FaceDisplay: Towards Asymmetric Multi-User Interaction for Nomadic Virtual Reality

Jan Gugenheimer[1], **Evgeny Stemasov**[1], **Harpreet Sareen**[2], **Enrico Rukzio**[1]
[1]Institute of Media Informatics, Ulm University, Ulm, Germany
[2]MIT Media Lab, Cambridge, MA
[1]*<firstname>.<lastname>*@uni-ulm.de, [2]sareen@mit.edu

Figure 1. FaceDisplay is a modified VR HMD consisting of three touch sensitive displays and a depth camera attached to its back (a-c). This allows people in the surrounding to perceive the virtual world through the displays and interact with the HMD user either through touch (e) or gestures (d).

ABSTRACT
Mobile VR HMDs enable scenarios where they are being used in public, excluding all the people in the surrounding (*Non-HMD Users*) and reducing them to be sole bystanders. We present *FaceDisplay*, a modified VR HMD consisting of three touch sensitive displays and a depth camera attached to its back. People in the surrounding can perceive the virtual world through the displays and interact with the HMD user via touch or gestures. To further explore the design space of *FaceDisplay*, we implemented three applications (*FruitSlicer*, *SpaceFace* and *Conductor*) each presenting different sets of aspects of the asymmetric co-located interaction (e.g. gestures vs touch). We conducted an exploratory user study (n=16), observing pairs of people experiencing two of the applications and showing a high level of enjoyment and social interaction with and without an HMD. Based on the findings we derive design considerations for asymmetric co-located VR applications and argue that VR HMDs are currently designed having only the HMD user in mind but should also include *Non-HMD Users*.

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INTRODUCTION
Mobile VR (Virtual Reality) HMDs (Head-mounted Displays) are currently mostly based on smartphones and a case outfitted with lenses (e.g. Samsung GearVR, Google Daydream). A recent development focuses on mobile VR HMDs which are not based on smartphones but offer an untethered headset with embedded hardware, inside-out tracking and some form of input capabilities (e.g. Intel Alloy). Both these device types enable the interaction scenario of Nomadic VR [18, 29], where users can immerse themselves inside a virtual world wherever and whenever they wish.

This nomadic interaction scenario comes with several challenges such as the unknown and uninstrumented environment [18]. Since current mobile VR HMDs are designed exclusively for the wearing user (*HMD User*), every other person in this environment

(*Non-HMD User*) is excluded and reduced to be a sole bystander [20]. This further leads to a complete isolation of the *HMD User* and could potentially lead to less social acceptance of the technology [40]. We identified two main challenges for this specific problem: *(1) How can we visualize parts of the virtual environment to Non-HMD users and (2) how can we enable a form of interaction between HMD and Non-HMD user inside the uninstrumented environment*. The overarching goal is to reduce *exclusion* for the *Non-HMD User* and reduce the *isolation* of the *HMD User* and enable a cohesive and enjoyable experience for both.

We propose *FaceDisplay*, a concept for a mobile VR HMD that is designed having the *HMD User* and the environment with all other people (e.g. friends, family and strangers) in mind. *FaceDisplay* consists of three displays arranged around the backside of the HMD to function as a visualization for the *Non-HMD User* (Fig. 1). To further enable a form of interaction, we attached a Leap Motion facing outwards allowing for gestural interaction. Additionally, we used capacitive touch displays to enable a second form of interaction by actually touching the HMD. We implemented three example applications (*FruitSlicer*, *SpaceFace* and *Conductor*) to show how different visualization and interaction metaphors can be used inside each application.

To investigate what specific interaction implications and social dynamics arise from such a concept, we conducted an exploratory user study (n=16). We recruited participants in pairs and let them interact with two applications (*SpaceFace* and *Conductor*) each as the *HMD User* and *Non-HMD User*, focusing on enjoyment, presence, social interaction and discomfort. We found that *FaceDisplay* enables the *Non-HMD User* to understand what the *HMD User* is doing and results in an equally enjoyable experience for *HMD User* and *Non-HMD User*. Additionally, we found a strong imbalance of the power level, putting the *Non-HMD User* in a more dominant position and derive design considerations based on our insights for co-located asymmetric virtual reality. We conclude by proposing a change in design perspective for future mobile VR HMDs. We argue that mobile VR HMDs should be designed having not only the wearer in mind (*HMD User*) but also the surrounding and everyone part of it. To truly overcome the future challenges for mobile VR, the negative aspect of isolation of the *HMD User* should be reduced.

The main contributions of this work are:

- The concept of *FaceDisplay* and the broader vision of designing mobile VR HMDs not only for the wearer, but also including people in the surrounding.
- A prototypical implementation of such a VR HMD and three example applications – each presenting multiple aspects of this novel design space.
- Results of an exploratory evaluation (n=16) explaining the implications such a design has on enjoyment, presence, social interaction and discomfort and deriving design considerations from these findings.

RELATED WORK

Our work is strongly influenced by the fields of *Mobile/Nomadic VR*, *Asymmetric Interaction/Collaboration for VR/AR* and *Asymmetric Co-located Gaming*.

Mobile/Nomadic VR

Since 90s' VR technology was not mature enough, the field of mobile and nomadic VR only became relevant in the more recent rise of VR around the 2010s. By combining a piece of cardboard, two lenses and a smartphone a simple VR viewer can be realised [4]. Google created Cardboard VR, one of the currently most spread mobile VR HMDs [17]. Following this trend, more smartphone-based (e.g. Samsung GearVR, Google Daydream) and self-contained (e.g. VIVE Focus) mobile VR HMDs were presented as consumer devices. This spread of VR technology into everyday consumer devices created the demand for HCI researchers to understand and design interaction concepts suitable for the nomadic VR usage scenario [18].

Several projects explored different input techniques designed for uninstrumented environments that work solely by modifying the HMD and without additional accessories [45, 28, 19, 31]. Smus et al. presented in [45] the original implementation of the magnetic input concept used throughout most first generation Cardboard VR viewers. Kent Lyons further enhanced this approach by extending the input from a binary selection to 2D input capabilities by applying magnetic field sensing to track the magnet on the side of the enclosure [31]. Instead of enhancing the magnet based interaction on the Google Cardboard, Kato et al. presented an modified Cardboard viewer that uses capacitive stripes attached to the case and running onto the normally unreachable touchscreen of the smartphone. This allowed users to create custom interaction interfaces and further extended the input space from the side of the HMD onto the backside of the HMD [28]. This form of back-of-device interaction for mobile VR was further explored and presented by Gugenheimer et al. [19].

A variety of research on mobile VR is conducted within the field of haptic feedback. Having the constraints of an uninstrumented environment and no accessories, researchers focused either on ungrounded haptic feedback systems [21, 41] or tried to leverage the feedback in the environment [23, 34]. Pohl et al. presented with "See what I see" a display attached to the back of a mobile HMD [40]. This work is conceptually closes to *FaceDisplay* but focuses only on the visualization and not the interaction and presents no user study. Most recently Chan et al. presented with "FrontFace" a single screen attached to the back of a mobile VR HMD to lower the communication barrier between *HMD User* and *Non-HMD User* [8]. The technical setup is similar to *FaceDisplay* but the focus lies on enabling a form of communication rather than letting the *Non-HMD User* be part of the experience (lower exclusion) or allow the *Non-HMD User* to interact with the virtual world. *FaceDisplay* on the other hand focuses more on exploring the design space of the interaction and uncover the underlying social dynamics occurring from this co-located asymmetric scenario. Misawa et al. presented a similar technical setup having a display attached to an HMD [35]. However, the focus was on enhancing telepresence and not in the field of virtual reality. To the best of our knowledge, *FaceDisplay* is the first concept enabling co-located asymmetric interaction for mobile virtual reality.

Asymmetric Interaction/Collaboration for VR/AR

Since augmented reality faces a similar challenge as virtual reality in terms of asymmetric interaction, a variety of approaches were presented. Collaborative augmented reality [2, 39] aims to enable collaboration and interaction between people using AR technology and further incorporates work with asymmetric setups (e.g. different visualization and different input capabilities [7, 46]). The Studierstube [43] 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.

Similar approaches for asymmetric collaboration were also explored in the field of virtual reality [12, 36, 11, 25, 20]. Duval et al. presented an asymmetric 2D/3D interaction approach which allowed *Non-HMD Users* to interact with users sitting at a PC [12], leveraging the advantage of each individual representation (2D and 3D). Oda et al. presented another asymmetric interaction between a remote user and a local user wearing an AR *HMD* [36]. 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* in comparison to writing annotations with a 2D interface. Also closely relevant to our work were projects exploring an asymmetric "god-like interaction" with the goal to enable people build worlds together [11, 24]. *HMD Users* could collaboratively create virtual environments with users at a PC. A similar approach was shown by Ibayashi et al. with DollhouseVR [25]. Most recently Gugenheimer et al. presented ShareVR, a projection-based concept that enables asymmetric co-located collaboration between a *HMD User* and *Non-HMD Users*. *FaceDisplay* follows a similar motivation but needs a different solution to satisfy the restrictions (e.g. no instrumentation, no accessories) of the nomadic interaction scenario. Additionally, we expected different social dynamics than with ShareVR due to our on body touch interaction and more extreme level of asymmetry.

Asymmetric Co-located Gaming

Despite the overall popularity of online multiplayer, co-located multiplayer games are still highly appreciated by many players [15, 37, 38] and researched by the scientific community [50]. Gajadhar et al. even showed that players experience a higher positive affect and less tension in a co-located than in a mediated setting or against a computer [14]. Since symmetric co-located settings are currently difficult to achieve for VR, developers tend to build asymmetric setups such as *Black Hat Cooperative*, *Ruckus Ridge VR Party*, *Playroom VR* and *Keep Talking And Nobody Explodes*. The *Non-HMD User* is either provided with an additional controller [42, 13], mouse and keyboard [49] or relying solely on verbal communication [47]. 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. Furthermore, Harris et al. presented additional guidelines for leveraging asymmetries in multiplayer games which we partially incorporated in some of our applications [22].

Although the aforementioned games all feature local multiplayer for VR, most game mechanics would still function if the games were implemented online and players had voice communication. For *FaceDisplay*, we strongly focus on the shared physical space and the resulting physical interaction (particularly in *SpaceFace*). Playing in co-located settings has been shown to have positive effects on players [14] and having physical engagement was further shown to increase enjoyment and social interaction. Lindley et al. found that an input device leveraging natural body movements elicits higher social interaction and engagement compared to a classic gamepad [30]. 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. [32] showed how aspects of games can encourage physicality in an extreme manner and derived guidelines for such games.

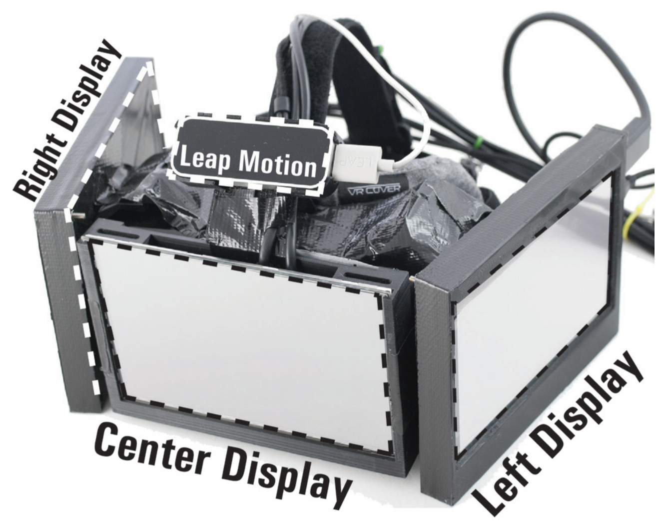

Figure 2. The hardware prototype of FaceDisplay, consisting of three touchscreens and a Leap Motion depth camera attached to the back and the sides of an Oculus Rift DK2

FACEDISPLAY

We designed *FaceDisplay* for the Nomadic VR interaction scenario [18], wherein an *HMD User* picks a location in which he wants to immerse himself and stays rather stationary[1] for the duration of the experience. This location can be either a public environment (e.g. subway) or a private one (e.g. at a friends home). Such a nomadic form of gaming was also recently presented by Nintendo with the Nintendo Switch. We consider the Switch as a nomadic device which was designed having the environment in mind, since its modular controllers (Nintendo Joy-Cons) allow users to spontaneously include people in the environment into their gaming experience.

The big difference between the Switch and the *FaceDisplay* concept is the asymmetry of the interaction. Since a single VR HMD can only offer the stereoscopic view to one user (*HMD User*) we had to come up with a different visualization concept for the *Non-HMD User*. We also had to create interaction concepts that work without additional accessories (nomadic context) and allow for different levels of engagement (socially familiar *Non-HMD User* and unknown *Non-HMD User*). We strive to cover the whole gradient of familiarity/engagement, since a mobile VR HMD could potentially be used in a public transport (unknown *Non-HMD User*) or at a friends home (socially familiar *Non-HMD User*). Both

[1]With rather stationary we mean a sitting or standing position with only little positional movement

scenarios would result in a vastly different form of interaction (e.g. observing by the unknown *Non-HMD User* vs playing with the socially familiar *Non-HMD User*) but should both be included to cover the wide range of engagement. Our goal was to allow for a similarly easy extension from single user to multi-user interaction as provided by the Nintendo Switch. However, similarly to ShareVR [20], our goal was not to create an identical experience, but embrace the asymmetry and allow the *Non-HMD User* to fully understand the virtual environment of the *HMD User*, allow the *Non-HMD User* to engage in an interaction and further enable a gradient of engagement from observing to participating.

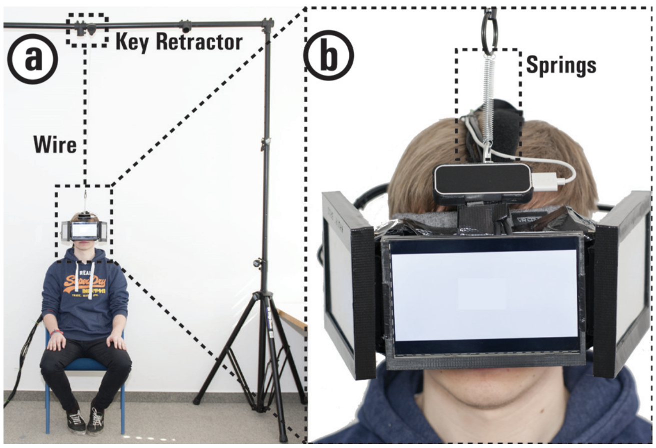

Figure 3. The technical setup used to reduce the weight of the FaceDisplay prototype, using a key retractor (a) and a pair of springs (b).

Technical Implementation

Our prototype consists of an Oculus Rift DK2, three touch displays and a Leap Motion on the back facing outwards (Fig. 2). We used two 7 inch Waveshare[2] screens for the sides (resolution: 1024x600) and a 7 inch ChalkBoard Electronics display on the back (resolution: 1280x800). The two screens on the side are attached with an angle of 75 degree to be still partially visible when looking straight onto the HMD. Each display is capable of capacitive multi-touch. The displays are attached using 3D-printed cases that match the shape of an Oculus Rift DK2. The Leap Motion controller was tilted by approximately 45 degrees, facing slightly upwards (Fig. 2). This allowed us to mainly see the hands of the *Non-HMD User* and a further away background (e.g. ceiling). This was necessary to increase the tracking accuracy since the Leap Motion has to conduct figure-ground separation of the depth image and fails if something (e.g. human torso) is at approximately equal distance as the hands. The overall weight of *FaceDisplay* is approximately 1.5kg. To compensate for the weight, we constructed a ceiling attachment similar to Sutherland's *Sword of Damocles* [48]. Our attachment consists of a 1.5m Key-Bak retractable keyholder, connecting the HMD and the keyholder through springs (Fig. 3 b). Furthermore, we hot glued additional padding around the nose and lens area. This allowed us to reduce the perceived weight, while keeping the freedom of looking around. We argue that in the future (and by a professional company) the prototype can be build significantly lighter to avoid this kind of apparatus.

[2]Each Waveshare screen was flashed with a custom firmware by Yannic Staudt – https://k16c.eu

The entire software was developed using Unity3D. The engine offers the *multi-display* feature which allows to open several rendering windows that can be later arranged onto each individual screen. Since the *multi-display* feature is currently under development, it does not offer touch capabilities for each window. Therefore, we implemented a second fully transparent application lying on top of our main application detecting the touches and sending them through a socket connection to the main application.

Interaction Concepts

When designing interaction concepts for *FaceDisplay* we had to initially realize the severity of the asymmetry of our setup. Similarly to the ShareVR concept [20], we created a highly asymmetric setup where a *HMD User* should be able to interact with an *Non-HMD User*. However, the big difference to ShareVR is that with *FaceDisplay*, the interface for visualization and interaction is physically attached to the *HMD User*. This results in the unique constellation that the interaction interface itself is not rigid but also moving around and every physical contact with the interface is perceived by the *HMD User*. During the design we kept our two goals in mind to reduce *exclusion* for the *Non-HMD User* and reduce the *isolation* of the *HMD User*.

Visualization: We incorporated this insight in the visualisation by using more than just one screen (in contrast to [40, 8]). Our initial prototype that consisted only of one display on the back led to the problem that users outside of the HMD had to follow the fast and unpredictable head rotations of the immersed user to be able to see the screen. The slightly angled side screens allow the *Non-HMD User* to be able to still see what is happening when the *HMD User* rotates left and right. This arrangement of displays allowed us to experiment with different visualization metaphors. The content on the screens displays the virtual environment mostly using a "window" metaphor. This should overall reduce the *exclusion*.

Interaction: Our goal for the interaction concept was that a wide gradient of engagement is covered (from observing to fully engaging Fig. 4) [51]. Observing was covered by offering the three screens as a visualization.

To be able to initiate a form of interaction from the outside, we implemented hand tracking for the *Non-HMD User* by attaching a Leap Motion to the backside of the HMD. This allowed us to visualize the hands of the *Non-HMD User* to the *HMD User*. This further enabled simple gestures (e.g. waving, pointing) as form of communication and interaction between the two users. Being able to know that a *Non-HMD User* is in the surrounding and where he is located should further help the *HMD User* to reduce the isolation and allows to further incorporate content outside of the HMD to the *HMD User* [33].

For the final level of engagement, we wanted to create a form of interaction that is capable of fast-paced gameplay and enables a strong social perception between *HMD User* and *Non-HMD User* to counter the isolation of the *HMD User*. We focused on FaceTouch [19] as an interaction technique since it fits the nomadic scenario and allows for physical contact (reduce isolation [20]). Both users interact with the virtual world by using the touch screens. Based on findings of Gugenheimer et al. on touch interactions for mobile VR HMDs, we decided to mainly use the screen on the back as a form of input for the *HMD User* [19]. The *Non-HMD*

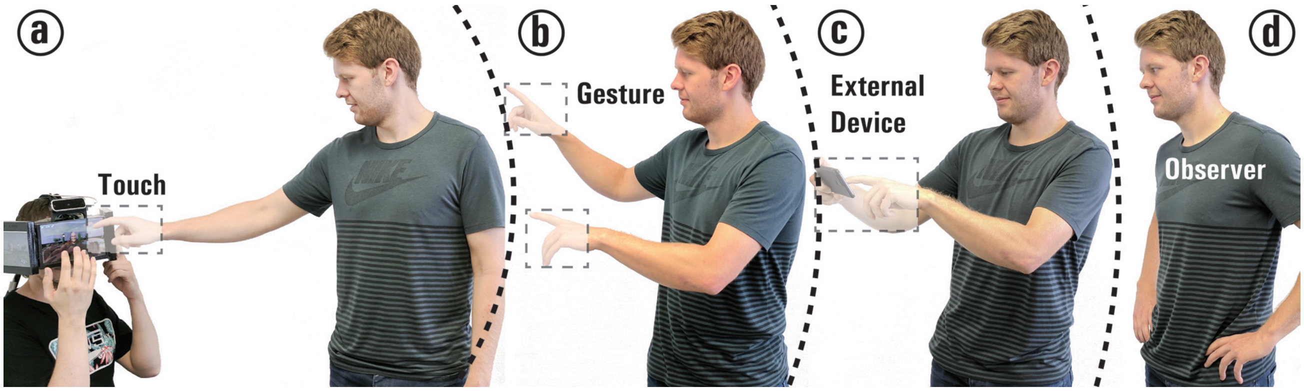

Figure 4. Interaction Gradient for *FaceDisplay*. Starting from the most engaged a: touch to b:gesture, c: external device and d: observing.

User influences the virtual environment by touching the corresponding point on any of the touch displays. This allows the *HMD User* to locate which of the attached screens was touched and further opens the interaction space to more physical forms of engagement (e.g. jousting hands or blocking head rotation). This additional physical contact can potentially increase the level of immersion for the *HMD User* [20, 9, 10]. We were particularly interested in how this form of interaction is perceived by both parties (*HMD User* and *Non-HMD User*) and which social dynamics arise from this (see section *Evaluation* for more details on these aspects).

Design Space/Interaction Gradient

Displaying the content of an immersed *HMD User* to the outside world, opens up a new and wide design space for different forms of interaction. Figure 4 shows the interaction/engagement gradient starting from the most engaged (touch) to the least engaged (observing). The displays on the *HMD* allow for multiple observers to understand the virtual environment and the current interaction state. The two outer most interaction concepts (observing and external device) additionally allow for multi-user interaction. One can imagine a scenario where several *Non-HMD User* observer the current virtual environment and interact with the *HMD* user via their own smartphone (e.g. spawn fruits in fruit slicer). Having the screens additionally on the HMD allows for observers be still part of the interaction.

In our user study, we focused on two concepts where the Non-HMD user is going to be in the immediate surrounding of the HMD user and use voice, gesture and touch as form of interaction so the HMD user can feel the presence (reduce feeling of *isolation*) of a second entity (Figure 4 a,b). Therefore, we did not explore interactions from slightly safer distances which lead to interactions that might as well be remote over the Internet. We also used touch deliberately to explore how far can we go with our 'close/intimate' interaction and tried to leverage the touch impact as active haptic feedback for the HMD user (e.g. SpaceFace: impact of an asteroid not only visual but also haptic). We wanted to explore what social dynamics arise when we bring the *Non-HMD User* close to the *HMD User* and design an interaction which is more physical. However, we do acknowledge that the smartphone is also an interesting form of input for *FaceDisplay* and should be considered for future research but was not in the scope of this work. Focusing on interactions from a slightly safer distance (Figure 4 c,d) enables additional applications without the need to battle exclusion and isolation (e.g. *Non-HMD User* guides *HMD User* through an application using gestures or an external smartphone).

APPLICATIONS

A general application scenario of *FaceDisplay* is the visualization of VR content to the environment (*Non-HMD Users*). It is important to realize that the content displayed on the screens should be under full control of the *HMD User* to still be able to keep a certain level of privacy and security. In its simplest form, this content visualization could be the title of the VR application or the face (or an avatar of the face) of the *HMD User* to try to conceal the fact that the user is wearing an HMD [16]. Since we were particularly interested in how to enable interaction between *HMD User* and *Non-HMD User* in a nomadic context, we focused on designing applications which offer a form of interaction by and between both users. In the following we will present three example applications (*FruitSlicer*, *SpaceFace* and *Conductor*) and discuss their design rationales.

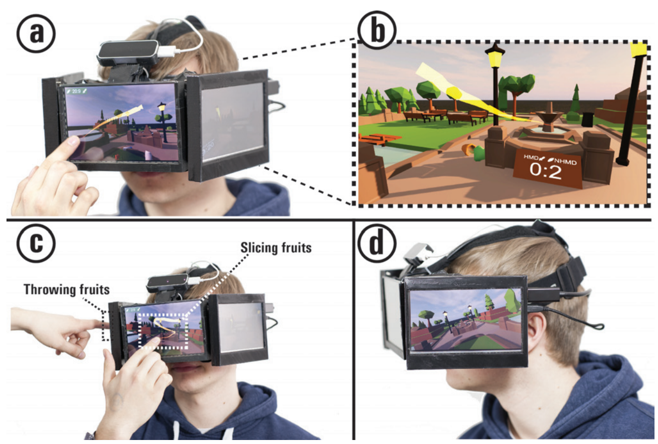

Figure 5. The FruitSlicer application with its outside view (a), inside view (b), interaction concepts (c) and visualization metaphor (d).

Fruit Slicer

FruitSlicer is a VR adaption of the popular Fruit Ninja game. The *HMD User* is located inside a virtual environment and different sorts of fruits and vegetables are thrown towards him. To collect points the *HMD User* has to slice all the fruits and vegetables and avoid slicing the bombs. The *Non-HMD User* can decide

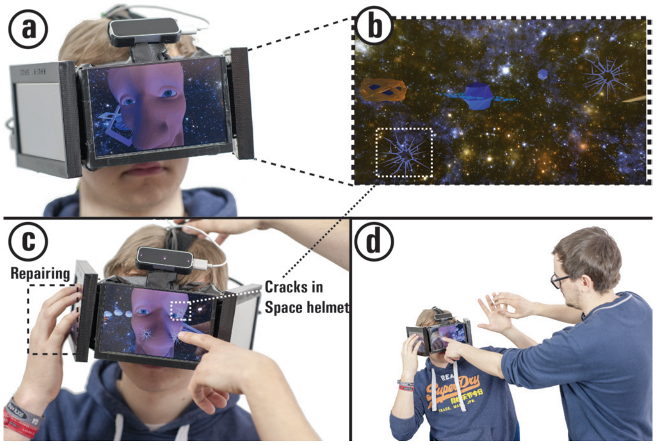

Figure 6. The SpaceFace application and its outside view (a), inside view (b) interaction and visualization concept (c) and physical interaction scenario (d).

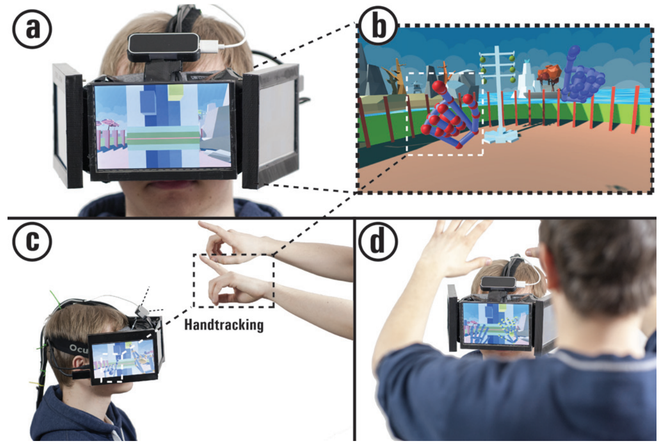

Figure 7. The Conductor application showing its outside view (a), inside view (b), hand tracking region (c) and interaction scenario (d).

at which frequency and what location the next object is going to spawn and "throw" them towards the *HMD User*. When the *HMD User* misses a fruit or slices a bomb, he loses one point and for every rightfully sliced fruit or vegetable, he gains a point. The first to get 10 points wins.

The *HMD User* sees the world from a first person perspective and can generate slices inside the virtual world by touching and moving his finger on the corresponding location on the center display (Fig. 5 a). This form of interaction was shown to be suitable for mobile VR HMDs [19]. The *Non-HMD User* is looking from a far distance into the virtual world and can see a visualization of the *HMD User* and the spawning objects and slices (Fig. 5 c). By touching one of the screens the *Non-HMD User* spawns a random object (fruit/vegetable/bomb) and throws it towards the *HMD User*.

We decided not to use a one to one mapping of the screen positioning and the camera positioning inside the virtual environment (i.e. no window metaphor). This allowed us to explore whether people would be able to understand the less intuitive visualization concept and how they would perceive it. We conducted a preliminary evaluation with two of the authors and gave several demonstrations to members and visitors of our institution. We mainly used *FruitSlicer* to gain an initial understanding of the interaction and social dynamics arising from it. We did not use *FruitSlicer* in the final evaluation but used it to gain knowledge for designing the two games used in the study (*SpaceFace* and *Conductor*).

Space Face

In *SpaceFace*, the *HMD User* is playing an astronaut who escaped an exploding spaceship and is now floating in outer space waiting to get rescued by another spaceship. The *Non-HMD User* is taking the role of the vicious space/cosmos and wants the astronaut to die before he gets rescued. In order to achieve this goal, the *Non-HMD User* can launch small comets at the glass of the astronaut's helmet. These comets generate an impact, sound (cracking of glass) and can be seen as a crack in the display by *HMD User* and *Non-HMD User* (Fig 6 b,c). Each screen can take up to 10 hits before it breaks and the astronaut suffocates. To avoid this, the astronaut is capable of repairing a screen by applying a special foam over a certain time period. After 2.5 minutes the astronaut gets rescued and wins the round.

The *HMD User* sees the environment from the first-person perspective of the astronaut. The *Non-HMD User* is looking directly onto the *HMD User* and the attached displays are functioning as a ”window” metaphor into the virtual world. The *FaceDisplay* prototype itself is representing the space helmet. The external screens show an androgynous avatar starting from nose to hairline to create the impression of the *Non-HMD User* user looking at a virtual representation of the *HMD User* (Fig. 6 a). Additionally, the *Non-HMD User* can look past the avatar and see parts of the space environment. The *Non-HMD User* can create the comets/cracks by touching any location on one of the three screens. This further generates a physical impact simulating the impact of a comet on the space helmet. To avoid constant attacking we implemented a cool down of approx. 1 second. The *HMD User* can repair a screen by holding down 5 fingers for approx. 1-6 seconds, depending on the amount of damage (Fig. 6 c).

We designed *SpaceFace* to explore what implications on social dynamics the physical interaction brings. The fact that the *Non-HMD User* is not visualized to the *HMD User* results in unpredicted impacts on the HMD. We further balanced the game so that the when played perfectly by both users, the *Non-HMD User* would always lose. This should further encourage the *Non-HMD User* to start using physical means to win the round (e.g. pushing away or even blocking the hand of the *HMD User*).

Conductor

Conductor is a VR adaption of a rhythm game such as Guitar Hero or AudioShield [1]. The *HMD User* is placed inside a virtual equalizer and listens to a music track (Fig. 7 b). Similarly to Guitar Hero, the music is also represented as blocks on three lanes and the *HMD User* has to tap one of each lane respectively to the rhythm and the visual indication (Figure 7 a). However, this block representation is only visible to the *Non-HMD User* who has to communicate (conduct) their timing and location using his hands (Fig. 7 c,d). The *HMD User* can only see the virtual hands of the *Non-HMD User* inside his virtual equalizer environment (Fig. 7 a). Every time the *HMD User* selects the correct lane with the correct timing, the score and the song volume increase and the visual equalizer starts to spark. Every missed block results in a decrease of volume and no points. To avoid frustration the thresholds of acceptance of a correct block are selected generously (approximately 0.5 seconds of tolerance). The goal of the game is to achieve the biggest high score.

The *Non-HMD User* sees the same block representation of the music track with indicators when to play which lane on each display. Furthermore, the hands are visualized so the *Non-HMD User* can notice occasional tracking imperfections. The *HMD User* sees the virtual equalizer and the hands of the *Non-HMD User* instructing him what lane to select and when. The lanes can only be selected by the *HMD User* through touching anywhere and with an arbitrary amount of fingers on one of the screens (left, center, right).

We intentionally designed a high level of asymmetry in the visualization and interaction of *Conductor* to explore how this impacts the already highly asymmetric setup. We further focused only on gestural interaction between *HMD User* and *Non-HMD User*. We were particularly interested if the *HMD User* perceives the virtual hands as part of the *Non-HMD User* or if they will be perceived as a computer generated part of the environment. Additionally, we wanted to explore how people incorporate the gestures inside their communication.

EVALUATION

To be able to understand the social and interaction dynamics arising from such a highly asymmetric scenario, we conducted an exploratory user study. We consider our evaluation exploratory since we chose a study method which is a mix between a quantitative and qualitative approach aimed towards better understanding the interaction and social dynamics arising from *FaceDisplay*.

Our main research questions were: *(1) What social and interaction dynamics arise from FaceDisplay, (2) how do people perceive the physical interaction as HMD User and Non-HMD User and (3) how do the roles (HMD User and Non-HMD User) and interaction concepts (touch and gesture) impact enjoyment, presence and emotional state*.

Study Design

The quantitative part of the study was conducted using a repeated measures factorial design with two independent variables *Role* (*HMD User*, *Non-HMD User*) and *Experience* (*SpaceFace*, *Conductor*). We designed each experience around the underlying form of interaction (gesture, touch). For the touch interaction we implemented a competitive game (*SpaceFace*) and for the gestures a collaborative one (*Conductor*).

Independent variables were *enjoyment* measured with the in-game Game Experience Questionnaire (GEQ) [27, 26] as well as dominance, valence and arousal from the SAM questionnaire [5], *presence* measured with Slater, Usoh, and Steed's presence questionnaire [44] and *social interaction* measured using the *social presence* module of the GEQ [27, 26]. In addition to these questionnaires, we added own questions asking about comfort of the interaction, agency of the interaction and understanding of the interaction. For the qualitative part of the study we recorded every session and two of the authors watched the footage and conducted an initial coding about observed behaviour. Afterwards, the two authors had one shared coding session (thematic analysis) in which notes were compared and themes identified and discussed.

The study took place inside a lab at our institution consisting of our technical setup (Fig. 3) and enough space so the *Non-HMD User* was capable to walk around the *HMD User* (Fig. 10). Participants were recruited in pairs being comfortable playing with each other. After a brief introduction they played each experience (*SpaceFace*, *Conductor*) and changed roles (*HMD User*, *Non-HMD User*) after 5 minutes (total of 4 x 5 minutes of pure play time). The experience and roles were both counterbalanced. After each role change, participants filled out the aforementioned questionnaires. Participants were instructed that they should behave as if they just bought *FaceDisplay* and visited their friend to try the new device. Therefore, no restrictions in terms of behaviour were given and participants were allowed to interact as they wish. The study took on average 1h and participants received 10 Euro.

Participants

We recruited 16 participants (4 female) in pairs so they would be comfortable playing with each other. The average age was 27.94 years (SD=2.94). Participants reported an average experience with VR devices of 17.6 months (range: 1 to 48) and a self-reported interest in VR technology of 6.3 (SD=0.7) on a 7-point Likert scale.

Quantitative Results

Scores from the GEQ ans SUS were analyzed using a 2x2 (*Role* x *Experience*) repeated-measures ANOVA with Bonferroni correction. All other single score items (SAM and own questions) were analyzed using a Wilcoxon signed-rank test. Figure 8 summarizes the scores of the GEQ, SUS and SAM and Figure 9 shows responses for our own questions. The focus in the following analysis is mainly on the *Role* as a variable. All the comparisons of the *Experience* are later combined with qualitative findings to abstract from the underlying application and highlight more general findings.

Enjoyment: The in-game GEQ consists of several components measuring each on a scale from 0 to 4. We used the positive affect component to get an overall enjoyment. There were no significant differences between *Role* and *Experience*. However, the average scores were all around 2.6 (scale: 0 to 4) indicating an overall enjoyment of the interaction. This is also in line with our single question *"I enjoyed using FaceDisplay"* that got in each condition (Role x Experience) on average a score of over 5 on a 7-point Likert scale. Therefore, we conclude that both experiences and both roles resulted in enjoyable play sessions.

Social Interaction: The social presence module of the GEQ consists of three subscales (empathy, negative feelings and behavioral involvement). Participants reported significantly ($F(1,15) = 7.899, p < .05$) more empathy playing *Conductor* (M=2.70, SD=0.52) than playing *SpaceFace* (M=2.03, SD=0.75) and significantly ($F(1,15) = 6.881, p < .05$) more empathy playing as the *Non-HMD User* (M=2.5, SD=0.65) than playing as the *HMD User* (M=2.25, SD=0.77). Participants also reported significantly ($F(1,15) = 41.472, p < .001$) more negative feelings playing *SpaceFace* (M=2.04, SD=0.95) than *Conductor* (M=1.01, SD=0.52). It is interesting that these negative feelings did not reflect negatively on the enjoyment.

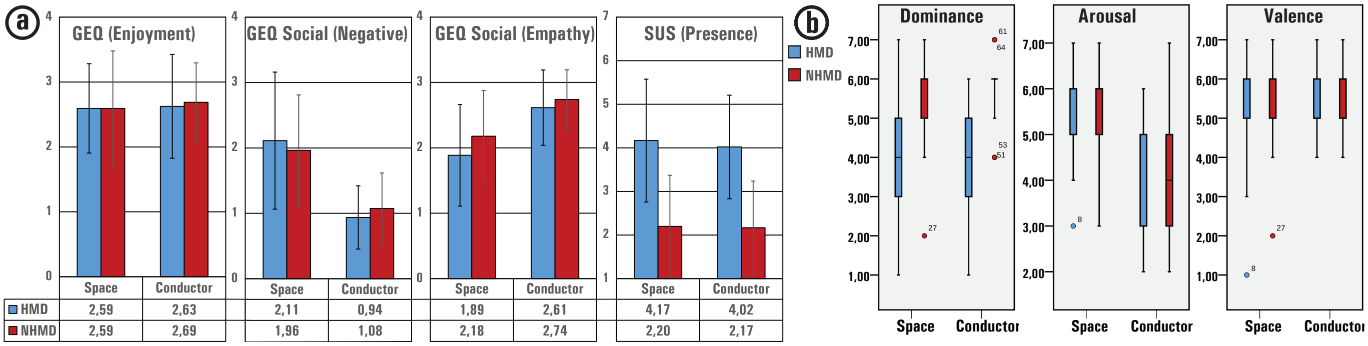

Figure 8. The distribution of our data from (a) the GEQ In-Game Module, GEQ Social Module, the SUS and (b) the SAM questionnaire. All bar charts showing the mean with standard deviation.

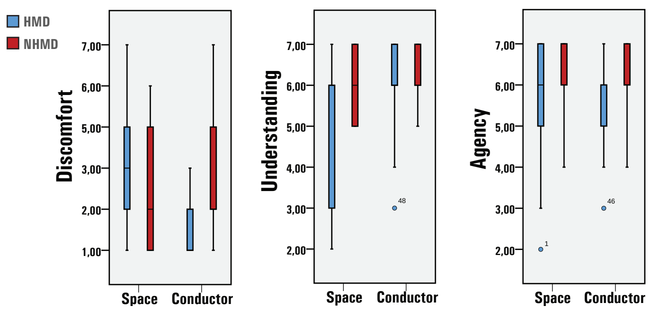

Figure 9. Boxplots of our own questions on discomfort *"I felt uncomfortable touching/being touched/gesturing/being gestured at"*, understanding *"I was always able to understand the current state of the game"* and agency *"I was always able to influence the outcome of the game"*

Presence: Participants reported feeling significantly ($F(1, 15) = 38.399, p < .001$) more present (SUS) in the experience being the *HMD User* (M=4.09, SD=1.30) than being the *Non-HMD User* (M=2.18, SD=1,12). There were no significant differences between the experiences.

Emotional State: For *SpaceFace* ($Z = -2.567, p < .01$) and for *Conductor* ($Z = -2.939, p < .01$) participants reported a significantly higher level of dominance being the *Non-HMD User* (Mdn=6) than being the *HMD User* (Mdn=4). Participants also reported a significantly higher level of arousal as *HMD User* ($Z = -2.811, p < .01$) and *Non-HMD User* ($Z = -2.979, p < .01$) playing *SpaceFace* (Mdn=5.5) than *Conductor* (Mdn=4). There were no significant differences in terms of valence.

Discomfort, Agency and Understanding: For the *Conductor*, participants reported a significantly ($Z = -3.219, p < .001$) higher level of discomfort (*"I felt uncomfortable touching/being touched/gesturing/being gestured at"*) of the interaction as *Non-HMD User* (Mdn=2) than as the *HMD User* (Mdn=1). As the *HMD User*, participants reported a significantly ($Z = -3.103, p < .01$) higher level of discomfort playing *SpaceFace* (Mdn=3) than playing *Conductor* (Mdn=1). This was expected, since the touch interaction of *SpaceFace* is far more intrusive than the gestural interaction in *Conductor*. For *SpaceFace*, participants also reported a significantly higher level of agency (*"I was always able to influence the outcome of the game"*) being the *Non-HMD User* (Mdn=7) than being the *HMD User* (Mdn=6). For *SpaceFace*, participants reported a significantly ($Z = -2.555, p < .01$) higher level of understanding (*"I was always able to understand the current state of the game"*) being the *Non-HMD User* (Mdn=6) than being the *HMD User* (Mdn=5.5).

Qualitative Feedback and Observations

Based on the coding of the video footage, qualitative feedback of the participants after the study and our own experience with *FaceDisplay* we derived the following social and interaction dynamics. Since those dynamics were highly different for each experience, we will present our observations for each individual experience.

SpaceFace had a bigger variety of different interaction dynamics in comparison to *Conductor* (Figure 10). Both participants (*HMD User* and *Non-HMD User*) were often in constant motion and at the end of a round were often times exhausted. Couples (two in our sample) tended to have an overall more intimate form of interaction (e.g. hugging, tickling). After the game pace increased, the *Non-HMD User* often times started to ignore the content on the screens and only focused on the actions of the *HMD User* and used the screens only as a form of input. *Non-HMD Users* often used the whole physical space around the *HMD User* and gained a level of advantage by not giving away their location and sneaking up and around to the *HMD User*. One participant reported after the study that he even felt bad abusing this level of power. The *HMD User* on the other hand, had to constantly repair his space helmet (hold 5 fingers to one screen) with one hand and used the other hand to either locate and repel the *Non-HMD User* or repair a second screen. Physical interactions (e.g. stretching feet, grabbing hand, waving arms) were often times initiated by the *HMD User* to estimate the location of the *Non-HMD User* around them. Overall, the level of power asymmetry (due to the game design and due to the role) resulted in highly different gaming experiences for *HMD User* and *Non-HMD User*.

When playing *Conductor*, participants had a more or less similar procedure. At the start participants negotiated the gestures they want to use for the directions (left, right and center) and the *HMD User* communicated his vision and tracking boundaries. When each song started, the *Non-HMD User* focused strongly on the "score sheet" while the *HMD User* was sitting mostly still, trying to hit each note. Both (*HMD User* and *Non-HMD User*) were spending the whole experience in almost the same posture (*HMD User*: facing towards the hands, *Non-HMD User*: standing right in front of the *HMD User*). *Non-HMD Users* often mentioned

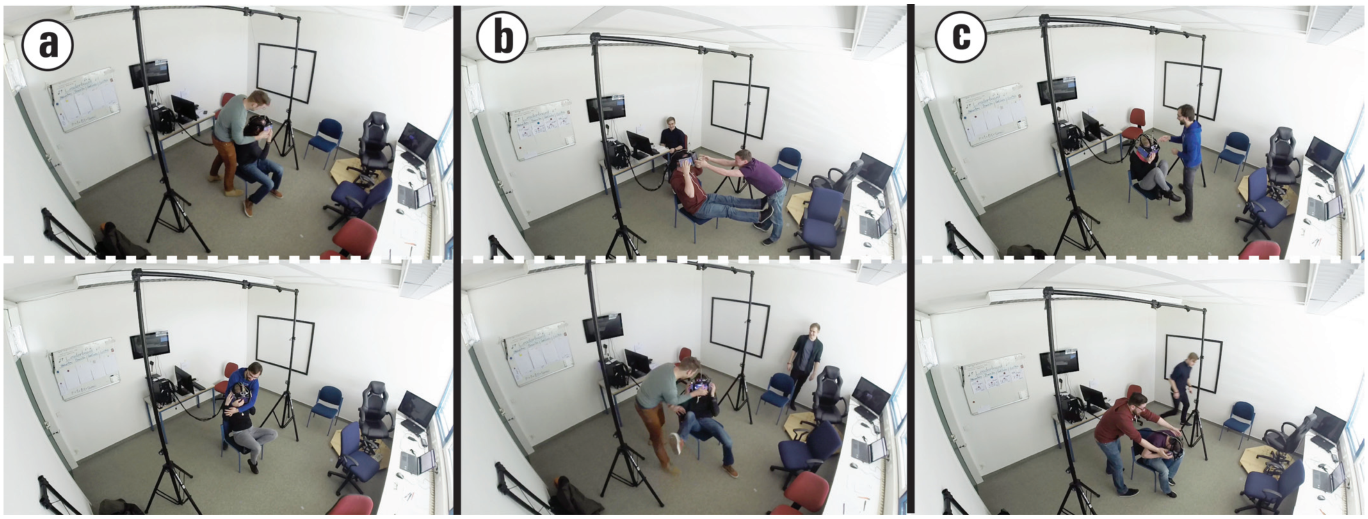

Figure 10. A variety of physical interaction poses participants used during the study emphasizing the vast possibilities of physical interaction arising from SpaceFace: (a) *The Kraken*: The *Non-HMD User* abused his power and wraps around the *HMD User* to restrict his motions. (b) *The Leg-press*: the *HMD User* utilizes his legs to either find or push the *Non-HMD User* away. (d) *The Hedgehog:* the *HMD User* rolls in like a hedgehog to hide from the attacks.

a certain level of fatigue holding their arms up over the duration of one play session and came up with coping mechanisms (e.g. conducting with one hand and supporting with the other). Since gestures were occupied indicating game-relevant actions, the main form of communication between the participants happened verbally. Similarly to *SpaceFace*, the *Non-HMD User* had a more dominant role but was perceived as having the more "responsible" role. When one note was missed or falsely selected, the *HMD User* often tended to blame the *Non-HMD User* since he was considered "the one in charge". Overall, the *Non-HMD User* had again a higher level of power but in the collaborative context this power was not abused but resulted in responsibility (*Non-HMD Users* often adapted to the *HMD Users*).

Combining these qualitative observations with the quantitative measures we found the following dynamics between *HMD User* and *Non-HMD User*. The *HMD User* had a higher understanding and control over the virtual world, while the *Non-HMD User* had a higher understanding and control of the real world. Using *FaceDisplay*, we allowed both users to have a certain level of understanding and control of the other users environment. Having the control over the real environment pushes the *Non-HMD User* in the role where he has more dominance over the physical body of the *HMD User* but also more responsibility that no physical harm occurs. Being the *HMD User*, we found that people enjoyed the additional haptic feedback from the outside and the fact that they were able to share a VR experience with someone in the surrounding, but needed a high level of trust in the *Non-HMD User*.

DISCUSSION

The goal of our study was to understand: *(1) What social and interaction dynamics arise from* FaceDisplay*, (2) how do people perceive the physical interaction as* HMD User *and* Non-HMD User *and (3) how do the roles (*HMD User *and* Non-HMD User*) and interaction concepts (touch and gesture) impact enjoyment, presence and emotional state*.

(1) Social and interaction dynamics: We found that the concept of *FaceDisplay* resulted in a highly imbalanced power level between *HMD User* and *Non-HMD User* (see SAM:Dominance, GEQ:empathy/negative feelings). The *Non-HMD User* can either abuse this (e.g. *SpaceFace*) or ends up with a higher level of responsibility (e.g. *Conductor*). This power level arises from the fact that the *Non-HMD User* can now see the virtual environment and the *HMD User*, whereas the *HMD User* only sees the *Non-HMD User* when he decides to show himself. This asymmetry of power could potentially be abused and impair the experience of the *HMD User*. However, since this form of interaction would only occur within a certain social familiarity, the *Non-HMD User* constantly balanced this out, resulting in a high level of enjoyment for both users (see GEQ, SAM:Valence).

(2) Impact of physical interaction: The physical interaction was overall used by the *HMD User* to somehow balance out the power level. When asked directly about the level of discomfort when touching the screen or being touched, participants reported a significantly higher level of discomfort compared to the gestural interaction (see Fig 9). However, when looking at the level of enjoyment (see GEQ, SAM:Valence) participants accepted this discomfort as part of the experience (impact of a comet on the helmet) and were less concerned being "touched" due to their social connection to the *Non-HMD User*. Despite being unconventional at first sight, we argue that touch interaction for *FaceDisplay* can lead to an immersive and enjoyable experience when played with a closely familiar partner.

(3) Enjoyment, presence and emotion: Overall, the majority of participants reported they had fun during the study and generally liked both game concepts. Since our goal was to include the *Non-HMD User* into the virtual environment and experience of the *HMD User*, we consider these high levels of enjoyment and presence to be a positive outcome. The *Non-HMD User* had an even higher level of agency of the interaction and a higher level of understanding of the virtual environment (see Fig. 9). The different interaction approaches (touch and gestures) had no

significant impact on the experience and can therefore both be used according to the envisioned experience.

Our overall goal was to include the *Non-HMD User* into the experience of the *HMD User* and to break out of the isolation current VR HMDs force upon the *HMD User*. This has been partially tried already through the concept of "social VR" where an *HMD User* can experience games and videos with other *HMD Users* online. We argue that for the nomadic VR scenario this must be also done for *Non-HMD Users* in the surrounding. This could potentially break the isolation *HMD Users* experience when using VR HMDs with friends and family in the surrounding. Therefore, HMDs should not only be designed having the *HMD User* in mind but should also include all people (*Non-HMD Users*) in the environment.

DESIGN CONSIDERATIONS/INSIGHTS

The following design considerations and insights are derived from the observations during our study, user feedback and our experience demonstrating *FaceDisplay* on several occasions.

Comfort and Safety. We found that touch on the screen is perceived as part of the experience when it is synchronized with events inside the virtual environment (e.g. crack in screen). However, game designs including heavy movements can results in too strongly perceived touch impacts on the *HMD User*. Having an unpredictably moving user could also result in safety hazards for the *Non-HMD User*. We observed that the *Non-HMD User* takes the responsible role of "protecting" the *HMD User* and therefore we never had an incident during our studies or demos. Nevertheless, experiences involving heavy movement should be played using an alternative input such as gestures or remote displays (Fig. 4 b,c).

Responsibility and Dominance. Since the *HMD User* is exposed to the impact from outside and is automatically in a less dominant role (see SAM score of results) fitting game designs can be selected to make this asymmetry part of the experience (e.g. *Conductor*). Embracing this asymmetry and using it as part of the narrative, results in experiences that feel more tailored towards the scenario and interaction. Similar to [20], we suggest to embed this asymmetry inside the game design to create novel types of experiences.

Physical Interaction. The physical interaction on the screen can be embedded inside the VR experience to generate haptic feedback for the *HMD User*. When embedded smoothly (e.g. *SpaceFace* impact of asteroids) it increases the immersion of the *HMD User* and results in a more enjoyable experience. However, due to the strong dominance asymmetry an over usage can lead to a negative experience since the *HMD User* feels exposed to the surrounding. We observed this in several scenarios where multiple users played the outside part in *SpaceFace*, resulting in an even stronger outside dominance and a quite claustrophobic experience. This could potentially be used in strong horror experiences or psychological experiments but goes beyond the entertainment scenario.

Exposure to Outside Observers. Sitting practically 'blindfolded' in front of one or several users lead to a highly exposed perspective of the *HMD User*. We actively created a friendly environment (only interaction with close friends) where this feeling is not negatively amplified. *HMD Users* were mostly capable to perceive outside users based on sounds, voices and motion. However, this effect can also be used as part of a story narrative (e.g. being monitored, stalked) to increase the emotions of the experience. Overall, designers should be aware of the fact that the *HMD User* often feels observed due to the head mounted displays.

CONCLUSION

In this work, we presented the design and implementation of *FaceDisplay*, a mobile VR HMD prototype consisting of three touch sensitive displays and a depth camera attached to its back. *FaceDisplay* enables people in the surrounding to perceive the virtual world through the displays and interact with the *HMD User* via touch or gestures. We presented three applications (*FruitSlicer*, *SpaceFace* and *Conductor*), each focusing on one specific aspect of the asymmetric co-located interaction. We further conducted an exploratory user study (n=16), observing pairs of people experiencing two of the applications. Our results showed that *FaceDisplay* was able to let the *Non-HMD User* perceive and interact with the *HMD User* but resulted also in a high level of dominance and responsibility of the *Non-HMD User* over the *HMD User*. We argue that VR HMDs are currently designed having only the HMD user in mind but should also include all the people in the environment to break out of the current isolation an *HMD User* experiences when using VR HMDs.

Limitations and Future Work

The applications we implemented only outline a small subset of all possibilities arising from the *FaceDisplay* concept. We also tailored our applications around specific forms of interaction to create an overall enjoyable experience. It is therefore difficult to distinguish between the impact of the experience and the interaction on the measurements. That is why we did not follow a standard comparative study design, but had a more exploratory approach also including codings of the observations of the interaction. Since our goal was to reduce isolation and exclusion, which both currently mainly occur in social settings with entertainment applications (e.g games, movies), we argue that within this entertainment scenario our findings are more generalizable.

In the future we are planning to explore each individual form of interaction and its impact on the experience. We also plan to extend *FaceDisplay* to incorporate not only one *Non-HMD User* but create experiences where multiple *Non-HMD Users* can interact with one or multiple *HMD Users*.

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