A Projection-Based Interface to Involve Semi-Immersed Users in Substitutional Realities

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Abstract

Virtual Reality (VR) allows users to experience Immersive Virtual Environments (IVEs) in a multi-sensory fashion and is about to make its way into many different fields. Becoming an everyday technology, VR has the potential to transform entertainment at home, professional work in the office, and also the way users engage in everyday sports activities. The concept of Substitutional Reality (SR) maps a virtual onto a real environment and enables users to physically interact with IVEs, which allows for an increased feeling of presence. While most previous work focused on providing the VR user with a realistic and highly immersive VR experience, bystanders in the real environment are often not involved. In this paper, we introduce a projection-based system to involve bystanders in the virtual experience, by projecting the virtual environment onto the registered, physical counterpart. Using controllers, the system allows bystanders to interact with the IVE and to perceive the virtual environment in a semi-immersive way. We further present a case study where we applied the system in a substitutional reality climbing scenario and discuss potential application areas.

Index Terms: H.5.1 [Information Interfaces and Presentation (e.g., HCI)]: Multimedia Information Systems—Artificial, augmented and virtual realities; H.5.2 [Information Interfaces and Presentation (e.g., HCI)]: User Interfaces;

1 Introduction

Virtual Reality (VR) is on its way to becoming a ubiquitous technology. It has the potential to change the way we work, do sports, and the way we entertain ourselves at home. In the past, researchers and developers have primarily concentrated on inventing and improving the basis for affordable and powerful VR. The main goal was to provide the immersed user with the best experience possible, allowing the user to feel *present* in Immersive Virtual Environments (IVEs) [10]. Fueled by the progress in the display and graphics technology, Head Mounted Displays (HMDs) today allow users to experience interactive IVEs, even with commodity hardware.

On the way towards an everyday human-computer interface, concepts evolved that aim to enable immersive experiences in everyday environments, even in the presence of associated spatial restrictions posed by our everyday physical surroundings. Among these concepts, Substitutional Reality (SR) [8, 9] represents the central idea of adapting the experienced IVE to the physical environment of the user. A virtual space is mapped onto an exiting physical space and real objects are substituted by virtual counterparts. Real objects thereby provide tangibility and a sense of touch, i.e. passive haptic feedback [1, 2], to the virtual surroundings, which improves the sense of presence experienced by the VR user.

With many of the basic hurdles overcome, today, different areas explore the power of VR to discover how they can benefit from the technology: among them the entertainment sector, the sports sector, and professional sectors like architecture, education, simulation, training, communications, therapy, medicine, design, and more [3]. These areas cover large parts of our everyday life and many of them are based on collaboration. Joint activities, be they working together with co-workers in the office, a game with friends at home, or a sports session with a trainer, crucially rely on collaboration and interactivity. Thus, for VR to provide a benefit compared to established solutions and to receive acceptance by a broad base of people, future systems are expected to provide means for collaboration with non-immersed or semi-immersed users – a dimension mostly ignored in current VR solutions. We see a need for everyday VR systems to open up for users that do not need to, do not want to, or cannot be immersed by wearing a HMD. Instead, we envision systems that implement the SR concept and allow bystanders to perceive and actively take part in the experience of the VR user. Home environments rarely provide enough space for multiple users to be engaged in a fully-immersive way wearing a HMD, and systems are often designed for only a single user. To still provide a semi-immersive experience for bystanders, a solution that does not use worn displays is desirable. Similarly, in VR sports applications, bystanders, like trainers, need to be flexible enough to provide help and to intervene in certain situations, while they also need to have an overview of the IVE faced by the athlete. This also prohibits the use of HMDs or sitting in front of a screen in those settings. As the examples above illustrate, different setups and use cases provide a rich set of requirements for VR systems that need to be taken into account when developing applications for everyday use. VR systems should not isolate the user; instead, they should integrate ways to involve others in the experience.

In this paper, we introduce a projection-based solution for substitutional environments to provide users with means to passively observe and to actively take part in the IVE. We illustrate our solution in a case study which implements our approach in a substitutional reality system for climbers and outlines potential application scenarios.

2 Related Work

This section reviews work related to our concept. First, we review the idea of substitutional reality and we then discuss approaches to involve non-immersed or semi-immersed users in a VR application. Finally, we present work crucial for the projection-based solution introduced in our paper.

2.1 Substitutional Reality

The concept of Substitutional Reality (SR) in the context of VR was introduced by Simeone et al. [8, 9] and encompasses IVEs that adapt to the physical environment of the user. Objects and furniture present in the surroundings of the user are used to provide passive haptic feedback [1, 2] for different virtual environments to allow for an enhanced feeling of presence. Such substitutional environments

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can either be generated automatically, e.g. using a 3D scan of the physical room and an abstract representation of the IVE to map onto it, or can be constructed by hand [8]. Moreover, Simeone distinguishes three classes of SR systems differing in their scale [8]: desktop SR, room-sized SR and large-scale SR.

The concept of SR is based on the assumption that each substitution involves a certain degree of mismatch between virtual and physical objects. In previous work [9], the influence of different levels of mismatch was investigated and a set of mismatch layers was identified: replica (no mismatch), aesthetic (minor mismatch, e.g. in material), addition/subtraction (medium mismatch, e.g. in shape), function (mismatch, e.g. in affordances) and category (high mismatch, e.g. no recognizable connection between the virtual and the real object). The concept unifies two different advancements as it allows users to make use of their existing physical surroundings to enhance their experience in the IVE through haptic feedback on the one hand, and on the other hand, prevents unintended collisions of the user with the physical environment by mirroring physical obstacles inside the IVE. In this way, users are more likely to feel present and they are less likely to experience events that can result in breaks of presence [3, 11].

2.2 Involving Users in VR Applications

In most VR applications, the primary focus lies on the user experiencing the IVE in a fully-immersive way, today mostly wearing a HMD. However, since recently, several commercial VR systems and applications show support for an inclusion of other users as well.

As a basic means of including real-world information in the virtual experience, systems like the HTC Vive[1] and the Samsung Gear VR[2] implement features which allow immersed users to receive specific notifications from their smartphone, e.g. text messages, phone calls or calendar events, while being immersed in the IVE. The received real-world information is then displayed as a pop-up to the user. In contrast to displaying generic pop-up notifications, recent research is also concerned with solutions that notify the user of real-world information in a more adaptive and immersive way[3] [13]. However, from the perspective of the non-VR user, sending text messages with a smartphone application is too tedious in many settings. To allow for seamless collaboration, interaction interfaces for bystanders should be responsive and should provide the non-immersed user with a general conception of the IVE and the virtual situation the VR user is immersed in.

Another approach, that serves these requirements better, is called *asymmetric gameplay*. It is a concept used to generate a cooperative experience in VR games. Here, one user experiences the game being immersed while wearing a HMD. Simultaneously, non-VR players take part in the game by playing it either on a desktop monitor using conventional user input hardware like a keyboard or a game controller, or they assist the user verbally in solving puzzles or other challenges faced by the VR user. A key component of this concept is that the gameplay of the VR user, as well as the semi-immersed non-VR users, differs and is tailored to their respective abilities. In the game *Keep Talking and Nobody Explodes*[4], for example, non-VR users assist the VR user by reading a bomb defusing manual in the real environment to provide the user facing a virtual time bomb in VR with instructions to defuse it. As reading a manual is easier in the real environment than in VR, and as simulating a time bomb is easier and safer in VR than in reality, the game nicely demonstrates how to unify the strengths of reality and VR into a single immersive experience for every user.

[1] https://www.vive.com/
[2] http://www.samsung.com/global/galaxy/gear-vr/
[3] https://github.com/AndreZenner/notifications-framework
[4] http://www.keeptalkinggame.com/

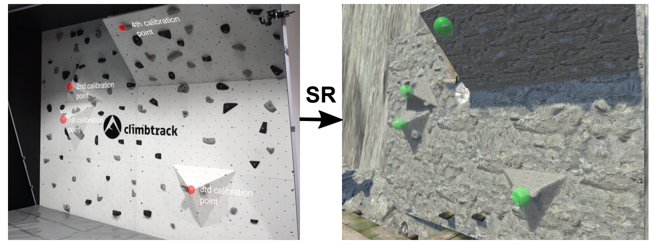

Figure 1: The main substitution of the SR climbing system. The physical climbing wall is substituted by a virtual rock wall inside an immersive virtual mountain environment [7].

While these approaches represent great solutions in their respective fields of application, their integration of non-VR users to the virtual experience might not be suitable for some scenarios. Using a smartphone application to interact with the immersed user, for example, might be too frustrating and tedious in serious work or training scenarios. Moreover, for sports applications, sitting at a desktop monitor to observe the IVE might be too static for trainers. A direct spatial link between the virtual and the real world, as given for example in SR systems, might be crucially important for non-VR users to assess the situation of an athlete training in VR. Thus, we propose an engaging projection-based solution to involve semi-immersed users in the virtual experience.

2.3 Immersive Projections in Everyday Environments

As an alternative to conventional computer displays or TV screens, projections offer a variety of benefits that render them suitable for providing a semi-immersive experience for several people at once. Projections can be large-scale and immerse users located in the environment observing the displayed content. Our technique builds on previous work which introduced and explored projection techniques suitable for use in non-instrumented everyday environments. IllumiRoom [5], for example, is a self-calibrating projection system used to augment content seen on a TV screen in the living room. It projects peripheral content onto objects and furniture in the room to augment it and to enhance the user's immersion. Similarly, the RoomAlive [4] system uses a multi-projector setup for large-scale projections in the user's real environment, combined with an automatic analysis of the environment's geometry. It uses depth sensors to find planar surfaces in the room and uses this information to project content, like games, in the user's surroundings. Here, depth sensors also enable users to interact with the virtual content.

Both approaches can be regarded as spatial augmented reality and are related to the SR concept. But in contrast to the systems focused on in this paper, they do not involve VR users that are fully immersed in a substitutional environment using a HMD. However, they both represent the technical basis of our solution, which we introduce in the following. Showcasing how to project immersive content onto everyday environments, which are also the core focus of SR systems, allows us to combine the SR concept with projections to involve bystanders in VR experiences.

3 Case Study: Climbing in Substitutional Reality

In the following, we introduce our projection-based interface to involve bystanders in a SR experience. We demonstrate our interface in the context of a SR sports application for rock climbers.

3.1 Motivation

With VR technology becoming widely available, novel interfaces and systems for everyday sports evolve. We present a case study that is based on a fully-immersive SR system for rock climbers by Kosmalla et al. [7].

Climbing gyms, which can be found in every major city, allow climbers to climb for training and fun without much preparation or the need to travel to remote outdoor climbing spots. Here, artificial climbing walls with holds of various shapes offer routes of different difficulties. Lately, systems that enhance and augment artificial rock climbing emerged, some based on projections offering games or training assistance [6, 12].

Leveraging the immersiveness of HMD-based VR and the haptic feedback of a physical climbing wall, the system we investigate in this case study registers a physical climbing wall with a virtual rock wall inside an immersive virtual mountain environment. The corresponding substitution is depicted in Fig. 1. The SR climbing system utilizes a precise spatial registration of the physical and virtual wall. This allows climbers to physically climb in the IVE while wearing a HMD. Having control over the IVE, the system can be used to simulate dangerous situations in a physically safe environment. With this system, difficult weather situations like fog, day and night changes, dangerous events like falling rocks, or the sudden appearance of wildlife could be simulated, allowing climbers to train for them. Moreover, the system supports the first three different layers of mismatch as defined by Simeone et al. [9]:

- **Replica** - The physical wall is substituted by a 3D scanned model of the wall, displayed in the IVE.
- **Aesthetic** - The virtual wall displayed in the IVE is textured with a rock texture, providing a realistic visual appearance matching the rough haptic feeling of the wall and holds.
- **Addition/Subtraction** - The system adds a complete virtual mountain environment to the scene, around the wall the user climbs on. Additionally, the system could remove holds from the virtual rock to force a user to climb a specific route, consisting only of the visually displayed holds on the virtual wall.

3.2 System

As described in the work by Kosmalla et al. [7], the system's real environment consists of an artificial climbing wall (width $4m$, height $3m$) with various holds, an overhanging panel and three volumes (see the left image in Fig. 1), and a thick mat to prevent injuries.

The substitutional environment is manually authored using a spatial calibration procedure[5] based on singular-value decomposition to register the physical and virtual wall. The VR user is immersed using a HTC Vive HMD and the base stations are fixed to the right and left of the wall in $\approx 2.5m$ height. The climber's hands are tracked with a Leap Motion[6] controller. The SR application is implemented in Unity and executed on a powerful notebook. A 3D model of the wall, obtained by scanning the wall with a Kinect v1 and the Skanect[7] software, represents the virtual rock. In line with the layers of mismatch described in the previous section, the 3D model can be displayed textured with a rock texture, and inserted into a virtual mountain environment scene. The mat in front of the wall was partly overlaid with a virtual wooden ledge on which the user enters the SR and approaches the virtual mountain.

In addition to these components, which are central for providing the user wearing the HMD with an immersive SR climbing experience, the system can create large-scale projections on the physical climbing wall. It uses a camera projection unit as in the work by Wiehr et al. [12], the Microsoft RoomAlive Toolkit[8] [4] and a corresponding Unity Plugin[9] to project the substituted virtual rock onto the physical wall. To drive the projection, a network connection between the notebook connected to the HMD and a second notebook used for the projection was established. By synchronizing the game state with the SR application via network, the projection notebook projects a real-time view of the IVE onto the wall and the climber. This projection is used for our semi-immersive interface for bystanders.

3.3 Semi-Immersive Interface for Bystanders

The central idea of our projection-based interface is to open up a SR experience to bystanders in the physical environment. Without interfaces that provide other people in the real environment with information about the VR user's virtual situation, the user experiencing VR would be mostly isolated from others in the room. Moreover, as substitutional environments make use of existing physical objects in the room, bystanders need to know the virtual counterparts these objects are substituted with in the IVE, to better understand the virtual situation of the VR user. We identified two types of bystanders, with different requirements, to such a SR interface:

- **Passive Spectators** – Passive spectators are located in the real environment and want to passively perceive the substitutional environment experienced by the user wearing a HMD. They want to conceive the spatial relation between the real environment and the substitutional environment to understand how the immersed user acts inside the SR. Moreover, they want to see individual substitutions, i.e. which virtual objects the physical objects in the room represent. They can thereby assess the layers of mismatch [9] of individual objects and the scene as a whole.
- **Active Spectators** – Active spectators have the same requirements as passive spectators, but additionally want to interact with the substitutional environment experienced by the VR user. Besides perceiving the SR, the spatial relations between the immersed user and the IVE, and the layers of mismatch of individual substitutions, they aim to trigger events in the virtual world or "reach into" the IVE to directly interact with it. By triggering events, the active spectator can influence the IVE experienced by the VR user, and by directly reaching into the IVE, she can change the environment, provide hints or even interact with the immersed user in the IVE. Moreover, the active spectator could adjust the present layers of mismatch by modifying the virtual substitutions, based on her knowledge about the real-virtual mappings.

In our investigated scenario for SR climbing, interested bystanders that observe the ascent of the immersed climber represent passive spectators. In contrast, a trainer providing hints in the IVE and controlling the substitutional environment would represent an active spectator.

To meet the requirements of passive and active spectators, we propose a system that consists of two main components.

3.3.1 Passive Component

The passive component of the system uses camera projector units [4, 5, 7, 12] in the real environment, to project the virtual substitutions of the SR onto the physical objects in the room. This allows bystanders in the room to simultaneously perceive the real environment and the IVE faced by the immersed user. In addition, users are still free to move around the physical environment to understand spatial links between the user and the IVE, as well as the current state of the IVE. Comparing the projection and the underlying physical object, bystanders can also understand the present real-virtual mismatches. This visual augmentation of the real environment transforms the physical room into a spatial augmented reality experience and provides bystanders with a semi-immersive look into the SR.

[5] https://github.com/felixkosmalla/unity-vive-reality-mapper
[6] https://www.leapmotion.com/
[7] http://skanect.occipital.com/
[8] https://github.com/Kinect/RoomAliveToolkit
[9] https://github.com/Superdroidz/UnityRoomAlive

Figure 2: A bystander's semi-immersive view on the SR experience of an immersed climber in the collect-the-presents game. Our interface projects the substitutional environment onto the physical environment.

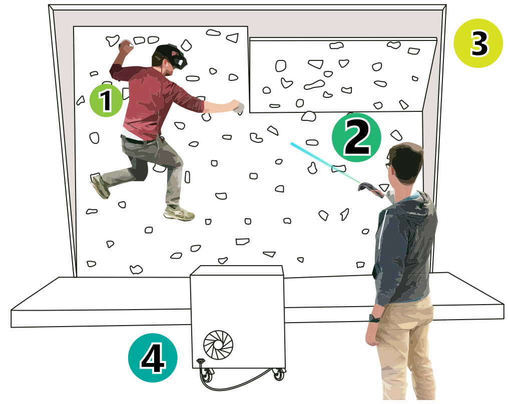

Figure 3: The setup of our projection-based interface. The VR user (1) physically climbs in a SR climbing environment while being immersed wearing a HMD. An active spectator (2) observes the climber's ascent and suggests a hold by pointing into the virtual environment with an HTC Vive controller. Meanwhile, the physical environment (3) is transformed into a spatial augmented reality experience as a projector unit (4) projects the substitutional environment onto the physical environment. In combination with the sounds of the substitutional environment played by the projector unit, this allows the spectator to semi-immersively perceive the IVE.

To provide a multi-sensory impression, the system can also play the sound of the IVE with speakers, which further improves the bystanders' perception of the SR.

In our case study implementation, the camera projector unit is used to project the virtual rock wall onto the physical climbing wall. This allows bystanders to understand where the immersed climber is in the IVE, and the situation faced by the climber. Bystanders can see the *Addition/Subtraction* mismatch present, i.e. which subset of the physical holds is actually displayed in the SR, and also all *Aesthetic* differences. In addition, special events like virtual falling rocks, weather changes, etc. can be perceived in an audio-visual experience. Based on our SR climbing simulation, we implemented a game in which the climber needs to collect presents floating in the IVE by hitting them with a hand while climbing. In this scenario, spectators can see an overview of the IVE, with the projected location of the presents and the score of the user, as shown in Fig. 2.

3.3.2 Active Component

An active component complements the bystander interface and allows active spectators to interact with the substitutional environment. Using the input controllers of the HTC Vive system, spectators can point "into" the IVE to trigger events, provide hints or otherwise act therein. The spatial tracking of the controllers and the spatial registration of the projection enables the system to raycast from the bystander's controller into the IVE and to compute intersections with virtual or substituted objects. Visualizations of the ray or corresponding hit points in the IVE will be visible to the bystanders when pointing at virtual objects that are covered by the projection. In this way, the bystander receives feedback corresponding to the input and can interact in a controlled fashion. The design space for such interactions is large. One can, for example, imagine the bystander giving hints to the immersed user, using a virtual stick to show points of interest inside the IVE. Moreover, by "shooting" at substituted objects, the bystander could change their virtual representation. This would enable the bystander to selectively control the level of mismatch present in the scene.

We implemented this concept in the SR climbing system, as sketched in Fig. 3, to provide an interface for trainers and other active spectators, which allows them to adapt the climbing environment. As illustrated in Fig. 4 and Fig. 5, bystanders can point a virtual flashlight at holds on the wall to aid the immersed climber. Moreover, active bystanders can trigger specific events in the IVE like day and night changes or falling rocks. These events can be regarded as *Aesthetic* changes or *Addition/Subtraction* events controlled by the semi-immersed bystander. To demonstrate interactive collaboration between an immersed user and semi-immersed bystanders, bystanders can take part in the collect-the-presents game by steering a virtual flying Santa Claus to help the climber collect presents in the IVE.

4 Discussion

The concept introduced in this paper can be applied in many different SR systems. Previous work, especially IllumiRoom [5] and RoomAlive [4], provides a great technical basis for the introduced semi-immersive SR interface to be implemented in everyday environments. Using multi-projector setups allows for a spatial augmented reality experience that covers large parts of the room. One can imagine suitable camera projector units to be shipped with future VR systems, allowing for use at home or in work environments. This paves the way for exciting new applications for entertainment, training, education, design, simulation and professional collaboration in general. In VR games that automatically adapt the virtual level to the space available to the player, for example, room-sized or large-scale SR experiences [8] that involve non-VR players can make use of the introduced interface. Similarly, other SR sport activities could benefit from such an interface. Imagine a soccer player practicing penalty kicks by shooting against a goal wall while being immersed in a crowded virtual stadium. A trainer could interactively provide hints by pointing at the virtual goal's projection on the goal wall. Besides that, a teacher could hint at interesting spots inside an IVE experienced by the students wearing HMDs, while still keeping an eye on every student. Another example would be the designer that uses her skills in VR to prototype a product design while being immersed with a HMD. Others involved in the product development process could easily see the designed object in a meeting using a projection interface, leveraging the active component to annotate the design in the IVE. Moreover, an interface as proposed here could enhance VR applications that visualize abstract data in an immersive way. Using projections in the physical environment would allow bystanders to take part in the creation, exploration or modification of abstract data sets like graphs or charts. Besides introducing this large space of potential applications, our system can also be useful to compensate for the drawbacks that limited physical environments pose to SR systems. In the absence of sufficient physical proxy

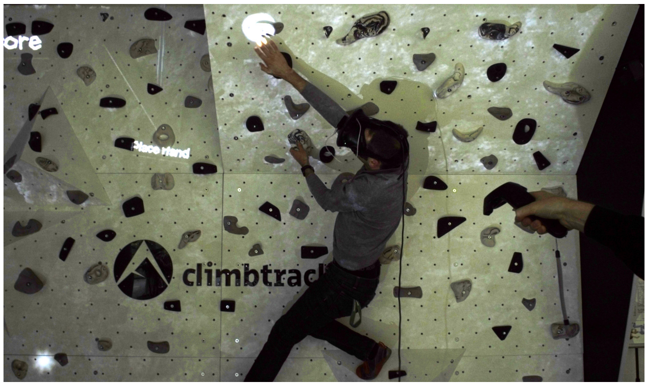

Figure 4: A VR user climbing in the SR climbing system. The bystander observes the ascent using our projection-based interface and switches to midnight in the IVE by pressing a button on the controller. To help the climber, the bystander uses the controller as a virtual flashlight inside the IVE. The bystander thereby points “into the IVE” and lights up a hold on the virtual rock to guide the immersed climber.

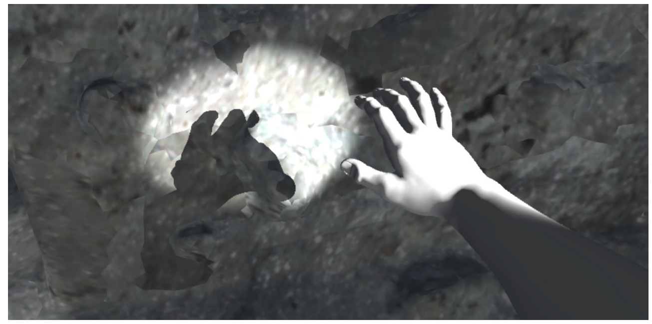

Figure 5: View of the immersed climber wearing a HMD. The climber sees the virtual flashlight of the bystander in the IVE. The light highlights a hold on the virtual rock, guiding the climber through the simulated SR night climb.

objects in the room, bystanders could interactively swap the virtual substitutes of physical objects to help the user by fulfilling a task in the IVE.

While today, VR experiences mostly isolate the immersed user from the real surroundings and other people in the room, the concept of SR aims to link real and virtual environments, and so does our associated interface for bystanders. While SR focuses on enhancing the experience of the VR user, our projection-based system complementarily aims to enhance the experience for spectators. While both the introduced active and passive components work in tandem to inform spectators about virtual events and to allow them to influence the IVE, the passive component might suffice for certain application areas. While a user could use a passive + active system when preparing with a trainer for a VR sports event, the passive projection component alone might suffice at the event to illustrate the user’s performance to the audience. However, we believe that involving bystanders in VR experiences is crucial to help VR become a ubiquitous and accepted interface. Experiencing VR while being immersed with a HMD is impressive and comes with exciting possibilities. But in current HMD-based VR systems, these possibilities are not seen by others but rather remain inside the HMD. Involving bystanders without HMD with suitable interfaces, such as the one presented in this paper, might transfer the potential that comes with VR to others in the environment. This helps non-VR users to understand the simulated virtual environment and the possibilities therein. As a consequence, this lowers the barrier for multi-user collaboration.

5 Conclusion & Future Work

In this work, we introduced a projection-based interface for bystanders of SR experiences. The introduced system is based on previous work about projections in everyday environments [4, 5] and enables bystanders to perceive the substitutional environment in a semi-immersive way. We identified two types of bystanders, passive and active spectators, and summarized their general requirements for such an interface. Passive spectators aim to perceive the SR while maintaining an overview of both the real and virtual environment. In addition, active spectators also want to interact with the virtual environment while observing the experience of a VR user. To meet the requirements of passive and active spectators, our proposed interface provides audio feedback by playing the sound of the IVE and projects the virtual substitutions onto their physical counterparts in the real environment. This allows bystanders to perceive the IVE and spatial relationships between the immersed VR user and the substitutional environment. Moreover, it enables bystanders to assess the layers of mismatch present between virtual and physical objects. To complement this, the system also allows active spectators to interact with the IVE using tracked input controllers. By pointing with the controllers onto the projection and “into the IVE”, users can trigger virtual events or provide hints to an immersed VR user. In a case study, we integrated our interface into a SR system for climbers [7]. We further discussed potential application areas and the importance of involving bystanders in a VR experience.

Evaluating the concept and conducting user experiments is the next step on the future work agenda, to gain further insights into how beneficial our approach is for the different types of spectators. Future work can also further elaborate on the introduced interface concept and investigate other application areas, e.g. integrating the system in a game or in professional applications used for the visualization of abstract data in VR. For a universal system to work in interactive SR experiences, adding support to automatically detect and track physical objects in real time is crucial. Moreover, the development of an easy-to-integrate framework to add support for our interface technique to existing VR applications would ease the investigation of this approach. In addition, as our case study utilized only a spatially limited projection onto the climbing wall, it would certainly be interesting to see if large-scale projections covering larger areas of the real environment enhance the experience of bystanders or allow for better interactions with the IVE. Here, projecting information about the VR user or his virtual avatar onto the user wearing the HMD might be an interesting approach. Besides that, it is also unclear how shadows, distortions, or projection areas that are too small impact the bystanders’ assessment of a substitutional environment. When substituted by, for example, a larger virtual object, it is unclear how projections onto a smaller physical object can convey its virtual appearance well. Finally, interaction techniques which allow bystanders to seamlessly interact with the immersed user might be worth investigating in future research.

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