shield visualizer. Shield tools are tangible widgets that allow external users to claim a region in the physical space for their activity. The shield visualizer helps them examine the allocation of virtual shields. This section discusses the functions of shield tools, design of visualization, and system-enabled interactions.

Shield Tools: Circle or Edge Shield
Each shield tool can be set as either a circle shield or edge shield. A shield tool consists of a Vive tracker, LED-matrix display, dial control enabled with a rotary encoder, and Wi-Fi-ready Arduino board, as shown disassembled in Figure 2. All components are assembled with 3D-printed parts that consist of an adapter at the bottom to connect with various attachment methods. Each shield tool measures 7.8 cm in height and 9.5 cm in both width and depth. The dial control and LED display in the shield tool allow users to select a shield type to use. Once a shield type is determined, the corresponding virtual shield is added to the virtual environment.

Figure 3 shows the three attachment methods of a shield tool. The surface-suction attachment allows the addition of a shield tool to a wall or table surface. The arm-belt attachment can be easily worn on a user's arm. The standing attachment allows

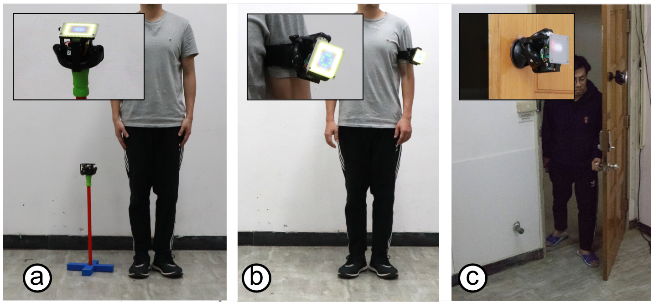

Figure 3. Shield tools consist of an adapter to connect with three attachment methods: (a) standing, (b) arm-belt and (c) surface-suction.

the positioning of a shield on the floor, or when using multiple standing attachments, to form a wall shield in the VR zone.

Circle Shield

The circle shield is meant to protect external users. A circle shield represents a standing cylinder within the virtual environment. Each circle shield can be set to either be normal- or double-sized in either of the two modes: protective and aggressive modes. The normal-sized circle shield is set to be 50 cm in radius, about the size of someone's personal space [9]. The double-sized circle shield allows protection of a larger-sized object, such as a round table or a group of two or three external users. To reduce the interface options, we have assumed that the external users would wear the shield tool on their left arm. Further, we have added an offset to the corresponding virtual cylinder to properly center it around the external user.

Edge Shield

The edge shield caters to complex and malleable spaces. An edge shield represents a standing line in the virtual environment. Edge shields can be inter-connected with a *proximity gesture*, so that connected two edge shields would form a wall shield in the virtual environment (Figure 5). Multiple edge shields can form a complex shape. Because the positions of the shield tools are tracked in real-time with the Vive lighthouse system, connected edge shields allow capturing of the transformation of a space which they form and monitor. For instance, to model the space taken by a foldable table, three edge shields are arranged as shown in Figure 6(a). Two edge shields attach to the door edge and door frame can capture the required space for the opened and closed door (Figure 6(b)).

Display and User Control on Shield Tools

In total, there are seven modes of shield tools, as shown in Figure 4(b). We use three circles of different sizes on the LED display to represent the edge and circle shields of normal and double sizes. Furthermore, each virtual shield is either of the two modes (protective or aggressive), reflecting the external users' protective or aggressive shield demands, indicated with yellow or red edges on the LED display which is based on the design of traffic light colors. We arrange the modes adjacent across all modes, following the idea that the users would frequently switch between protective or aggressive shields of a given shape, according to the level of the activity. Finally, the *OFF* mode disables the shield tool.

Users select one of the seven modes via the dial control and the selection is completed with a *check* animation (Figure

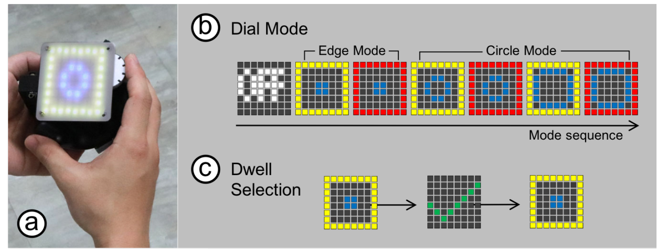

Figure 4. (a) Users select one of the seven modes via the dial control. (b) The seven modes consist of 2 edge modes, 4 circle modes and 1 off mode. (c) The selection is completed with the dwell selection animation.

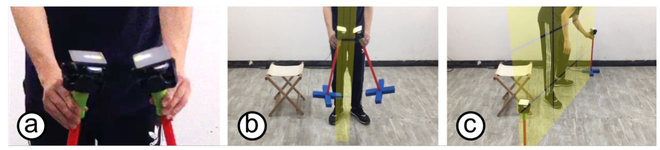

Figure 5. (a) Connecting two edge shields with a proximity gesture forms (b)(c) a wall shield in the VR zone

4c). Once shield tools are on edge shield modes, they can be connected with a *proximity gesture* which links two edge shields once they are in proximity (e.g., 10 cm) for 0.2 second (Figure 5). Then, the connection made is indicated on each of the paired shields with a line pointing to the other connected shield (see Figure 5a). Connecting two edge shields again removes the linkage. With this mechanism, complex connections can be formed with a group of edge shields.

Shield Visualizer

The shield visualizer is a portable display, here an Apple iPad, integrated with a Vive tracker, providing two examination modes. In the overview mode, we preload a 3D scene of the room so that the users can see the entire scene in a top view. On the screen, we highlight the real world boundary, the location of the visualizer and the HMD user in the VR zone to help the users better understand the arrangement during examination (Figure 8a). In the augmented reality (AR) mode, the user can examine a virtual shield with his or her perspective by aiming at with the display's built-in camera (Figure 8b).

INTERACTION TECHNIQUES

With the shield tools and their functions introduced, we present interaction techniques for resolving conflicts while minimizing the interference between the respective activities.

Protective Shields as Obstacles in Virtual Environment

Protective shields are virtual obstacles that, when appearing in the VR zone, restrict the VR activity. Together with the real world boundary, they define the available space for the HMD users' safe exploration. Since protective shields may move and alter according to the external activities, the available space in the VR zone also changes over time. The real world boundary or virtual obstacles are invisible to the HMD users until the following conditions are met: (1) HMD users are going to encounter any of them or (2) when sufficient changes in virtual obstacles are detected.

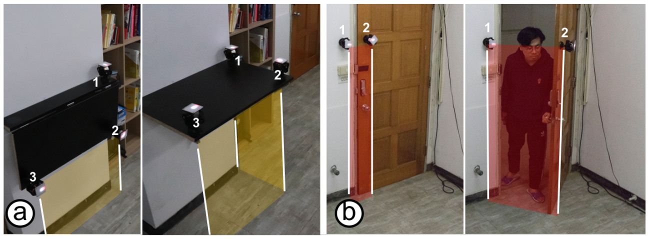

Figure 6. Two setup examples of edge shield. (a) Three edge shields are arranged to model the space taken by a foldable table. (b) Two edge shields attach to the door edge and door frame can capture the required space for the opened and closed door.

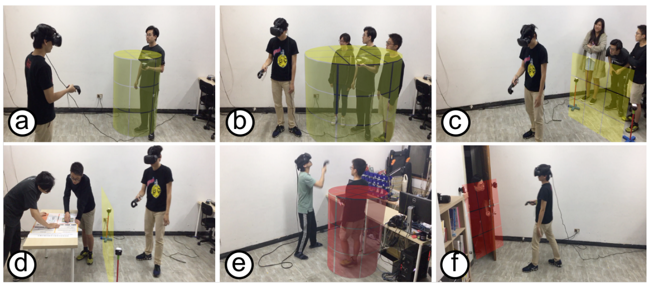

Figure 7. Usage of virtual shields: (a) A normal-sized circle shield protects a single user, (b) while a double-sized one protects a user group. (c) Wall shields formed by two edge shields define large space for a user group or (d) table discussion activity. (e)(f) Aggressive shields inform immediate needs of space such as acquiring space for furniture usage.

The first condition follows the existing design of the SteamVR* engine, which shows the real world boundary to the HMD users by displaying the boundary as a virtual fence in their viewport. In our implementation, we set the safety boundary at 50 cm from the HMD user's location, a personal space suggested by [9]. Once the HMD users' safety boundary encounters the real world boundary or any virtual obstacles, both the real world boundary and virtual obstacles appear, until the conflict is dismissed.

In the second condition, when sufficient changes in virtual obstacles are detected, the virtual obstacles become visible with a blinking effect to attract users' attention until the HMD users observe the changes in their viewport. For instance, if a shield, marked as changed, is located outside the region of the user's viewport, it will continue blinking until the user turns long enough to see it. Note that the real world boundary in this condition will stay invisible to avoid visual interference.

This informs the HMD users that the available space has been modified by an external activity. In our implementation, we detect the change by calculating the motion of a virtual shield. Once the motion of accumulation is greater than a threshold, the virtual obstacle is marked invalidated until it appears in the user's viewport for one second.

Resolving Immediate Conflicts of Aggressive Shields

Unlike protective shields, which are passive obstacles, aggressive shields are active requests activated by the external users asking for space. This happens in instances such as when external users need to access a doorway blocked by an HMD user. Conflicts of this kind need to be resolved immediately.

*SteamVR: http://steamvr.com/

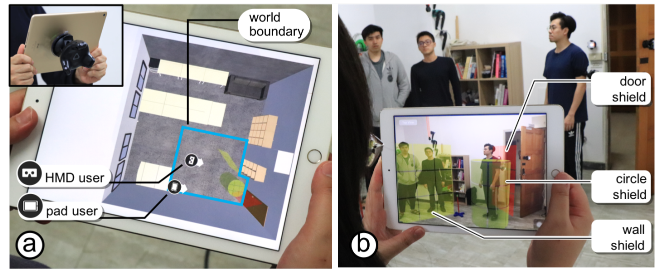

Figure 8. The shield visualizer provides two examination mode: (a) the overview mode gives a top-view of the entire scene, and (b) AR-view mode allows user to examine a virtual shield with his or her perspective.

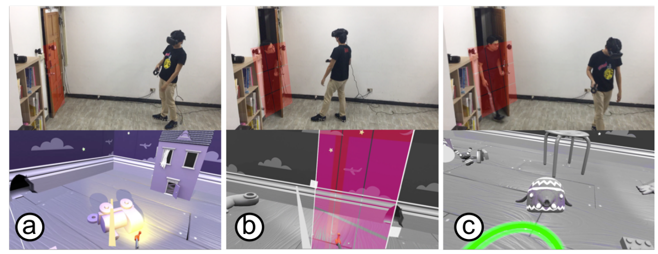

Figure 9. (a) Once the HMD user approaches the aggressive shield installed at the door, (b) the system pauses the game with a grayed out viewport, and (c) lead the user to the safe zone indicated by a green halo. The game resumes with a button on the controller.

We present two designs to resolve this kind of conflict. Once a conflict occurs, we pause the virtual world, which stores the HMD users' interaction states, so that their important moments in the experience would not be affected (Figure 9b). This *pause effect* grays out the user's viewport to simulate a time freeze moment and causes all virtual shields to become visible, as well as a green halo that indicates the location of the safe zone (Figure 9c), so that the users can move to a 'clean' area. Our second design allows a HMD user to piggyback the virtual world, in such a way that he or she carries the virtual world and resumes the gameplay with a button on the hand controller. We locked only the ground location of the user in the virtual environment; thus, he / she can still look around the environment while everything moves with the user.

Retaining HMD Users at Safe Zone

To ensure the HMD user's safety further, the system should inform the VR program about the free space, so that the VR program could lead the HMD users to a safe zone to maximize their freedom during their experience. This requires all the VR programs to comply to a system-wide mechanism of safety. Cheng et al. [6, 5] proposed interactively modifying a game mechanism to enable Haptic Turk applications. Following the same concept, we demonstrate using a safety mechanism to retain the HMD user at a safe zone with a customized shooting game (explained further in the User Study section).

In this case, the safe zone is defined as a personal region (e.g., 50 cm in radius) located at the center of the maximum inscribed circle[14] found in the available free space (Figure 10). The game mechanism would guide the users back to a safe zone whenever allowed by the game, while maintaining

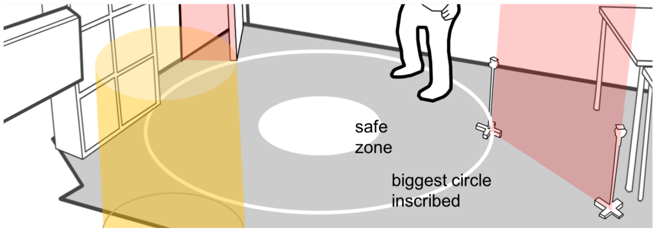

Figure 10. Safe zone is defined as a personal region located at the center of the maximum inscribed circle found in the available free space

Figure 11. (a) When a large region in the VR zone is used e.g., by an external table discussion activity, (b) the HMD user activates the AR function to understand the modification made by external activities and (c) redeem the space face-to-face. Note that the sub-figure (a)(c) are the AR view for explanation.

the gaming experience. Two tricks, attraction and threat, are implemented in our shooting game. To guide the users to move toward a new location or away from the current location, attractions (e.g., health supply) are placed in the direction of the safe zone, while threats (e.g., enemies or obstacles) can block the user from going away from the safe zone.

Let Us Talk Face-to-Face

Our shield tools allow the external users to claim a desirable space for their activities. The HMD users are informed about any modifications to the available space, though there is no negotiation channel for the HMD users yet. In fact, we try to avoid mutual negotiation as long as possible, so that the HMD users can continuously engage in the VR experience as long as they accept the modification.

However, when HMD-users are unwilling to accept the change due to e.g., too much space being taken or simply curious about the external activity, we add an AR function on the HMD that allows them to see the real world and talk with the external users face-to-face. Figure 11 displays a situation where a large region in the VR zone is temporarily used for an external table discussion activity. The HMD user insists on redeeming the space by moving the shield stands toward the table. We implement the AR function with a video see-through approach using the Vive HMD's built-in front camera.

USER STUDY: TARGET SCENARIOS

To better understand how the shield tools help users manage interaction spaces in the environment and explore how ShareSpace improves the communication between HMD users and external users, we conducted a user study. We hypothesized that ShareSpace can increase users' willingness to share use of the same physical space by avoiding potential conflicts between the VR and external activities.

Study Design

This study followed a within-subject design with two independent variables, *SYSTEM* and *USER*. *SYSTEM* conditions are the *ShareSpace* condition, in which participants followed the user tasks with the help of our system; and the *Baseline* condition, which consists of the same tasks but without the ShareSpace system. There are two *USER* conditions, *HMD user* and *external user*. The user tasks are two sets of four trial scenarios, each for the HMD and external user participants, to simulate conflicts in the physical space.

Procedures

Our study took place in a university lab containing a 3 x 1.5 m VR playground surrounded by furniture (such as, doors, cabinets, and tables) to resemble the kind of mixed-activity space normally found in a living space. The participants were recruited in pairs. After briefly being introduced to the study, a hands-on training session of ten minutes was provided to ensure that the participants understood the study goal and could use the shields tools and the visualizer correctly.

User tasks consist of two phases: setup phase and activity phase. In the *Setup* phase, we want to ascertain how users might deploy the shield tools within the environment. We assume that a static real world boundary has been created using the SteamVR approach (e.g., tracing the boundary with a Vive controller); thus, the paired participants were only asked to deal with three pieces of dynamic furniture (a swinging door, a foldable table, and a cabinet drawer) using the shield tools. They were informed that the furniture would be involved in later study tasks, and they were instructed to determine the deployment, so that the utilization of the physical space would be maximized. In this phase, a think-aloud protocol was applied to collect the participants' ideas for deployment.

In the *Activity* phase, each pair of participants played all possible permutations of our independent variables (*SYSTEM* x *USER*), resulting in four sessions counterbalanced with a Latin square. In each session, the paired participants played the role of HMD and external users and completed the corresponding tasks explained in next section. Each session took 5-10 min.

After each session, the participants completed a corresponding questionnaire about the experience of their role playing, consisting of three statements for rated agreement in regard to the *Safety*, *Engagement* and *Interruption* dimension, namely: "I feel safe during the activity of the task.";, "I can concentrate on the activity of the task."; and "The activity of the task was not interrupted b VR/external user's activity." in continuous 7-point Likert Scale (1: not agree, 7: very agree). After all sessions, an interview was conducted to gather further feedback. The study took on average 1.5 h per pair of participants.

Tasks in Activity Phase

In the *Activity* phase, we prepared respective tasks for the HMD user and external user.

Tasks for the HMD participant

The participant was engaged in a first-person shooting game that leads to conflicts in use of space, and was only instructed to clear away the enemies by shooting with the hand controller while avoiding enemy attacks. Thus, their sense of the physical environment would soon become disoriented. Further, by arranging enemy attacks and bonuses to appear in the virtual

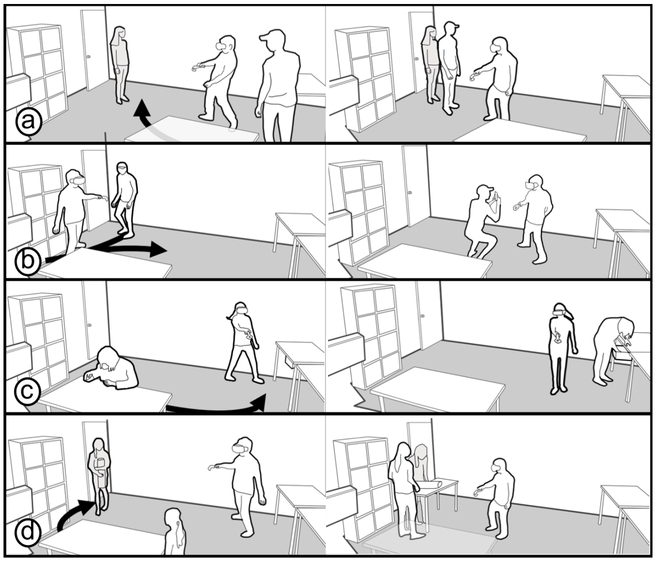

Figure 12. Four study tasks in the *Activity* phase. Note that the experimenter is filled in gray in the figure.

environment, we can drive the users to move toward a certain location in the physical space, corresponding to the tasks.

Tasks for the external participant

There were four tasks for the external participant (Figure 12). First, two tasks involved participants being an onlooker and the other two being an outsider. In each of the four study conditions, the participant experienced all tasks in random order. In each new session, we slightly changed the configuration of these tasks (e.g., change standing or table locations); hence, the same tasks across sessions were not identical.

Task 1: Join an onlooker group: In the beginning, one experimenter playing the role of an onlooker stood on a spot beside the playground. After wearing a circle shield, the external participant joined the first onlooker to form an onlooker group, and the participant was instructed to stand ahead of the experimenter so that his/her body would be exposed to the playground. Then, the HMD participant was prompted to walk toward the onlooker group by a bonus attraction, followed by enemies sent to further detain the HMD participant. This task is completed when the enemies are dismissed.

Task 2: Open a foldable table and take photos: In the beginning, the external participant was positioned at a corner of the room and the HMD participant was located beside a foldable table (folded). The external participant was then instructed to place the backpack on the table, retrieved a camera, and took photos from three different distinct angles and distances. This task is completed when nine photos are taken.

Task 3: Assemble LEGO bricks: The external participant sat at a desk with his/her back facing the playground, assembling a LEGO model following graphical instructions. A key-featured LEGO brick was missing so he/she needed to retrieve it from a cabinet drawer located at the other end of the playground, at which moment the HMD participant was guided to the side of the cabinet, blocking the drawer. This task is completed when the LEGO model is completed.

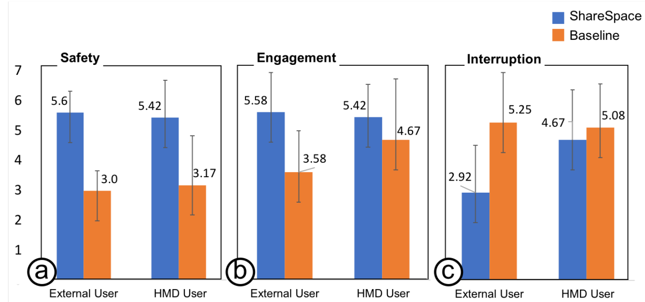

Figure 13. Averaged user ratings regarding the levels of perceived *Safety*, *Engagement*, and *Interruption* during their experience across the study tasks.

Task 4: Poster discussion on a table: The external participant was instructed that he/she will join a discussion activity and need to set up a space on a table to review a poster. His/her mission was to prepare a space that can accommodate four people in discussion around the table. This task is completed after spending one minute reviewing the poster.

Participants

A total of 12 paid participants (four female and eight male participants) with an average age of 23.6 years (SD = 0.67) were recruited in pairs. Among them, 10 participants had experience in virtual reality gaming, and 11 of them had the experience of being onlookers of virtual reality demo events. One participant had a virtual reality system set at home.

Results and Discussion

We initially applied a two-way repeated measure ANOVA analysis of the data from rating the task types and system treatments in regard to external users' safety. There was no significant effect of task type ($F_{2,22}$=0.089, p= .916), and there was no interaction effect. We therefore aggregated external users' safety ratings across task types to compare those with the HMD users' safety ratings. Finally, Figure 13 shows the averaged ratings of external and HMD users regarding the levels of perceived *Safety*, *Engagement*, and *Interruption* during their experience. Here, *Interruption* refers to the interruption felt when caused by activities of other user types.

Regarding *Safety*, external users rated high scores (M=5.6, SD=0.71) to ShareSpace, compared to Baseline (M= 3.0, SD= 0.67). HMD users also rated higher safety with ShareSpace (M=5.42, SD=1.24) than Baseline (M= 3.17, SD= 1.64). A two-way ANOVA test demonstrated a significant effect of *SYSTEM* ($F_{1,11}$=53.474, p= .000), indicating that the ShareSpace system significantly improved the perception of safety for both the external and HMD users. There was no interaction effect.

Regarding *Engagement*, external users engaged in their activity in ShareSpace (M= 5.58, SD= 1.31) found higher scores compared to Baseline (M= 3.58, SD= 1.38). The average engagement of HMD users was slightly higher in *ShareSpace* (M= 5.42, SD= 1.08) than in *Baseline* (M= 4.67, SD= 2.01). ANOVA test demonstrated a significant effect of *SYSTEM* ($F_{1,11}$=8.166, $p<$ 0.5), indicating that the ShareSpace system improved engagement of both the external and HMD users on their respective activities. There was no interaction effect.

For *Interruption*, external users rated feeling less interrupted when using *ShareSpace* (M= 2.92, SD= 1.56) compared to *Baseline* (M=5.25, SD=1.66). HMD users gave similar scores on interruption between *ShareSpace* (M= 4.67, SD= 1.67) and *Baseline* (M=5.08, SD=1.44). ANOVA test found a significant effect on *SYSTEM* ($F_{1,11}$=4.84, p= .05) and an interaction effect between *SYSTEM* and *USER* ($F_{1,11}$=10.796, $p<.05$).

The results of the post-hoc pairwise comparisons revealed that the *External Users* felt less interruption caused by HMD users when using the *ShareSpace* than in *Baseline* condition ($p<.005$). But this significant effect was not found with the *HMD User*. We found, according to our observations, that the HMD users encountered various interruptions from the external users. In the *Baseline* condition, the external users alerted the HMD users about their existence by voice or a physical nudge to the HMD user when they felt intruded upon. External interference was efficiently replaced by the visual protection provided by *ShareSpace*. However, HMD users instead encountered virtual shields as internal interference, which caused a perception of interruption at high levels. According to the user ratings for Engagement, the HMD users were more engaged in the VR experience with our system than without our system. This is because the HMD users stayed completely in the virtual world while experiencing internal interference, in contrast to external interference, which dragged the HMD users' attention back to physical reality.

In addition, when the ShareSpace system was applied, the external users felt less interrupted than the HMD users (p= 0.01) felt. This echoes the goal of this study to enable external users to define their space with the ShareSpace system, though at the cost of affecting the HMD user's ownership of the VR zone. It is an important issue to know the extent to which the ownership of the VR zone can be negotiated [3] and will require more study in the future. To deal with this issue, we suggest an AR function that allows the HMD users to communicate directly with the external users and negotiate any novel modifications whenever they feel necessary.

Our goal is to prevent mixed activities from affecting each other as much as possible by interactively addressing the external users' need for space allocation. This study's results find that both external and HMD users reported improved engagement and safety while working on their respective activities with the support of our system. The HMD users feel that virtual shields are distracting to their experience, though the internal visual interference is considered less interrupting than the direct physical, real world interference from external users.

Usage of Shield Tools

Figure 14a shows the usage count of shield tools with three pieces of furniture during the setup phase.

All participants felt that the doorway is a frequently-used and dangerous area, and decided to install a circle shield on aggressive mode to remove the area from the VR zone, instead of using edge shields for maximized space usage. In the case of drawers, four pairs of participants deployed edge or circle shields on protective mode. The participants mentioned they could protect the drawer with their own circle shields as long as

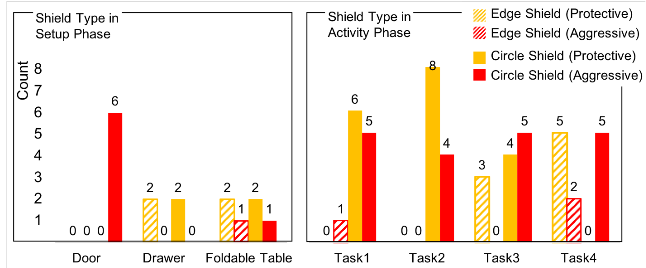

Figure 14. Usage count of shield tools in *Setup* phase and *Activity* phase.

they close the drawers upon leaving. Shields for the foldable-table desk were deployed with variance; participants either chose to fully remove the space using a single double-sized circle shield, or to better use the space with edge shields.

Figure 14b shows the number of usages of shield tools for tasks in the activity phase. In the task of the onlooker group, half of the participants considered protective shields sufficient for protection while the other half set their shields on aggressive mode. Most of them used circle shields, except one participant who did not want to be constrained thus using edge shields instead. When taking photos, more participants used protective mode than aggressive mode (8 v.s. 4); they felt they could easily avoid the HMD user's sudden motions due to the sufficiency of space. Similarly, when crossing the VR zone e.g., to the other end of the zone, more participants chose protective mode. Participants who selected aggressive mode felt more willing to approach the HMD user in order to take close shots, and suggested that they needed the aggressive protection when holding expensive equipment or carrying food.

In task 3 (LEGO assembly), more participants used circle shields and they were split into protective and aggressive modes with different concerns. Half of the participants selected protective mode because they did not consider the VR activity harmful. The other half felt more protected using aggressive shields when having their back to the VR zone. In task 4 (poster discussion), more participants used edge shields for their ease of securing a large space, while 5 participants decided on using circle shields worn on their arm but then that would require a shield for each discussion member.

Counting the usage of protective and aggressive shield in all tasks, we found comparable frequency of usage (26 vs. 21) and different reasons for usage. In general, participants found that protective mode was sufficient when their activities were stationary. When walking into the VR zone, they also felt that protective mode was sufficient when there was space to avoid HMD users' activities. Aggressive mode was needed when accessing a space occupied by HMD users.

Two participants who had a lower usage of aggressive mode said that they were annoyed by the pause effect caused by aggressive shields when they played the HMD user role. Therefore, they would try to avoid using aggressive mode when playing the external user role. It seems that users may have been underestimating the influence of aggressive shields on the HMD user when they were external users. Considering the aggressive protection is often for short-term activity, another solution would be to set a time limit, say 5 seconds, to aggres-

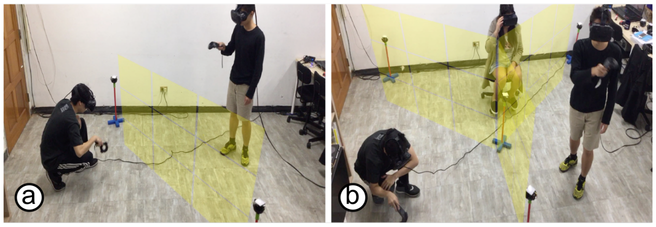

Figure 15. Virtual wall shields made by edge shields allow to divide spaces for multiple HMD users gameplay.

sive mode, such that shields in aggressive mode would revert back to protective mode automatically.

Usage of shield visualizer

The use of the shield visualizer was not frequent during this study. Three pairs out of six used the visualizer during the *Setup* phase, but none of them used it during the *Activity* phase.

Participants found the visualizer most helpful in the beginning; however, once they learned how virtual shields work, the visualizer became unnecessary because the tangible shield tools provide sufficient information about the shield deployment. Participants also mentioned that the shield visualizer may be helpful in supervising VR activity. For instance, parents could ensure that their kids' activities are safely protected, and likewise with teachers and students.

Qualitative Feedback

Regarding the usability questions, participants agreed that our system increased their willingness to install a VR system at home (M=5.75/7, SD=0.86), was easy to learn (M=6.33/7, SD=0.49), and simple to use (M=6.17/7, SD=0.57).

All participants found that our system improved safety and engagement for their respective activities; their remarks included "*the system allows greater flexibility for (use of) limited physical space*";, "*land is expensive, it (ShareSpace system) saves space*";, "*I can concentrate on my own thing while besides a VR activity*"; and, "*despite knowing someone is next to me, I am not afraid of actually hitting him.*".

Participants also suggested other use scenarios for shield tools. For instance, using edge shields would be useful for arranging multiple VR demos in an event or to divide space for multiple HMD users, as shown in Figure 15. Circle shields can protect non-HMD users during cooperative interactions with HMD users, such as protecting haptic-turk users [4].

Some room for improvement has been suggested by participants. HMD users are concerned about the increased chances of being interrupted and concerned about the pause effect which stopped their experience. They still wish to keep a space exclusively for VR experience, though they agree on the difficulty of maintaining such a space at home. The users would like to adjust the size of circle shields and have accepted that the restricted options improved the ease of the interface.

DISCUSSION

Protective shields accommodate external users' long-term activity, while aggressive shields are necessary for immediate needs. Since aggressive shields have a strong influence on the HMD users (e.g., pause the game when in conflict), external users should be taught about the consequences in advance, to encourage them to not overuse the feature. Pad visualizers help in learning the system but seem to not be necessary once users feel comfortable, as long as the shield tool itself provides sufficient information. However, in cases where safety is a critical concern and activities are complex, the pad visualizer is helpful for safety stakeholders in order to quickly ensure the deployment of virtual shields.

While our goal is to provide a communication channel for negotiation between users of both sides, HMD users are concerned their rights are being sacrificed due to the ShareSpace system. This is an interesting topic that has been rarely explored in recent development of virtual reality technologies. FrontFace[3] presents ways for external users to actively initiate a communication with HMD users (e.g., to bring the HMD user into the real world), and discusses the extent with which an HMD user may allow interruptions from outside the VR zone. In the case of ShareSpace, the sacrifice is weighed against safety, for instance, parents supervising kids' safety at home or teachers supervising class safety during VR activities. Conversely, the system should allow HMD users to refuse interruption from external users with varying levels of permission. We see ShareSpace as a beginning of a discussion of the pros and cons of allowing such negotiation within the space between HMD and external users.

In ShareSpace, we chose to implement virtual shields with tangible interfaces to allow users more accessibility and simplicity. Another form of implementation is using a scanning approach, such as multiple Kinects scanning the room and deploying the shields automatically. We believe that dynamic user-defined boundaries will be the ultimate solution to accommodate mixed users in a VR environment, which should retain the strengths of both approaches.

CONCLUSION

We have presented our ShareSpace system, a means to enable external users the capability to negotiate space with HMD users, with the goal to accommodate their respective activities in the same physical space while avoiding direct communications as long as possible, so that their engagement in respective activities is protected. To this purpose, we have presented shield tools, a pad visualizer and related interaction techniques, which are herein evaluated via a user study of four trial scenarios. The results demonstrate enhancement of safety and engagement for respective activities using the ShareSpace system. Through our preliminary exploration and study, we believe that ShareSpace is an effective way to facilitate mixed activities in a VR room, but also that there are a number of concerns that remain to be addressed requiring further study regarding the handling of conflicts.

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