ShareVR: Enabling Co-Located Experiences for Virtual Reality between HMD and Non-HMD Users

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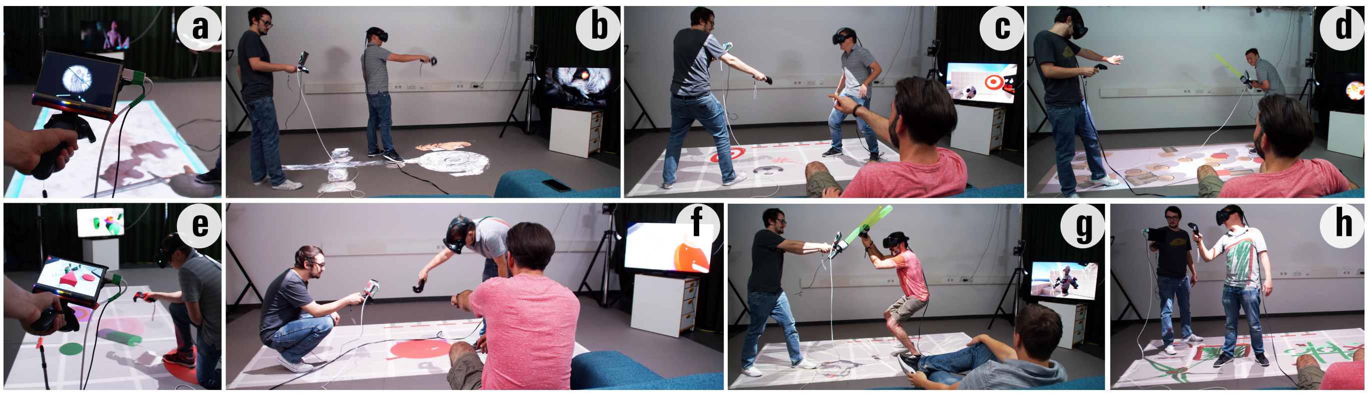

Figure 1. ShareVR enables co-located asymmetric interaction between users wearing an HMD and users without an HMD. ShareVR uses a tracked display (a, e) as a window into the virtual world and a floor projection to visualize the virtual environment to all Non-HMD users. It enables collaborative experiences such as exploring a dungeon together (b), drawing (h), sports (c) or solving puzzles (e, f) as well as competitive experiences such as "Statues" (d) or a swordfight (g). ShareVR facilitates a shared physical and virtual space, increasing the presence and enjoyment for both HMD and Non-HMD users.

ABSTRACT

Virtual reality (VR) head-mounted displays (HMD) allow for a highly immersive experience and are currently becoming part of the living room entertainment. Current VR systems focus mainly on increasing the immersion and enjoyment for the user wearing the HMD (*HMD* user), resulting in all the bystanders (*Non-HMD* users) being excluded from the experience. We propose *ShareVR*, a proof-of-concept prototype using floor projection and mobile displays in combination with positional tracking to visualize the virtual world for the *Non-HMD* user, enabling them to interact with the *HMD* user and become part of the VR experience. We designed and implemented *ShareVR* based on the insights of an initial online survey (n=48) with early adopters of VR HMDs. We ran a user study (n=16) comparing *ShareVR* to a baseline condition showing how the interaction using *ShareVR* led to an increase of enjoyment, presence and social interaction. In a last step we implemented several experiences for *ShareVR*, exploring its design space and giving insights for designers of co-located asymmetric VR experiences.

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INTRODUCTION

Virtual Reality (VR) head-mounted displays (HMD) are currently getting released as consumer devices (e.g. Oculus Rift, HTC Vive, and PlayStation VR) and are becoming part of the home entertainment environment. The technical progress allows for creating highly immersive virtual environments (IVEs) where users can even physically walk around and interact using their hands (roomscale VR) [13]. Having this physical exploration leads to a higher spatial understanding and therefore further increases immersion and enjoyment for the *HMD* user [4].

Despite VR aiming to become an essential part of the future living room entertainment, most current VR systems focus mainly on the *HMD* user. However, Alladi Venkatesh describes the living room as a highly social environment where people experience content together and interact through technology [61]. Since the level of engagement may vary between members of the household (e.g. some want to watch, some want to have some form of interaction and some want to be fully part of the experience), a VR system has to cover a wide bandwidth of engagement [63]. Solely observing participants would benefit from a more spatial representation of the virtual world such as the approach of Valve, which uses a green screen in combination with a tracked camera to create a mixed reality video for the observer [60]. People who only want a brief experience without committing to an extensive gaming session would benefit from a form of interaction with this mixed reality representation without having to put on an HMD. We argue that for VR to become part of this social living room environment, a way of interaction between users with an HMD and without an HMD is essential. Therefore, the focus of our work was on including the *Non-HMD* users into the VR experience and enhancing their way to interact with the *HMD* user.

We propose *ShareVR* (Fig.1), a proof-of-concept prototype enabling *Non-HMD* users to be part of the VR experience and interact with the *HMD* user and the virtual environment. We use a tracked display and a floor projection to visualize the virtual space for the *Non-HMD* user (Fig.1 a,e) and potential bystanders. To increase the engagement and enjoyment of *Non-HMD* users, we bring both (*HMD* and *Non-HMD*) into the same physical space enabling the same form of interaction. Prior work showed that this physical interaction can potentially increase enjoyment, social interaction and has cognitive benefits [39, 21, 42].

We conducted an initial online survey (n=48) with early adopters of VR, investigating how they currently deal with interactions between *HMD* and *Non-HMD* users and what future concepts should provide to improve this interaction. Based on those insights, we designed and implemented *ShareVR*. In a user study (n=16), we compared *ShareVR* with a baseline condition (gamepad and television), showing the increase of enjoyment, presence and social interaction for *HMD* and *Non-HMD* users using *ShareVR*. We further explored the design space of *ShareVR* and implemented three example applications, showing the novel possibilities for asymmetric co-located experiences and give insights on how to design future experiences for asymmetric co-located VR interaction. The contributions of this work are:

- Concept, design and implementation of *ShareVR* – a proof-of-concept prototype for co-located asymmetric experiences in VR, based on the feedback (n=48) of VR early adopters.
- Insights from a user study (n=16), exploring the impact of *ShareVR* on enjoyment, presence and social interaction and showing its advantage compared to a baseline consisting of a gamepad and television.
- Exploration of the design space for co-located asymmetric VR experiences and implementation of three example applications, giving insights for designers of future asymmetric co-located VR experiences.

ENVISIONED SCENARIO

Our envisioned scenario is centered around a living room where VR already became an essential part of the home entertainment. Future systems will be designed having asymmetric co-located interaction in mind and provide appropriate visualization for *Non-HMD* users (e.g. embedded display in controllers) and an in-situ visualization of the physical tracking space (e.g. embedded projectors in already used hardware such as the tracking system of the HTC Vive).

Our final vision further incorporates additional devices such as nomadic VR *HMD*s [24], AR *HMD*s and smartphones. These devices are all additional points on the interaction gradient between fully immersed user (VR *HMD*) to bystander (*Non-HMD* user). This work will mainly focus on spanning and exploring this design space between *HMD* and *Non-HMD* users. Future research projects should further explore additional devices on this gradient which generate different asymmetries and come with different concepts of visualization and interaction (e.g. [17, 25, 30]). Each of these devices will presumably have an individual impact on enjoyment, presence and social interaction.

RELATED WORK

Our work builds upon three general fields of research: *Collaborative/Spatial Augmented Reality*, *Collaborative Virtual Environments* and *Asymmetric Co-located VR Gaming*. We will not specifically focus on prior art having a different research direction but sharing a similar technical setup such as [38, 43].

Collaborative/Spatial Augmented Reality

Since presented in 1998 by Raskar et al. [51], spatial augmented reality aims to augment the environment by using projection technology instead of head mounted displays [35, 34]. The field is closely related to projector camera systems which were developed to enable these kind of experiences [50]. A recent example of this approach is RoomAlive by Jones et al. which is closely related to our work [34]. Using a set of projector camera systems, an approach to transform the living room into a gaming environment and enable multiple users to play and interact together was presented. This work beautifully displays and explores the design space of spatial augmented reality inside the living room. Our work is closely related to Jones et al.'s RoomAlive since we apply a similar approach to visualize the virtual world, but we focus mainly on interaction between *HMD* and *Non-HMD* users.

Collaborative augmented reality [2, 49] focuses on enabling collaboration and interaction between people using AR technology and further incorporates work with asymmetric setups (e.g. different visualization and different input capabilities [7, 55, 26]). The Studierstube [53] by Schmalstieg et al. and "Shared Space" [2, 3] by Billinghurst et al., are systems presenting a variety of interaction and visualization concepts for co-located augmented reality collaboration. A similar approach was presented by Benko et al. with VITA, a collaborative mixed reality system for archaeological excavations [1]. VITA combined projected interfaces, a large screen and tracked handheld displays to enable collaboration in a multi-user scenario. Stafford et al. further presented "god-like interactions", an approach to enable asymmetric interaction between a user with an AR *HMD* and a user with a tablet [55]. *ShareVR* follows a similar approach by offering individual interaction and visualization concepts for users without an *HMD*.

Collaborative Virtual Environments

Churchill et al. initially defined Collaborative Virtual Environments (CVE) as distributed virtual reality systems that enable users to interact with the environment and each other [11]. The focus was initially mainly on the distributed aspect [47]. DIVE, a distributed interactive virtual reality environment was presented by Carlsson et al., focusing on multi-user and 3D interaction aspects in distributed collaborative virtual environments [8]. Oliveira et al. further presented a distributed asymmetric CVE, where an *HMD* user would receive guidance and instruction from a user sitting at a PC using a traditional GUI [45]. However, the focus of the work was mainly on training applications and e-commerce scenarios. *ShareVR* incorporates several concepts from distributed CVEs in its prototype but mainly focuses on co-located synchronous interaction as defined by Johansen et al. [33]. In C1x6, Kulik et al. presented a co-located CVE that was realized using six projectors and active shutter glasses to provide correct perspectives to six users inside a virtual environment. This allowed each user to perceive the same experience, whereby *ShareVR* focuses on creating different perceptions of the same experience leveraging the advantage of each individual visualization approach. Kulik et al. found that people are more enthusiastic about exploring a virtual environment as part of a group which was one of the main motivations for *ShareVR*.

Similar to prior work, one essential characteristic of *ShareVR* is the asymmetry of the experience [17, 44, 12, 30, 29, 18, 15]. Duval et al. presented an asymmetric 2D/3D interaction approach which allows users who are immersed in an IVE to interact with users sitting at a PC [17]. The approach works by leveraging the advantage of each individual representation (2D vs 3D). Oda et al. presented a further asymmetric interaction between a remote user and a local user wearing an AR *HMD* [44]. In a user study, the remote user had to explain a specific task to the local user either through a 2D interface or a VR *HMD*. The results show that local users understood faster when the remote users actually demonstrated the task wearing a VR *HMD* vs writing annotations with a 2D interface. *ShareVR* incorporates these findings by letting the *Non-HMD* user have the same way of interaction as the *HMD* user. Also closely relevant to our work were projects exploring an asymmetric "god-like interaction" with the goal to let people build worlds together [12, 29]. Users with an VR *HMD* could collaboratively create virtual environments with users at a PC. A similar approach was shown by Ibayashi et al. with DollhouseVR [30]. *ShareVR* differentiates itself from those approaches by strongly focusing on enabling a co-located experience which aims to increase enjoyment, presence and social interaction instead of increasing performance.

More recently Cheng et al. presented HapticTurk [9] and TurkDeck [10]. In contrast to prior work on generatic haptics in VR [27, 28], HapticTurk and TurkDeck leverage human workers to generate haptic feedback for the *HMD* user. Our work was highly inspired by both systems and the haptic feedback was incorporated into the concept (e.g. lightsaber duel). However, in contrast to Cheng et al. *ShareVR* tries to enable an equally enjoyable experience for the *Non-HMD* user by literally sharing the virtual world of the *HMD* user with all people in the surrounding. To the best of our knowledge, *ShareVR* is the first system to enhance co-located asymmetric experiences between *HMD* and *Non-HMD* users who share the same physical space. This is a scenario that we argue will become more relevant as consumer VR technology progresses and attempts to become part of the living room entertainment.

Asymmetric Co-located VR Gaming

Despite the recent popularity of online multiplayer, co-located multiplayer games are still highly appreciated by many players [22, 46, 48] and researched by the scientific community [62]. Gajadhar et al. found that players experience a higher positive affect and less tension in a co-located than in a mediated setting or against a computer [20]. In the VR context, co-located settings are difficult to provide as usually only one VR HMD is available and only one player can wear it at a time. However, there are a few co-located VR games that make use of other means to circumvent this limitation. Games such as *Black Hat Cooperative*, *Ruckus Ridge VR Party*, *Playroom VR* and *Keep Talking And Nobody Explodes* apply an asymmetric interaction approach by either providing the *Non-HMD* user with an additional controller [52, 19], mouse and keyboard [57] or relying solely on verbal communication [56]. Recently, Sajjadi et al. presented *Maze Commander*, a collaborative asymmetric game in that one player uses a VR HMD while the other interacts using Sifteo Cubes. Although game experience did not differ between both interaction methods, players generally did enjoy the asymmetric game play.

Although these games all feature local multiplayer for VR, most game mechanics would still function if the games were implemented online and players had some form of voice chat. In contrast, *ShareVR* strongly focuses on the shared physical space and the resulting physical interaction to enhance the experience. While playing in a co-located setting does have positive effects on players [20], we argue that physical interaction in particular does enable novel play experiences for VR. Prior research has already shown that enjoyment and social interaction can be increased through physical engagement and interaction [39, 21, 42]. Lindley et al. found that an input device leveraging natural body movements elicits higher social interaction and engagement compared to a classic gamepad [39]. Similar results were found by Brondi et al. who showed beneficial effects of body movement on player engagement and flow for a collaborative game in a virtual environment [6]. Recently, Marshall et al. [41] studied aspects of games that encourage physicality in an extreme manner and derived guidelines for such games. *Johann Sebastian Joust* [16], is a game in that players have physical interaction in a shared play space. The players hold motion controllers and have to grab the other players' controllers in order to win while the played music restrains their allowed movement. To the best of our knowledge, *ShareVR* is the first VR system enabling physical gaming experiences between *HMD* and *Non-HMD* users.

ONLINE SURVEY

We conducted an online survey to elicit the demand for co-located asymmetric interaction and further explore how early adopters are currently coping with this (e.g. during demonstrations) and what they would expect from future technology to support co-located asymmetric interaction. The survey was posted in online forums (e.g. Reddit) and was sent out to mailing lists of early adopters. We were focusing on an audience which already uses the technology at home and falls under the category early adopter. Overall we received 48 responses.

Demographics

The majority of the early adopters were male (46 males, 2 females), held a college degree ($\approx 77\%$), and were on average 30.85 years old (*SD*=7.87, range: 19-49). The most used headsets were the HTC Vive (54%) followed by the Google

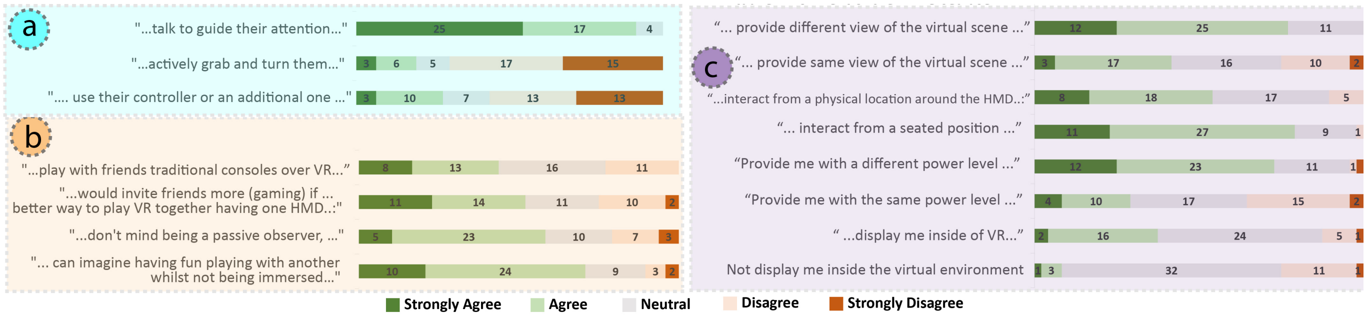

Figure 2. An excerpt from our online survey on the questions: (a) "When demonstrating my VR headset to friends and family I tend to:", (b) "Assuming that you own and actively use only one headset, please rate the following statements:", (c) "A technology which would allow me to actively influence the virtual environment of the immersed user should..." (Note: the statements are shortened and rephrased to fit into one figure.)

Cardboard (41%), Oculus Rift CV1 (33%), Oculus Rift DK2 (21%) and Samsung GearVR (19%). On average the respondents used the VR HMD 7.06 hours a week (*SD*=6.44, range: 0-30). Rated on a 5-point Likert scale, 73% stated a very high interest in virtual reality technology, 21% a high interest and 6% a moderate interest.

Current Coping Techniques

We asked people about the occurrence of asymmetric interaction (e.g. demoing a VR HMD) and how they are currently dealing with situations of asymmetric interaction (an overview of a subset of the questions can be found in Figure 2). The vast majority of our respondents reported they experienced asymmetric interaction during demoing of a VR HMD (94%) whereby only (38%) experienced it in a gaming scenario. Overall, only 13% played asymmetric co-located multi-user VR games (e.g. *Ruckus Ridge VR Party*) whereby 40% reported having regular ($\approx$ 4 times a month) gaming sessions sharing one HMD (average group size of $\approx$ 3 friends).

When asked about the form of communication used in such asymmetric scenarios, the majority agreed to use speech (91%)[1] followed by controllers (28%) and physical interaction (20%). When asked about their social coping, respondents agreed (48%) to prefer traditional consoles over VR HMDs when friends are around and would invite friends over more often (52%) for gaming sessions if there would be a better way of playing together having one HMD. Furthermore, respondents agreed that they would not mind being a passive observer (58%) and can imagine having fun playing with another person with an HMD whilst not having an HMD themselves (71%).

Demand and Future Requirements

When asked directly about asymmetric gameplay having one HMD, a vast majority agreed that they would love to be able to actively influence the virtual environment of the immersed user while not being immersed themselves (92%). When asked about specific aspects of asymmetric gameplay (Fig.2 c), respondents often preferred the asymmetric option (e.g. different view of the virtual scene: 77%, different power level: 75% and different way of interaction: 79%). Nevertheless, the alternative options such as same view (42%) and physical interaction (54%) were still more towards an agreement as towards a disagreement. When asked about the representation of the *Non-HMD* user inside the IVE respondents slightly preferred to be visualized inside the virtual world (38%).

[1] All the following reported percentages are based on the number of strongly agrees and agrees towards a statement

Discussion of the Online Survey

Our survey identified the users' desire to be able to actively influence and interact with *HMD* users while not not having an HMD themselves. We found dedicated co-located asymmetric games such as Ruckus Ridge VR Party are not widely known/spread, whereby 40% of the respondents already play with multiple users having one HMD. The main form of interaction between *HMD* and *Non-HMD* users is mainly speech. People further reported that they currently prefer using a traditional console with friends but would invite friends more often for VR gaming session if there would be a better way for playing together having one *HMD*. When asked about future concepts such a system should have, respondents preferred an asymmetric approach but still were interested in the alternatives. This indicated that these design decisions would have to be dependent on the underlying game dynamics. We used this feedback and incorporated it (e.g. speech as interaction, focus on asymmetry in visualization and power level) into our concept and implementation of *ShareVR* and its experiences.

SHAREVR CONCEPT AND IMPLEMENTATION

We designed and implemented *ShareVR* with the goal of enabling *Non-HMD* users to become a part of the virtual experience of the *HMD* user and enable them to interact and explore the environment together. Furthermore, we wanted to allow bystanders who are not interested in actively influencing the IVE to be able to follow and understand the events happening inside the IVE and be able to interact with the *HMD* and *Non-HMD* user (e.g. point and scream "watch out behind you"). A main goal for the design of *ShareVR* was to increase the enjoyment, presence and social interaction for *HMD* and *Non-HMD* users. We aimed for developing an entertainment system which would fit right into the social dynamics of a living room.

One of our major design decisions was not to design an *HMD* to *HMD* system but focus on asymmetric interaction with *Non-HMD* users. While we agree that the direction of *HMD* to *HMD* interaction is also highly relevant and (as presented in the related work section) a highly researched field, we decided to focus on scenarios where only one *HMD* is available. Similarly to Voida et al. [62], we argue that for the living room scenario, it is important to design a system which enables a gradient of participation. This allows users who are not eager to use an *HMD* to still be part of the virtual experience and maybe get interested in participating themselves. Furthermore, this approach allows a rich social interaction between *Non-HMD* users and bystanders since they both can see and talk to each other. This further creates an interesting social dynamic which we are going to discuss in more detail in our user study.

In our concept we focused on room-scale VR systems such as the HTC Vive and partially PlayStation VR, since they offer a larger design space, result in a high level of immersion and are expected to be widely spread systems in the future [59]. A second major design decision was to bring the *Non-HMD* user into the tracking space and let him explore the virtual world from the same position as the *HMD* user. This should result in an equal level of agency and engagement between *HMD* and *Non-HMD* users and further add the dimension of physical interaction (e.g. touch the *HMD* user). Prior research showed that this form of physical engagement and interaction results in an increase of enjoyment and social interaction [39, 21, 42].

Concept and Hardware Implementation
Our proof-of-concept prototype of *ShareVR* was built using an HTC Vive, two oppositely positioned short throw BenQ W1080ST projectors to visualize the tracking space and a 7 inch display attached to one of the HTC Vive controllers serving as a "window into the virtual world" for the *Non-HMD* user (Fig.3). We additionally added a TV which mirrored the view of the *HMD* user. The whole software was running on an i7 machine with an Nvidia GTX 970. The two main design variables we had were how to realize *interaction* and *visualization* for the *Non-HMD* users.

Interaction: Since we decided to bring both users in the same physical space we had to track the position and interaction of the *Non-HMD* user. We dedicated one of the HTC Vive controllers as the *Non-HMD* controller and used the Lighthouse tracking system of the HTC Vive to estimate the location of the *Non-HMD* user inside the physical space and let him interact with the IVE using the controller inputs. To leverage the advantage of sharing the same physical space we used physical props attached to the tracked controller as a second form of interaction between *HMD* and *Non-HMD* users. This enabled the *Non-HMD* user to generate haptic feedback for the *HMD* user (e.g. impact of lightsabers can be felt, cf. Fig.6). Based on the feedback of the online survey, we decided not to use headphones for the *HMD* user, to allow for oral communication between all users and directional sound (e.g. hearing the steps of the *Non-HMD* user).

Visualization: We designed the visualization having the *Non-HMD* user and additional users sitting on the couch in mind. To reduce the amount of shadows, we positioned two projectors opposite of each other directed towards the floor covering the full tracking space of the Lighthouse system. Both were calibrated through software to be perfectly aligned, visualizing the full tracking space to all people in the surrounding. This should help to develop a spatial understanding of the IVE for *Non-HMD* users. Furthermore, we attached a 7 inch display on top of the *Non-HMD* controller allowing to function as a "window" into the virtual world. We used a 5m hdmi cable to connect the display with the PC and supported it with power through a portable power bank inside

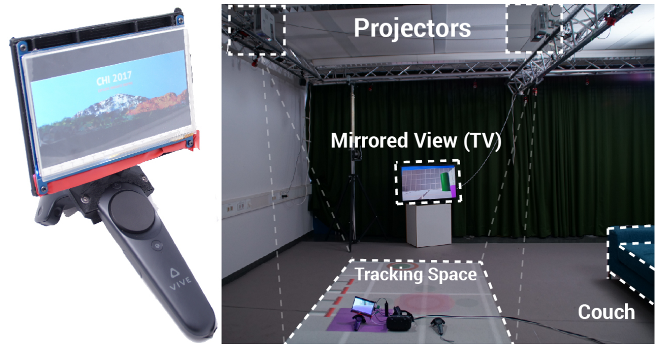

Figure 3. Left: Display mounted on the controller of the *Non-HMD* user. Right: Physical setup of *ShareVR*, replicating a living-room layout

the users pocket. We initially tried to remove all cables using wireless hdmi which resulted in a too big delay. Additionally, we used a TV to render the mirrored view of the *HMD* user.

Software Implementation
The whole software side was implemented using Unity® and the SteamVR Unity plugin. We used NewtonVR [58] as an additional layer on top of SteamVR to quickly prototype physical interaction such as grabbing virtual objects. We created a prefab in Unity consisting of the NewtonVR camera rig, an orthographic camera positioned above to cover the whole tracking space and a camera on the virtual *Non-HMD* controller. The orthographic camera rendered their image onto a mesh in which we could adjust individual vertices to correct for distortion and align both projectors. Two individual versions of this mesh were positioned in front of two additional cameras which rendered the projection images. We used this prefab throughout all our implemented experiences.

IMPLEMENTED EXPERIENCES
We implemented three different applications: *BeMyLight*, *SneakyBoxes*, and *SandBox* consisting of four smaller experiences (lightsaber duel, soccer, puzzle and drawing). The first two *BeMyLight* and *SneakyBoxes* were later used in our comparative user study, whereby the *SandBox* was used in the final exploratory study.

Collaborative: Be My Light
The experience *BeMyLight* places both users in a pitch black cave full of creatures and riddles to solve (Figure 4). The goal of the game is it to escape the cave system. Therefore, both users have to cooperate to be able to fight the monsters and solve the riddles. The *HMD* user plays an adventurer who holds a sword which he can swing to damage monsters and teleports[2] himself through the map. The *Non-HMD* user plays a magic fairy light which floats around the *HMD* user and is the only source of light inside the pitch black cave system. The fairy is furthermore able to cast a fireball which lights up the cave and damages monsters in its way. The riddles are designed in a way that both users have to work together to be able to solve them.

The *HMD* user sees the world through the eyes of the adventurer (point of view) and the fairy is visualized as a floating light (point light and spotlight in Unity). The *Non-HMD* user has

[2] we reimplemented a form of Valves The Lab teleport for locomotion

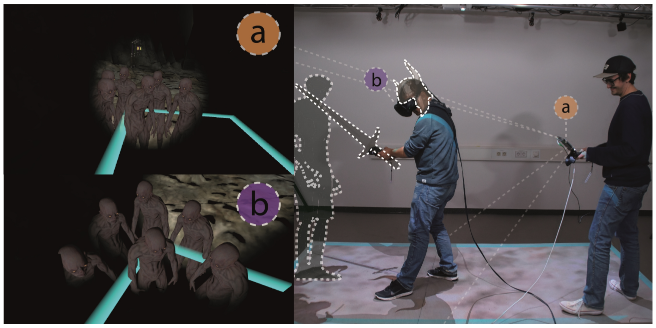

Figure 4. Two users (a: handheld view, b: HMD view) fighting monsters in the caves of *BeMyLight*. Note that the HMD user (b) only can see where the Non-HMD user (a) shines light on.

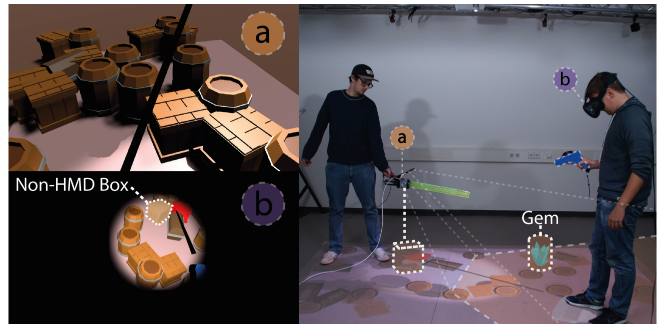

Figure 5. Two users playing SneakyBoxes and their individual views: (a) handheld (b) inside the HMD. Note that the HMD user (b) can not distinguish between a regular box and the Non-HMD box.

a top down view of the current tracking space visualized on the projection. This allows him to see the directions from which monsters are approaching or attacking the *HMD* user. He is further capable of controlling the scale of the projection (zooming) to use the projection as a map. The handheld screen is used as a "window into the world" metaphor and controls the direction of the spot light (flashlight metaphor). To further increase the dependency between both users, some information is only displayed to the fairy and some only to the adventurer, encouraging them to collaborate (e.g. "please shine some light here I think I saw something you can't see").

This basic dynamic highly encourages a form of collaboration since the *HMD* user needs a light to see monsters and the environment and the *Non-HMD* user can not explore the world on his own since only the *HMD* user can teleport. Both have an asymmetry of information (e.g. only the adventurer can see the key for the exit but the fairy has to shine light on the key to make it visible) and an asymmetry of power (e.g. the fairy knows the path through the cave system since he can see cues on the projection but only the adventurer can move both).

Competitive: Sneaky Boxes

SneakyBoxes is based on a popular children's game [64] which has different names through the world (e.g. RedLight, GreenLight in the US). *SneakyBoxes* is further highly inspired by Ruckus Ridge VR Party [19] which is one of few currently available co-located asymmetric VR games. The *HMD* user is positioned at the edge of the tracking space and uses one controller which represents a "marker" which can shoot projectiles. When looking into the tracking space the *HMD* user sees randomly positioned boxes, chests and barrels (Fig.5). The *Non-HMD* user is visualized as one of those boxes and is positioned inside the tracking space holding one controller which is mainly used for tracking his location. The goal of the *HMD* user is to find and "mark" the box which represents the *Non-HMD* user, whereby the *Non-HMD* user has to look through all the other boxes and find a randomly placed gem. All boxes are fixed in the scene and only the *Non-HMD* users' box moves when he physically moves his controller. This allows the *HMD* user to distinguish and tag the *Non-HMD* user.

To create a bigger challenge for the *HMD* user, the lights in the scene go out after approximately 10 seconds. To turn the lights back on, the *HMD* user has to turn away from the tracking space and hit a floating target behind him. This gives the *Non-HMD* user time to reposition himself and look through some of the boxes. To further exploit the physical proximity we attached an inflatable sword on the controller of the *Non-HMD* user. By hitting the *HMD* user with the inflatable sword, the lights inside the scene can be "hit out" every 15 seconds, forcing the *HMD* user to turn around and turn the lights back on. The handheld display is used as a "window" into the virtual world and the projection visualizes the tracking space (top down view of all boxes).

SneakyBoxes was designed to explore the competitive possibilities which arise from the co-located asymmetry enabled through *ShareVR*. We deliberately avoided the use of headphones for the *HMD* user, since the direction of the noise the *Non-HMD* user does is an essential part of the gameplay. We further actively decided to use a physical prop (inflatable sword) as a tool for the *Non-HMD* user to interact with the *HMD* user. We were mainly interested what implications this physicality has on the social dynamic.

Exploratory: Sandbox Application

In addition to *SneakyBoxes* and *BeMyLight*, we implemented a *SandBox* consisting of several smaller experiences which individually explore a novel aspect of the unique design space of *ShareVR*.

Soccer: The soccer application further explores the concept of high interaction asymmetry. The *Non-HMD* user uses both HTC Vive controllers and becomes the "Curator/Master" of the experience (Fig. 6 a). He can position targets inside the scene and spawn balls which he then can throw for the *HMD* user. The *HMD* user has to redirect the ball into the target using his head (header in soccer). The soccer application explores how an experience can be designed for *ShareVR* which puts the *HMD* user in a passive role and the *Non-HMD* user into an active and dominant position.

Lightsaber Duel: With the lightsaber duel we wanted to explore an interaction where the *Non-HMD* user is capable of interacting with the *HMD* user without the need for a visualization. To achieve this we mounted an inflatable light saber onto each of the HTC Vive controllers (Fig. 6 d). For the *HMD* user, we modeled a virtual lightsaber instead of the controllers which is exactly the same length resulting in a 1-to-1 mapping of the physical lightsaber and the virtual lightsaber. This allows the *Non-HMD* user to adjust his actions based on the physical location of the *HMD* user and his inflatable

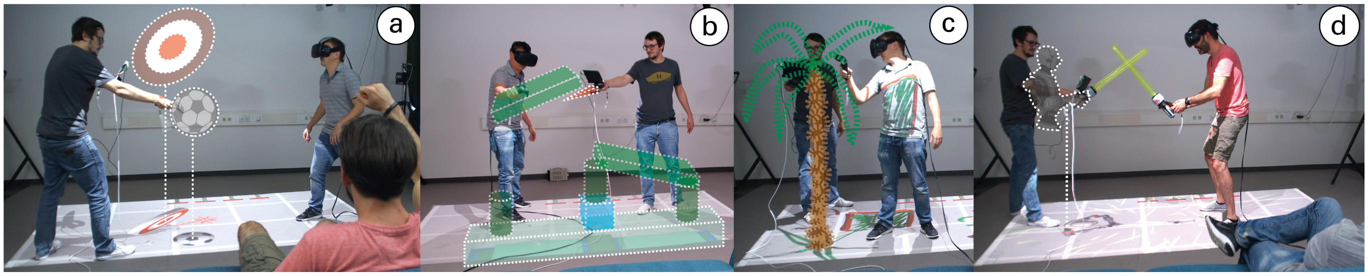

Figure 6. An overview of the individual applications with overlaid visualizations from the Sandbox: (a) throwing a ball to the HMD user in the soccer application, (b) instructing the HMD user in the puzzle application, (c) drawing a palm tree together and (d) having a lightsaber duel.

lightsaber. To represent the *Non-HMD* user inside the virtual scene, we used a robot avatar with simple inverse kinematics. The *HMD* user benefits from the high fidelity of the experience (e.g. feel the actual impact of the lightsaber).

Puzzle: The puzzle application was designed to explore the capabilities of more user involvement. Several 3D geometrical shapes are spawned around the *HMD* user with which he can interact using an HTC Vive controller (Fig. 6 b). His goal is to bring them into a certain arrangement. Only the *Non-HMD* user sees the building instructions on the projection and the handheld display on his controller. The only form of interaction between *HMD* and *Non-HMD* user is a virtual arrow attached to the *Non-HMD* user controller he can use to point at objects. The main form of communication is verbal, which includes all the potential additional users sitting on the couch. The puzzle application was designed so everyone can be involved in the experience since the building instruction is prominently visible and people on the couch can also direct actions of the *HMD* user (e.g. the red piece behind you should be a little more left).

Drawing: We implemented a drawing application to show how simple it is to extend an existing VR experience to be working with *ShareVR* and multiple users (Fig. 6 c). The basic principles are simple, both the *HMD* and *Non-HMD* user have one controller which they can use to draw with one color in midair (similar to Google's Tilt Brush [23]). The projection shows a top-down view of the tracking space (drawing space) and the handheld display works again as a "window" into the virtual world.

USER STUDY

To explore the interaction with *ShareVR* and measure the impact *ShareVR* has on the enjoyment, presence and social interaction between *HMD* and *Non-HMD* user, we conducted a user study. We compared *ShareVR* to a baseline condition consisting of a gamepad and a TV. In the baseline condition the *Non-HMD* user would sit on the couch and interact with the *HMD* user using a gamepad and a TV screen. This setup is currently used in most asymmetric co-located VR games (e.g. Ruckus Ridge VR Party [19], PlayStationVR [14]). The main difference between *ShareVR* and the *Baseline* was the shared physical space and physical engagement of the *Non-HMD* user.

Study Design

The study was conducted using a repeated measures factorial design with three independent variables. As independent variables we selected System (*ShareVR*, *Baseline*), HMD (*HMD*, *Non-HMD*), and Experience (*BeMyLight*, *SneakyBoxes*). For the *Baseline* system separate versions of *BeMyLight* and *SneakyBoxes* were created that were played with a regular gamepad instead of a tracked Vive controller. Further, smaller changes to the *Baseline* versions of games were made in order to provide a fair comparison of the systems (e.g. a button press can be used to trigger a sword hit in *SneakyBoxes*).

Independent variables were *enjoyment* measured with the post-game Game Experience Questionnaire (GEQ) [32, 31] as well as valence and arousal from the SAM questionnaire [5], *presence* measured with Slater, Usoh, and Steed's presence questionnaire [54] and *social interaction* measured using the *behavioural involvement* component of the GEQ's social presence module [32, 31]. In addition to these questionnaires we added a final comparison and asked participants to rate their enjoyment, presence and social engagement on a 7-point Likert scale.

Procedure

The study took place in a university lab that was prepared to resemble a realistic living room scenario containing a couch, a TV screen, and the play area of the HTC Vive (see Fig. 3). Participants were recruited in pairs. After a brief introduction, they played all 8 possible permutations of our independent variables (System x HMD x Experience). The order was counterbalanced using a Latin square. All play sessions were interrupted after 5 minutes in order to guarantee fair comparisons. After each play session, participants completed a questionnaire measuring their experience and additional data (e.g. visual attention). The study took on average 1.5h and participants received 10 currency.

Participants

For this study we recruited 16 participants (5 female, 11 male) with an average age of 27.63 (*SD*=3.181). Participants were recruited in pairs and with the premise that they have such a social connection that they feel comfortable playing with each other. They reported an average experience with VR devices of 8.76 months (*SD*=7.22). Their average interest in VR technology was very high (*M*=6.13, *SD*=0.62), but their intention to buy a VR HMD in the next 12 months was low (*M*=2.81, *SD*=2.04, both variables measured on 7-point Likert scales).

Results

Scores for positive experience and presence were analysed using a 2x2x2 (System x HMD x Experience) repeated-measures ANOVA. As the other variables were not normally distributed, nonparametric Aligned Rank Transform [65, 36] was applied. Figure 7 summarizes the collected data of the GEQ and SUS

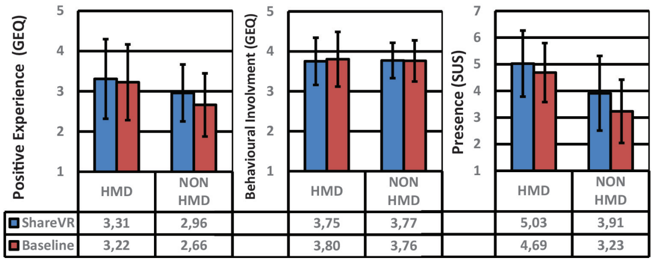

Figure 7. Averages (with standard deviation) of the positive experiences subscale (GEQ), behavioural involvement (GEQ) and presence (SUS).

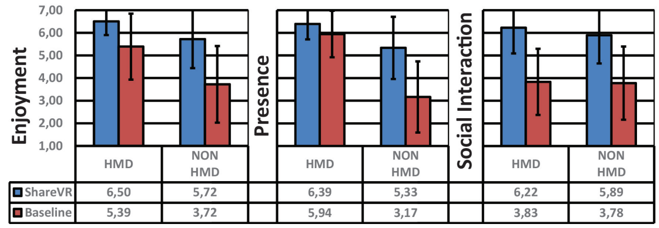

Figure 8. Averages (+/- sd) of the final questions on enjoyment ("I enjoyed using *{System}*"), presence ("I felt being in the game using *{System}*") and social interaction ("I felt engagement with the other using *{System}*").

questionnaire and Figure 8 shows an overview of the final comparison (enjoyment, presence and social interaction).

Enjoyment

The post-game GEQ consists of four components: *positive experience*, *negative experience*, *tiredness*, and *returning to reality*. *HMD* users reported a significant higher positive experience compared to *Non-HMD* players ($F(1,15)=11.573$, $p=0.004$, $r=0.660$). As expected, *Non-HMD* participants reported significantly higher scores for tiredness using *ShareVR* compared to *Baseline* ($F(1,15)=12.060$, $p=0.003$, $r=0.829$). Participants further reported significantly higher scores for *"returning to reality"* when using an *HMD* compared to *Non-HMD* ($F(1,15)=33.067$, $p<0.001$, $r=0.668$).

Participants playing with *ShareVR* ($M=7.47$, $SD=1.01$) reported significantly higher valence scores compared to *Baseline* ($M=6.95$, $SD=0.92$) ($F(1,15)=10.952$, $p=0.005$, $r=0.650$). Additionally, using an *HMD* led to significantly higher scores for valence than without ($F(1,15)=7.213$, $p=0.017$, $r=0.570$). Furthermore, significantly higher scores of arousal were reported using *ShareVR* ($M=6.1$, $SD=1.61$) compared to *Baseline* ($M=5.36$, $SD=1.50$) ($F(1,15)=7.145$, $p=0.017$, $r=0.568$), as well as for *HMD* ($M=6.01$, $SD=1.28$) compared to *Non-HMD* (M=5.31, SD=1.60) ($F(1,15)=8.809$, $p=0.010$, $r=0.515$).

For the concluding questionnaire ("I enjoyed using *{System}*", Likert scale from 1 (= strongly disagree) to 7 (= strongly agree)), a Kruskal–Wallis test revealed that ratings were significantly affected by the system ($H(3)=19.995$, $p<0.001$). {*ShareVR* x *HMD*} was rated significantly more fun than {*Baseline* x *Non-HMD*} ($U=27.781$, $p<0.001$). Furthermore, participants stated that they enjoyed {*ShareVR* x *Non-HMD*} significantly more than {*Baseline* x *Non-HMD*} ($U=-19.062$, $p=0.016$, adjusted significances are indicated for the Dunn-Bonferroni post-hoc tests).

Presence

Participants felt significantly more present (SUS) using *ShareVR* (M=4.5, SD=1.3) compared to the *Baseline* system (M=4.0, SD=1.1) ($F(1,15)=10.024$, $p=0.006$, $r=0.633$) as well as while using an *HMD* (M=4.9, SD=1.2) compared to *Non-HMD* (M=3.6, SD=1.3) ($F(1,15)=52.745$, $p<0.001$, $r=0.882$).

In the concluding questionnaire ("I felt being in the game using *{System}*", Likert scale from 1 (= strongly disagree) to 7 (= strongly agree)), we found a significant effect of the system used ($H(3)=29.240$, $p<0.001$). {*Baseline* x *Non-HMD*} was rated significantly lower than {*Baseline* x *HMD*} ($U=25.844$, $p<0.001$) as well as {*ShareVR* x *HMD*} ($U=32.812$, $p<0.001$) and also lower as {*ShareVR* x *Non-HMD*} ($U=-20.469$, $p=0.008$).

Social Interaction

Regarding social interaction, *SneakyBoxes* led to significantly higher scores for the *behavioural involvement* component of the GEQ social presence module compared to *BeMyLight* ($F(1,15)=6.877$, $p=0.019$, $r=0.560$).

In the concluding questionnaire ("I felt engagement with the other using *{System}*", Likert scale from 1 (= strongly disagree) to 7 (= strongly agree), the system significantly affected the reported social engagement ($H=26.942$, $p<0.001$). {*ShareVR* x *HMD*} was rated significantly more engaging than {*Baseline* x *Non-HMD*} ($U=25.656$, $p<0.001$) as well as {*Baseline* x *HMD*} ($U=-24,781$, $p=0.001$. Further, ratings show that {*ShareVR* x *Non-HMD*} was significantly more socially engaging than {*Baseline* x *Non-HMD*}, $U=22.094$, $p=0.004$) and {*Baseline* x *HMD*} ($U=-21.219$, $p=0.006$).

Additional Observations

Between each gaming session, we asked *Non-HMD* participants to state their visual attention on a 7-point Likert scale (7=most attention) between player, projection, tracked display and mirrored view (TV). Playing *BeMyLight*, participants reported a high focus on the handheld display (M=5.63) and a moderate on the projection (M=3.81). However, playing *SneakyBoxes* the focus switched to high on the projection (M=6.75) and low on the handheld display (M=1.37). This indicates the importance of alternative visualizations between experiences. Finally, participants were asked if they would want to have a system like *ShareVR* at home. Results show that *ShareVR* was highly positively perceived, $M=6.31$, $SD=0.873$ (measured on a 7-point Likert scale). This is also confirmed by the qualitative feedback we received, where participants actively stated that they want the system and asked about availability.

Discussion

The goal of our study was to examine the impact of *ShareVR* on enjoyment, presence and social interaction for *HMD* and *Non-HMD* players in comparison to the *Baseline* condition. Even if no significant differences were found for the GEQ questionnaire, in the final comparison we found a significantly higher rating of enjoyment using *ShareVR* for *Non-HMD* users. Even if not significant, we were surprised that overall participants rated using (*Non-HMD* x *ShareVR*) slightly higher than (*HMD* x *Baseline*). Furthermore, *ShareVR* did elicit more positive emotions, higher valence and higher arousal which can be both linked to positive player experience [37, 40]. These findings further correlate with our observations and qualitative feedback of participants *"I think both games should be further developed ... they are really fun"*. These findings confirm that with *ShareVR* we could increase enjoyment for *Non-HMD* users for co-located asymmetric experiences in VR.

Similar to enjoyment, no significant differences were found using the GEQ behavioural involvement subscale. This can be explained with the strong effect each individual game had. The GEQ measures how much a player's actions depend on the other player. This was in fact very different for both games which might have had more impact on participants than the system used. However, when rating only the systems regarding how engaged they felt with the other player, participants reported a significantly higher rating using *ShareVR* for both *HMD* and *Non-HMD* players. We explain these findings with the aspect of the shared physical space. When wearing an *HMD*, users are visually isolated from the space around them. Even if playing with another user located on the couch, not actually seeing the other reduces the experience to something similar to online gaming. This was similarly mentioned by participant 2: *"The projection helps to be part of the experience but using the controller felt more like playing online since you don't share any physical space"*. This further shows how *ShareVR* not only positively impacts the overall experiences for *Non-HMD* users, but also for *HMD* users.

Compared to the *Baseline*, *ShareVR* overall significantly increased the presence of the *Non-HMD* user measured by the SUS questionnaire and in the final comparison. Interestingly, in the final comparison participants rated (*Non-HMD* x *ShareVR*) only slightly lower than playing with an *HMD* in the *Baseline*. This suggests that *ShareVR* did in fact improve presence over the *Baseline*. Further, it might even be possible that the system can elicit presence in the *Non-HMD* player that is comparable to playing with an *HMD*.

Summarized, we found that *ShareVR* did improve enjoyment, social engagement and presence over the *Baseline* condition. Unsurprisingly, we found several effects of playing as *HMD* or *Non-HMD* player as well as effects from the individual experience. This suggests that although *ShareVR* showed promising results, experiences have to be specifically designed for the co-located asymmetric approach. Therefore, the next section is going to focus on the design space of *ShareVR*.

DESIGN SPACE AND GUIDELINES

To gain a deeper understanding of the design space, its implications and to be able to derive design considerations we conducted a second smaller exploratory study with two groups of 3 participants (n=6). The main goal was to further expose participants with the system and observe behavior and interactions using *ShareVR*.

Exploratory Study

We invited two groups of three participants each into our lab and let them experience an approximately 30-40 minutes long gaming session with the *SandBox* application (see Video Figure). Participants were again recruited as a group with a strong social bond and enjoying playing together. The first recruited group were three male HCI researchers (age: M=31, SD=3.56) and the second group consisted of three male VR enthusiasts (age: M=28.7, SD=0.47). After a short introduction into the control mechanics of *ShareVR*, participants were free to explore each application and had no further restrictions. Our only request was that each participant should experience each possible role (*HMD*, *Non-HMD*, and observer on the couch). Afterwards, we conducted a semi structured group interview on aspects of *ShareVR*, each individual role and the experienced gameplay. During the study three of the authors were present taking notes about observed behaviour and the group discussion afterwards. After both sessions the three authors had one shared coding session (thematic analysis) in which notes were compared and themes identified and discussed.

Additional Findings

The overall findings were directly integrated into the *Design Guidelines* and the *Design Space*. In this part we will briefly give insights on findings not covered by these two sections but seemed noteworthy to us.

Non-HMD users tend to form a certain bond with the observer since they both experience a similar perception of the virtual world and the *HMD* user. Participants often teased the *HMD* user with his inability of seeing the physical space (e.g. poke with a not tracked inflated sword). Nevertheless, *HMD* participants reported feeling safe when immersed to not bump into things and walk out of the tracking space since two *Non-HMD* users were around watching out for them. This shows that both accepted the teasing as part of the individual game without a negative influence on the whole experience. We further observed several occasions where the *HMD* user made mistakes resulting in a group laughter that started simultaneously. This shows that everyone was fully capable of understanding what is going on in the scene. Participants further reported they felt as they were entertaining the observer on the couch and that this feeling could potentially be higher if there would be several people on the couch. In terms of experiences, participants reported they had fun in every role but would prefer games which are not based on activities they can experience in real life (e.g. soccer).

Design Space

In the following we will present four variables of the design space we identified as essential factors and explain their implications. This categorization is based on insights we gained from actively implementing and testing *ShareVR* and both user studies.

Asymmetry in Visualization and Interaction: The main variable of every experience implemented for *ShareVR* is the level of asymmetry in visualization and interaction. The starting situation already has a strong asymmetry in terms of visualization, since the *HMD* user has stereoscopic perception of the virtual world and the *Non-HMD* user gets his understanding of the world through flat displays. Both have inherent advantages and disadvantages and should be considered when designing interactions for both users (see first guideline). The goal here is not to bring both on the same level but to leverage the advantages of each individual visualization. When done right, a high degree of asymmetry can lead to two entirely different experiences which results in a high replay value.

Dependency: The level of dependency in an experience controls how much coordination is necessary between *HMD* and *Non-HMD* user to achieve a goal. Dependency must be controlled and balanced in collaborative and competitive games. A too high degree of dependency will slow down the overall gameplay but a too low dependency results in both players having two separate experiences. Each user should contribute something to the games progress by leveraging the advantage of their modality in a non-artificial form (not a "job creation scheme"). In *BeMyLight*, we used several iterations to balance the dependency in such a way that both users felt they played a vital role for the progress of the game.

Power Distribution: Throughout our work with *ShareVR* we observed that the power level one has over the other user or the virtual environment highly influenced the enjoyment of the experience. The more I can impact the virtual environment or the other user (e.g. hit him with a sword) the more I enjoy the experience. It is hereby not necessary to fully balance the power between both users since users mostly wanted to have both experiences and will switch roles eventually. Throughout our study participants were always aware of this switch of roles and therefore restrained themselves from over using their power. However, for collaborative experiences the power level should be equally balanced so that both users have a feeling of playing a vital role in the progress of the game.

Physical Proximity: Each individual experience implicitly controls the allocation of the tracking space between *HMD* and *Non-HMD* users. If the physical proximity is embedded as part of the virtual experience, it can potentially lead to an increase of presence for the *HMD* user. However, if incoherent information is perceived acoustically or tactile it can break the presence and immersion for the *HMD* user (see fourth guideline). In general we observed that participants enjoyed a high level of physical involvement and were able to coordinate their position inside the tracking space easily. Here, it is a great advantage to have a *Non-HMD* user inside the tracking space since he was mostly in charge of the coordination.

Guidelines

From both studies and our own experience we derived four guidelines which we consider essential when designing for asymmetric co-located VR experiences such as *ShareVR*.

Leverage Asymmetry: Instead of assigning irrelevant tasks to the *Non-HMD* user to create any form of dependence and force collaboration, leverage the inherent advantages of each role. Offer isometric or orthogonal visualizations to the *Non-HMD* user since those help to perceive spatial relations in the virtual scene and allow the *Non-HMD* user to engage with further observers on the couch.

Design for the whole living room: Create visualizations not only for the engaged *Non-HMD* user but keep in mind that more participants can be around. We actively decided to use an orthographic camera for the projection and not a view dependent which could easily be adapted for the position of the *Non-HMD* user but only work from his perspective. Include as many observing roles as you wish in your application but keep in mind that *Non-HMD* users may tend to team up with observers against the *HMD* user.

Physical engagement is fun in moderation: Throughout our whole experience with *ShareVR* participants (both *HMD* and *Non-HMD* users) highly valued the ability to physically engage with each other. Introduce physical props which you can either mount onto one controller or track otherwise. Those can highly increase the presence of the *HMD* user. But be careful of physical engagement which is not visualized/transparent to the *HMD* user since this can result in discomfort.

Design for mixed reality in shared physical space: Keep in mind that your players are both located in the same physical space but perceive two different realities. Even if you do not visualize the movement and actions of your *Non-HMD* user, the *HMD* user will hear him interact in the surrounding. In some cases this can break the presence and immersion of the *HMD* user (e.g. hearing footsteps while his character is visually floating), but when considered in the game design can enhance the experience for both (e.g. physical props positioned by the *Non-HMD* user inside the tracking space).

CONCLUSION

In this work we presented *ShareVR*, a proof-of-concept prototype using floor projection and mobile displays in combination with positional tracking to visualize the virtual world for *Non-HMD* users and enable them to interact with the *HMD* user and become part of the VR experience. We designed and implemented *ShareVR* based on the feedback of early adopters (n=48) of VR technology. We implemented three experiences for *ShareVR* which each explore a different aspect of the novel design space. In a next step we conducted a user study (n=16) comparing *ShareVR* to a baseline condition (TV + gamepad) showing its advantage in terms of enjoyment, presence and social interaction. In a final step we conducted a short exploratory evaluation (n=6) which we used to help us explore the design space of *ShareVR* and give insights and guidelines for designers of co-located asymmetric VR experiences.

Limitations and Future Work

To entirely cover the gradient of engagement, an *HMD* to *HMD* interaction has to be modeled as well. We focused on asymmetric VR collaboration since it is likely to occur in the early days of consumer VR and appropriate concepts could benefit social acceptance. Furthermore, our findings are currently based on two or three people playing together. More research with a higher number of observers has to be conducted to fully understand the social dynamics happening in this asymmetric setup.

In the future, we are planning to extend *ShareVR* to incorporate more players and further integrate an additional *HMD*. This allows us to fully investigate the novel design space of asymmetric co-located virtual reality experiences and their impact on social dynamics.

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