ShARe: Enabling Co-Located Asymmetric Multi-User Interaction for Augmented Reality Head-Mounted Displays

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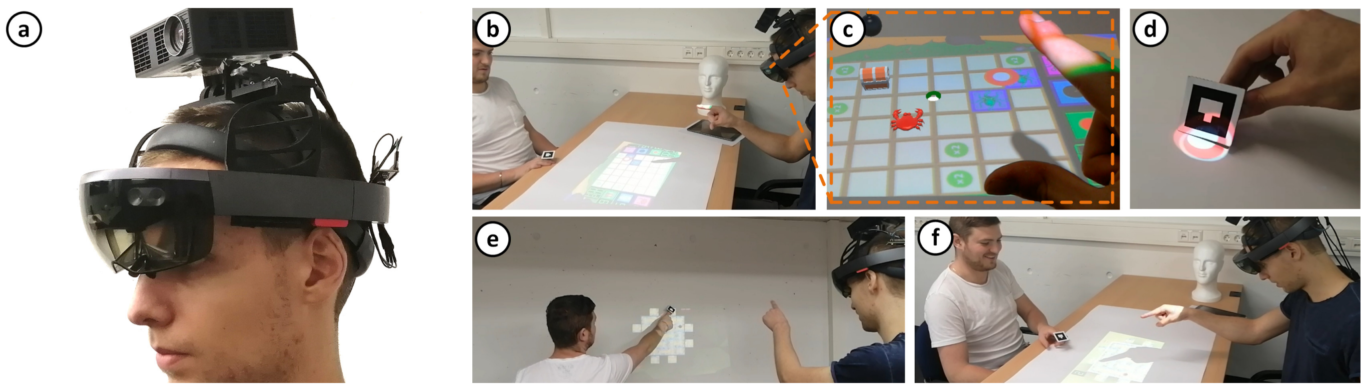

Figure 1. *ShARe* is a modified AR HMD consisting of a projector and a servo motor attached to its top (a). This allows people in the surrounding to perceive the digital content through projection on a table (b, f) or on a wall (e) and interact via finger-based gestures (c) or marker-based touch (d).

ABSTRACT
Head-Mounted Displays (HMDs) are the dominant form of enabling Virtual Reality (VR) and Augmented Reality (AR) for personal use. One of the biggest challenges of HMDs is the exclusion of people in the vicinity, such as friends or family. While recent research on asymmetric interaction for VR HMDs has contributed to solving this problem in the VR domain, AR HMDs come with similar but also different problems, such as conflicting information in visualization through the HMD and projection. In this work, we propose *ShARe*, a modified AR HMD combined with a projector that can display augmented content onto planar surfaces to include the outside users (non-HMD users). To combat the challenge of conflicting visualization between augmented and projected content, *ShARe* visually aligns the content presented through the AR HMD with the projected content using an internal calibration procedure and a servo motor. Using marker tracking, non-HMD users are able to interact with the projected content using touch and gestures. To further explore the arising design space, we implemented three types of applications (collaborative game, competitive game, and external visualization). *ShARe* is a proof-of-concept system that showcases how AR HMDs can facilitate interaction with outside users to combat exclusion and instead foster rich, enjoyable social interactions.

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CCS Concepts
•**Human-centered computing** → **Human computer interaction (HCI);**

INTRODUCTION

Due to recent progress in consumer technology, such as higher display resolution and miniaturization, Virtual Reality (VR) and Augmented Reality (AR) is getting dominantly realized using head-mounted displays (HMDs). While VR is recently seeing a larger consumer adoption (e.g., Oculus Quest), AR HMDs are still more focused towards an industrial application scenario (e.g., Microsoft HoloLens 2). While AR and VR technologies often are treated separately, they share common problems which arise from the underlying usage of a near-eye display such as isolation and exclusion [21, 22].

Isolation occurs when an HMD (e.g., VR HMDs) fully occludes the real world from the user and by that *isolates* them from the environment. Exclusion occurs whenever information is only visible to the user of the HMD (e.g., AR and VR) and every user in the environment without access to the HMD is *excluded* from the experience [20, 21]. While a large set of prior work is already addressing the issue of isolation [20,39,55] and exclusion [20–22] there is currently a lack of work focusing on the factor for *exclusion* for AR HMDs.

In this work, we propose *ShARe*, an instrumented AR HMD (Microsoft HoloLens) with a projector and a servo motor attached through a custom designed 3D-printed mount, enabling to display virtual content of the HMD-user to the environment (*Non-HMD Users*) on any planar surface (e.g., wall, Fig. 1e, or table, Fig. 1f). Leveraging the internal cameras of the HoloLens and the ARToolKit [3], we allow the *Non-HMD User* to interact with the projection via touch input. This enables a new form of asymmetrical interaction, in which the *HMD User* can share similar content (display the same content in *HMD View* and *Non-HMD View*, see Fig. 8b) or combine both technologies to create a new and more inclusive type of display (e.g., share overview in projection and only details in AR, see Fig. 7).

During the development process and internal testing with the co-authors, we discovered a set of unique problems that all such asymmetric AR systems will face (perspective, control of visualization, distribution of information) and propose and discuss possible ways of handling these. The contributions of our work are:

- The concept and implementation of *ShARe*, an asymmetric AR HMD designed to include people in the environment.
- Exploration of the arising design space through three example applications (collaborative game, competitive game and external visualization).
- The presentation and discussion of specific challenges occurring inside such an asymmetric projection setup.

RELATED WORK

ShARe is primarily influenced by and related to works in the areas of asymmetric interaction or collaboration for mixed reality systems and novel concepts in asymmetric co-located gaming. Furthermore, advances in collaborative spatial augmented reality are particularly relevant for *ShARe*. In the following, we will focus on related work that is conceptually close to *ShARe* and put less emphasis on work that had comparable technical setups, but either focused on achieving different goals or relied on different technical means (e.g., increasing field of view through combining projection and HMD [4], employing wearable [24, 56] or portable [9] projection systems, embedding of and interaction with tangible props [10] or leveraging retro reflective materials to increase projection visibility [31]). We consider the aforementioned works to be approaches to potentially achieve comparable interaction variety with different technical means and tradeoffs.

Asymmetric Interaction for Mixed Reality

While there is a large body of research involving largely *symmetric* multi-user interaction (e.g., all parties wearing an HMD [57], residing in the same CAVE [29] or carrying a phone [54]), there has also been a focus on *asymmetric* setups. The concept of asymmetric interaction applies to VR and AR Collaborative Virtual Environments (CVEs) [5, 6, 17] alike and can be considered in terms of devices, user roles or abilities, and (co-)location.

Research revolving around device asymmetries included HMDs+Tabletops [26, 35, 48], HMDs+Portable Displays [21, 58] or other, self-contained devices [8, 22, 36]. It generally yielded insights with respect to the benefits asymmetric interaction may have in different scenarios, such as more efficient collaboration, mutual understanding, enjoyment, social acceptance or social presence. These scenarios included teaching or training interfaces [30, 51], interfaces for design [50] and more entertainment-oriented scenarios [22]. Oda et al. combined AR and VR to allow remote experts to provide situated guidance to users [43]. Duval and Fleury presented an interaction method that bridges the disconnect between users in front of a traditional screen and users in a VE [12]. DollhouseVR by Ibayashi et al. combined a VR HMD with a tabletop to enable interaction and visualization in different scales [26], while Furukawa et al. enabled remote interactions in conjunction with tangible interaction [14]. When used in everyday social settings, challenges in visualization [22,27,36], interruptions [16], and space sharing [59] arise, which can likewise be considered aspects of asymmetric interaction. Interaction between "bystanders" (*Non-HMD Users*) and "primary" (*HMD Users*) users was recently explored by Lee et al. [32], Gugenheimer et al. [21, 22] and Xu et al. [58], enabling content visualization and interaction for previously passive bystanders.

All these works can be categorized as concepts to fight *exclusion* in Virtual Reality (presenting virtual content only to the HMD wearer and exclude *Non-HMD Users*). *ShARe* expands upon the aforementioned works by largely omitting instrumentation of the environment, and in particular of the bystanders interacting with the user. This is particularly relevant in mobile scenarios where untethered HMDs will be employed in the near future (e.g., HoloLens, NREAL Light, Magic Leap). Furthermore, *ShARe* allows the *HMD Users* to see both the visualisation provided by the AR headset and the one being projected for bystanders, enhancing their understanding of the shared physical and virtual space. To the best of our knowledge, *ShARe* is the first proof-of-concept system enabling co-located, asymmetric interaction combined with, situated content visualizations for an interaction scenario we call nomadic augmented reality [18, 19].

Asymmetric Co-Located Gaming

Co-located interaction with situated visualization of content is a concept that occurs in many co-located gaming scenarios such as tabletop board games that see increasing popularity amongst gamers [53]. Similarly, many players enjoy co-located digital gameplay such as split-screen gaming despite the decreasing prevalence in commercial games [44, 45]. From a player experience perspective, co-located play can have positive benefits, e.g., with research suggesting higher positive affect and less tension than play in mediated settings or against a computer [15].

With the increasing prevalence of commercial VR HMDs, there has been more interest in co-located gaming setups for HMD-based systems. There are many positively received commercial games, such as *Keep Talking And Nobody Explodes* [49] and *Batter Up! VR* [46], that use asymmetric interaction concepts and mechanics to solve issues arising due to the fact that only one player can wear an HMD at a time. This popularity can in part be explained by earlier research. Such play settings can benefit from positive effects of asymmetry [23], cooperation and interdependence [11], and physically shared interaction spaces [21, 22]. As such, there is evidence that co-located interaction in entertainment settings can be beneficial to users.

In contrast to these VR examples, challenges are different for enabling co-located interaction in AR settings. AR technology has been applied to a wide variety of leisure and gaming activities [52], e.g., with the widely popular games *Ingress* [41] and *Pokemon Go* [42], for augmenting and game balancing table tennis [1, 2] and foosball gameplay [47], or for enabling digitally augmented tabletop board games [25]. These approaches use AR technologies to provide additional benefits for users, but were not applied to HMD-based systems that use AR technology in general and therefore have unique challenge, such as one-sided visualization of AR content for the *HMD Users* resulting in exclusion of bystanders.

CONCEPT AND IMPLEMENTATION

We designed and implemented *ShARe* with the idea of enabling *Non-HMD Users* to become part of the virtual environment of the *HMD User* and enable them to interact and explore the augmented content together, so that the *HMD User* is less isolated and *Non-HMD Users* are less excluded from the experience.

ShARe is a proof-of-concept prototype comprising of an HMD to enable AR experiences that leverage the physical environment, a projector to visualize virtual content to the surrounding, and a servo motor for automatic alignment of HMD view and projected image. For realizing our goals, we had to develop concepts for (a) visualization and (b) interaction. Similar to the visualization concept of *ShareVR* [21], we used a projection for *Non-HMD Users*. However, *ShARe* further allows *HMD Users* to perceive projected content in addition to the AR overlay. In our concept, the projector is mounted on the HMD device and can be automatically moved with a servo

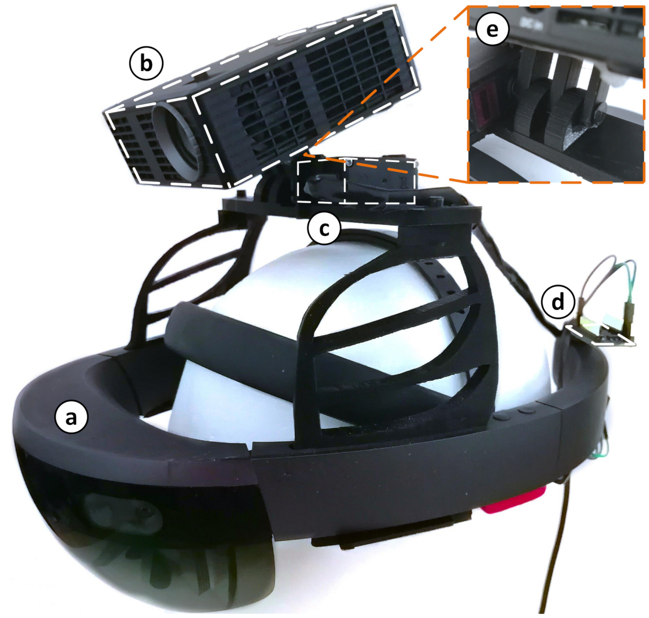

Figure 2. The Hardware setup of *ShARe*, consisting of (a) HoloLens AR HMD, (b) Projector, (c) Servo motor, and (d) Arduino Nano micro controller. (e) Thread connecting projector to servo motor.

motor. Such a single setup allows mobile use and explores the inherent capabilities of a future AR HMD with a built-in projector. We focused on visualization scenarios, in which an *HMD User* can utilize any planar surface in the environment to project shared virtual content. These surfaces can be large (e.g., table, wall, and floor) or small (e.g., a piece of paper in the user's hands). Inspired by the interaction concept of *FaceDisplay* [22], we used touch input on the projection area as interaction for *Non-HMD Users* by tracking the finger position using marker tracking.

Our approach offers different possibilities as well as challenges regarding the design of interaction and applications. Since virtual content inside the HMD is visualized with a higher level of information and detail than for *Non-HMD Users*, the interaction between them must be asymmetric. *ShARe* further enables the development of applications that include *Non-HMD Users* and allow them to join the experience spontaneously. Our approach represents one possible implementation for asymmetric co-located interaction in AR that is by no means the only way. In the discussion, we will discuss potential limitations associated with this particular implementation (e.g., visual conflict of projection and HMD content). With this research, we had the goal to create one of the first asymmetric co-located AR HMD systems and explore potential issues around interaction and implementation arising on the way.

Hardware Implementation

The hardware setup of *ShARe* consists of four main components: an AR HMD, a mount, a servo motor, and a projector (see Fig. 2). The instrumented AR HMD is a first-generation Microsoft HoloLens. The projector used for the visualization is an Optoma ML750e mini projector and is attached to the AR HMD with a custom-designed mount system. We used this projector as it is lightweight (380 grams) and bright enough (700 lumens) to make the projection well visible in a room illuminated by daylight. A TowerPro MG996R servo is used for the automatic rotational movement of the projector and is controlled by an Arduino Nano microcontroller. Because the projector could not be connected directly to the HMD device, we created a Unity multiplayer application to synchronize HMD and projection, that is running on an external laptop. With all devices attached, the overall weight of *ShARe* is approximately 1kg. To compensate for the weight, we used the additional head strap of the HoloLens and added cotton wool as additional padding to the nose piece to avoid unpleasant pressure points on the nose.

Mount: The projector is mounted on the HoloLens using two custom-designed 3D-printed struts, which were designed to interlock and fit with the existing slots of the HoloLens (see Fig. 2). The servo, used to rotate the projector in a vertical direction, is clipped into a mount on top of a plate and is wired to the microcontroller. The plate is connected to the struts via two rounded plugs so that the plate remains static while the HoloLens is flexible and can be adjusted to different head sizes. Early iterations of our mount showed that the prototype tended to tip over when the head is tilted too far in one direction. To combat this and to increase ergonomics while wearing the HMD, we aimed to place the connector plate as close to the head as possible.

Servo: We use a servo motor in our setup to (1) stabilize unwanted head movements (e.g., jittering), (2) dynamically align *HMD View* and *Non-HMD View*, and (3) enable the projector to rotate independently from the HMD (e.g., to enable *HMD Users* to avert gaze and have eye contact with *Non-HMD Users* while projecting on a surface). An ideal solution to provide all three may be the use of a gimbal suspension or a pan-tilt unit that has 3DoF and allows vertical (tilt) and horizontal (pan) movements. However, we used only a single servo motor in our hardware prototype, as tilting movements are already sufficient for our example applications. The servo gear is connected to the projector via a custom-designed thread (Fig. 2e). At home position, the projector is facing straight forward (90 degrees), and the tilt range is 50 degrees (5 degrees up and 45 degrees down, see Fig. 3b). This range is sufficient to cover all usage scenarios. At angles smaller than 45 degrees, the projection is partially covered by the device, while at angles greater than 95 degrees, the projection and the internal view no longer intersect. The servo angle is controlled by the microcontroller, which receives desired rotation angles via serial commands from the laptop.

Projector: The mobile use of *ShARe* requires a projector that supports a wide focal range (e.g., for near setups sitting at a table, or far setups looking at a wall). Besides, the projection has to be relatively bright, as *ShARe* should also be used outside or in bright rooms. An ideal solution may be a laser projector, as such devices support high brightness and offer a wide focal range. However, since there are currently no portable and lightweight laser projectors available at a reasonable low price, we used a DLP projector instead. To horizontally align the projected image with the internal view of the AR HMD, the

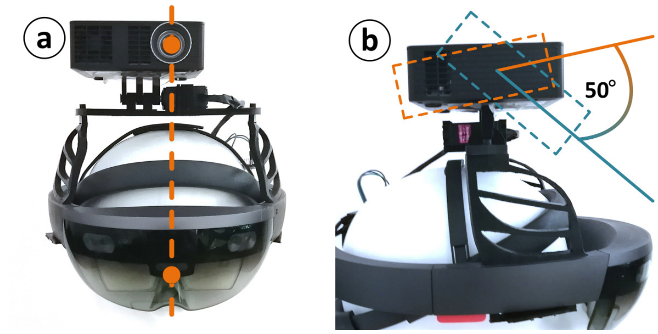

Figure 3. (a) Front view of *ShARe*, showing vertical axis alignment of AR HMD and projector. (b) Side view of projector, indicating available projector tilt range in degrees.

projector lens is positioned directly on the vertical origin axis of the HoloLens (Fig. 3a). Because of the lens not being in the middle of the device front, our projector thread mount had to be placed slightly off the vertical HMD axis. Therefore, we mounted the servo on the other side, so that the weight is as balanced as possible.

Software Implementation

We created a distributed software system consisting of two networked Unity applications that are communicating via a socket connection in a local Wi-Fi network. This implementation was only necessary because the HoloLens does not allow to connect additional peripheral displays. This workaround is not necessary if manufacturers design a future version of the HMD already focusing on the inclusion of *Non-HMD Users*. The application running on the AR HMD is acting as a server (app S), and the other running on the laptop has the role of a client (app C). We created a *virtual rig* in *app C*, consisting of three components: AR HMD, projector, and servo thread mount, that are needed to virtually represent the physical position and rotation of our hardware setup (see Fig. 4a). In order to achieve an accurate alignment of projected content and AR content (e.g., see Fig. 6a), we implemented the following solutions:

Projector Camera Calibration: We used the *ProCamCalib* tool proposed by Moreno and Taubin [40] to calculate intrinsic and extrinsic parameters of the projector and the built-in HoloLens camera. The extrinsic parameters were used in the 3D environment of *app C* for further calculations and to set the position of the virtual projector model in our *virtual rig*.

Projection Distortion Correction: A non-perpendicular projection on a flat surface results in a distorted quadrilateral output image. This effect is called *Keystone Effect* [33] and poses a problem for our visualization concepts, because we want our displayed objects to be the correct form and size to match the internal view of the AR HMD. Therefore, we implemented a distortion correction algorithm running on *app C* based on [34]. To be able to adjust the correction dynamically, we needed to preprocess each frame depending on current environment variables visible in Figure 4b: HMD and projector lens distances to surface (black, and red rays), and projection distortion on the surface (yellow rays). Our distortion correction algorithm consists of four steps: (1) estimate the projected quadrilateral

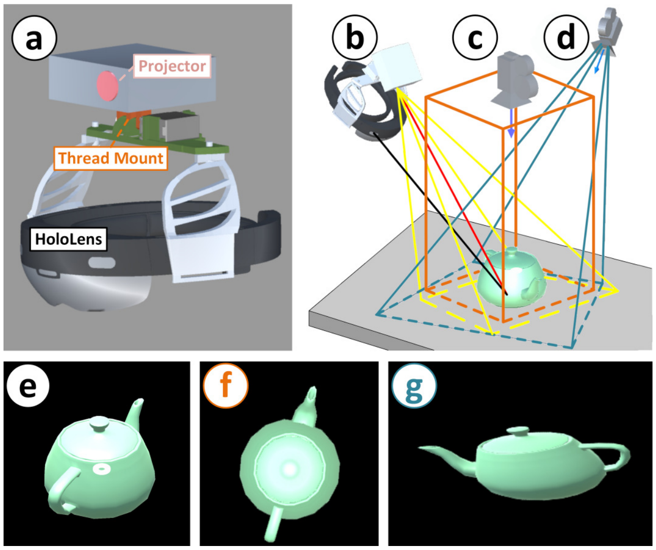

Figure 4. (a) Virtual representation of *ShARe* (*virtual rig*) in Unity, (b) used to estimate the projection distortion (yellow) in real-time. Positioning of (c) an orthographic and (d) a perspective Unity camera in our visualization concepts. (e) AR HMD view, (f) orthographic mode, (g) perspective mode.

on the surface, (2) find the largest inscribed rectangle of the quadrilateral, (3) transform the four rectangle vertices into the local camera coordinate space, and (4) apply the found homography matrix on each pixel. Prerequisite for step one is knowledge about the surface transform in relation to the HMD device. We use a printed *Hiro* marker to retrieve this information. The marker is tracked with the built-in camera of the HoloLens and is placed on the visualization surface to calibrate surface position and rotation. Our algorithm can maintain 150 frames per second in a typical usage scenario running on our hardware setup.

Rendering Mode: We used a Unity camera as a projection rendering source in *app C*. Based on this, we utilized two rendering modes for the projection: orthographic and perspective. In the orthographic mode, an orthogonal image of objects (e.g., a game board or 3D models) placed on the target surface is rendered (see Fig. 4f). To always render the area that is currently visible inside the HMD, the camera is positioned directly above the point where the HMD gaze hits the surface (point H) (see Fig. 4c). The orthographic camera is attached to the *virtual rig*, so that any HMD movement is transferred. In contrast to the orthographic approach, the perspective camera can be positioned at an arbitrary place while being detached from the *virtual rig* and facing *point H* (see Fig. 4d) during *HMD User* movement.

Visualization Concepts

The orthographic and perspective rendering mode allowed us to experiment with different approaches for displaying content for *Non-HMD Users*. Using the orthographic mode enables an accurate depiction of objects regarding their horizontal size and position. The perspective camera, however, allows bystanders to perceive projected content from their perspective and not only see the top view of an object. It further allows

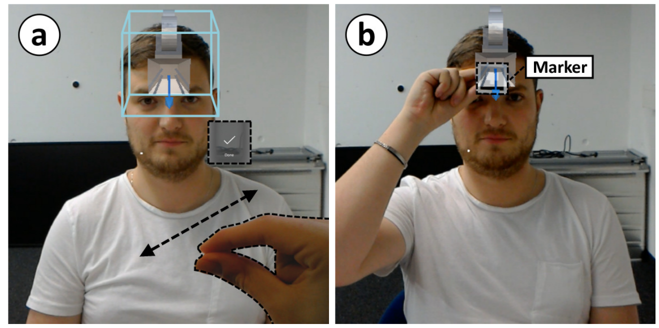

Figure 5. *HMD User* point of view: positioning of a perspective camera to setup the perspective projection for the *Non-HMD User*, (a) manually by dragging the blue bounding box around with the fingers, and (b) automatically by using a marker placed on the forehead.

to convey additional details into the projection (e.g., height and object side view). We added one functionality in which the *HMD User* positions the virtual camera for the *Non-HMD User* either manually (see Fig. 5a) or automatically by using marker tracking (see Fig. 5b).

There are various design implications for applications and games on how to utilize our interaction concept. The most significant is to decide between orthographic and perspective projection mode, as it heavily influences the observing and engaging interaction experience. One can imagine a scenario in which several *Non-HMD Users* observe and interact with the projection from different perspectives. In this case, it may be advantageous to use the orthographic mode to visualize the content regardless of different *Non-HMD User* perspectives. The perspective rendering mode can improve the experience for the *Non-HMD User* in a one on one scenario (e.g., playing a tabletop-like game for two players). However, one has to keep in mind that despite all our efforts to create a perfect alignment of projected and augmented content, the *HMD User* will almost always perceive two different images, and one should not optimize for no visual conflict but a minimal visual conflict (see section Specific Challenges).

Interaction Concepts

When designing interaction concepts for *ShARe*, we had to realize the severity of our setup's asymmetry. Similarly to the *FaceDisplay* concept, we created a highly asymmetric setup, in which a *HMD User* should be able to interact with *Non-HMD Users*. However, the big difference to *FaceDisplay* is that the *HMD User* using a see-through AR HMD can also see the *Non-HMD View*. Besides, content is projected away from the *HMD User*, but the visualization source is physically attached to the HMD. This results in a unique constellation in which the interaction interface itself is not rigid but also moving around and placed on a surface not being part of the HMD. This allows for potential interaction concepts in which the rotation of the projection is used as a game mechanic (e.g., the *HMD User* unveiling objects in the environment for the *Non-HMD User* by using the projection as a flashlight metaphor). We envisioned three different spatial configurations for *ShARe* involving two or more people, inspired by Marquardt et al. [37]: (1) face-to-face (e.g., sitting at a table, see Fig. 6c), (2) side-by-side (e.g., looking at a vertical surface, see Fig. 1e), and (3) corner-to-corner (e.g., a second *Non-HMD User* is observing a face-to-face scenario, see Fig. 6c).

Our goal was to cover a similar interaction gradient, as presented by *FaceDisplay*, ranging from observing to fully engaging. Observing was covered by offering a projection of virtual content to the outside. To be able to initiate a form of interaction from the outside, we implemented marker tracking for *Non-HMD Users* by attaching a small *ArUco* marker to their finger (see Fig. 1d). This was necessary since the built-in gesture recognition of the HoloLens only works for *HMD User* hands, and there is currently no technology that can reliably track and recognize hand/finger at a distance of up to two meters. The marker tracking allowed to use a finger for touch interaction with the projection and further enabled interaction via tracked marker movements like hovering and height alterations. The *HMD User* can interact with AR content and projected content via the HoloLens *airtap* gesture. In addition to physical interactions, *HMD User* and *Non-HMD Users* could talk to each other. This form of oral communication can be encouraged depending on the application, e.g., in collaborative games that require teamwork or in planning software for architectural and technical design.

APPLICATIONS

We implemented three applications that represent the different experiences of *ShARe*. The two asymmetric games *Labyrinth* and *Treasure Hunt* explore the interaction concepts of *ShARe*. The *Showcase Applications* include three smaller experiences (3D model viewer, floor planner, and video player) that demonstrate general capabilities of *ShARe*.

Collaborative: Labyrinth

The collaborative game *Labyrinth* is based on a German board game [38]. Implementations of this game have been used to foster and assess social closeness in collaborative game settings [11, 13]. The focus of the game is on *IndianaPac*, a pacman-like figure, continuously walking through a labyrinth. In contrast to other implementations of the game, *IndianaPac* uses random paths through the labyrinth and cannot be controlled by the players. Instead, they can influence the path of *IndianaPac* by shifting labyrinth elements. The goal of the game is to shift the labyrinth elements in a way that opens possible paths to treasures and blocks possible paths to bombs that fall from the sky and decrease the number of lives. Both users have to work together to be able to master a round (see Fig. 6).

We decided to use an orthographic projection for the labyrinth since this minimized the visual conflict for the *HMD User* and enabled a correct display for different *Non-HMD User* viewpoints. The labyrinth consists of 25 way- and wall-tiles) and eight additional elements that are placed around the labyrinth on specific shift-fields. By touching a shift-field, the *Non-HMD User* can shift all elements in the same row/column by one position, and generate a new random labyrinth element at the selected shift-field. Both users can see *IndianaPac*, but the *HMD User* also has a perspective view of *IndianaPac* as AR overlay. Further, the *HMD User* can exclusively see treasures, bombs, as well as hearts that give an extra life. The *HMD User* can place these hearts on the labyrinth by performing a *airtap* gesture.

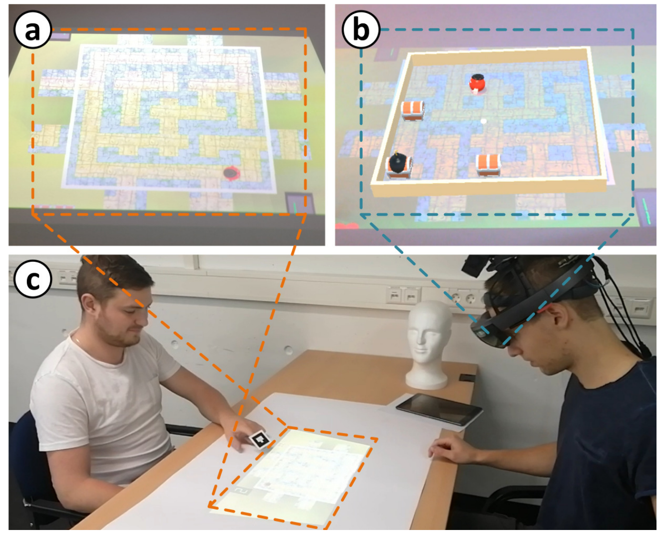

Figure 6. (c) *HMD User* and *Non-HMD User* playing the collaborative application *Labyrinth*. (a) *Non-HMD User* view, (red circle) player character: *IndianaPac*. (b) *HMD User* view, (red sphere) player character, (black sphere) bomb, (brown/grey cuboids) chests.

Labyrinth was designed to induce the users to solve each round collaboratively through the shared goal of reaching the treasures without getting hit by a bomb with interdependent gameplay through complementary roles [11]. The *HMD User* takes on the role of an omniscient observer who has knowledge about significant game elements but cannot actively intervene in the game process. The *Non-HMD User* can influence the walking path of *IndianaPac* by activating the labyrinth element shift but does not know the hidden game elements. Therefore, both users are encouraged to communicate with each other. The *HMD User* needs to regularly inform the *Non-HMD User* about the positions of treasures and bombs. Then both users can discuss a solution to solve the current round. Sometimes the entire labyrinth field cannot be seen on the projection surface, and the *Non-HMD User* must tell where the *HMD User* has to look in order to activate the correct labyrinth element shift. With this cooperative design, the game fosters social interaction between both users.

Competitive: Treasure Hunt

Treasure Hunt is a turn-based competitive board game in a pirate setting (see Fig. 7). The *HMD User* takes on the role of a pirate who buries treasures on an island, while the *Non-HMD User* has to find the buried treasures. Not all treasures on the game board are equally valuable. The *HMD User* can either bury gold chests or worthless skulls. In return, the *Non-HMD User* can either mark a field with a flag, to dig for a treasure at this position, or place a bomb, to destroy this field together with all possible treasures. The *Non-HMD User*'s goal is to mark as many fields that contain gold chests as possible and to destroy the fields that contain skulls.

The pirate island is projected in orthographic mode visible for both users and contains 36 treasure fields. Next to the fields,

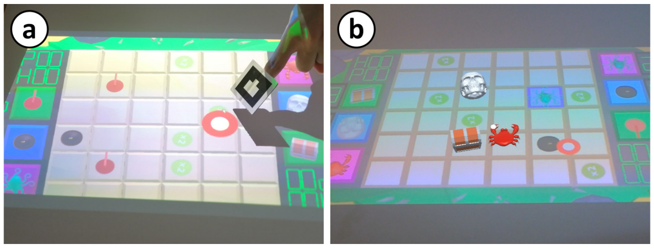

Figure 7. Two views of the competitive board game application *Treasure Hunt*. (a) *Non-HMD User* view, (red/white circle) finger position indicator, (black circle) bomb, (red circle) flag, (cyan contour) squid. (b) *HMD User* view, (white sphere) skull, (brown/gray cuboid) chest, (red object) crab.

there are two item stores, one for the *HMD User* (containing treasures, skulls, and crabs) and one for the *Non-HMD User* (containing flags, bombs, and squids), as well as the current score. All items are available in limited numbers.The *HMD User* can select a store item and "bury" it in an empty field via *airtap* gesture. The items that were "buried" by the *HMD User* are only visible in the *HMD View*. The *Non-HMD User* can select a store item by touching it and place it on a field. If a treasure is "buried" in this field, it gets revealed to the *Non-HMD User*, otherwise, the item remains there. Marked gold chests and destroyed skulls increase the score of the *Non-HMD User*, marked skulls and destroyed gold chests increase the score of the *HMD User*. Special items (crab and squid) and double score fields provide additional variety to the game. The user who has more points after all items are played wins the game.

Treasure Hunt was designed to explore the competitive possibilities which arise from the co-located asymmetry enabled through *ShARe*. Gameplay is interdependent as both players' performance depends on their opponents' behavior.While the *HMD User* is omniscient and can see all played items, the *Non-HMD User* remains unclear about the played items of the *HMD User*. The *Non-HMD User* can see what store element got selected by the *HMD User*, but does not know its board placement. This can lead to interesting interactions between both users. The *Non-HMD User* can guess the place by trying to determine where the *HMD User* is looking or tapping at. The *HMD User* can take advantage of this and try to confuse the *Non-HMD User*. This gameplay can facilitate social interaction because both users can talk with each other while doing their turns. The *HMD User* can give hints, but the *Non-HMD User* has no idea if the *HMD User* is telling the truth.Such a social interaction between the players can affect the interpersonal trust between the users [11].

Exploratory: Showcase Applications

In addition to our game applications, we implemented smaller experiences that further demonstrate and explore novel aspects of *ShARe*.

3D Model viewer: The model viewer application explores our perspective visualization concept. *HMD User* and *Non-HMD Users* can observe 3D models (e.g., rabbit, teacup, or 3D text) each with a height of 15cm (see Fig. 8b). The *HMD User* can change the model by clicking *next* and *previous* buttons only visible in the *HMD View*. Besides, there is no other interaction for either user. *Model Viewer* consists of two variants. In the first variant, the virtual perspective camera is moving in a semicircle at a fixed height around the 3D model. With this, we wanted to explore how well the perspective rendering is working for multiple bystanders without accurate camera positioning. In the second variant, the *Non-HMD User* can govern the perspective camera's position by holding an *ArUco* marker in front of their forehead. This allows the *Non-HMD User* to perceive the 3D model from their current perspective but has to be redone whenever a new camera position is needed, because the HoloLens cannot track the marker position while the *HMD User* is looking down on the surface.

Floor planner: With the floor planner application, we wanted to explore how *HMD Users* interact with *Non-HMD Users* while using software for architectural design instead of playing a game. We used a 3D model of a generic floor plan, which is projected in orthographic mode (see Fig. 8c). The *HMD User* has the role of a seller, and the *Non-HMD User* is the customer. Both users can interact with the floor plan using finger touch, shadow, or gestures. They can also discuss specific floors, rooms, or objects, and modify general aspects of the floor plan (e.g., add/remove models or color areas). The interaction is enabled by finger marker tracking for *Non-HMD Users* and *airtap* gesture for the *HMD User*. Large objects like walls, doors, windows, and stairs are displayed only in the *HMD View*. The idea behind this distribution was to show smaller frequently changed objects (e.g., tables) to both users to avoid misunderstandings when discussing such content due to different visualizations and avoid the visual conflict for the *HMD User* (seeing the objects twice).

Video player: We implemented a video player application to show how information can be distributed between *HMD View* and *Non-HMD View*. The application consists of several menu tiles representing possible future apps for *ShARe* (e.g., photo app, messenger, video player app, see Fig. 8d). All menu tiles except the video player are dummies and not clickable. The *HMD User* can *airtap* the video player tile to open a larger tile on which a short sample video is played. The *HMD User* gaze is made visible in the *Non-HMD View* through a yellow circle at the gaze position to give *Non-HMD Users* more information on what tile the *HMD User* is looking at. The video texture, is only visible in the *Non-HMD View*, to prevent the *HMD User* seeing the video twice. The menu tiles are visible in both views, as there is no need to distribute this information. However, it would be possible to show the video menu tile only in the *Non-HMD View* to indicate that this app will be visible in the same way.

DISCUSSION

Our goal was to develop a proof-of-concept system that combats the exclusion of *Non-HMD Users* with AR HMDs and instead fosters rich, enjoyable social interactions. To gain a deeper understanding of the arising design space and to find observations and insights, we tested our three developed application concepts in a preliminary use exposure. Based on these observations, we discovered various AR HMD + projection specific challenges and discussed their future implications.

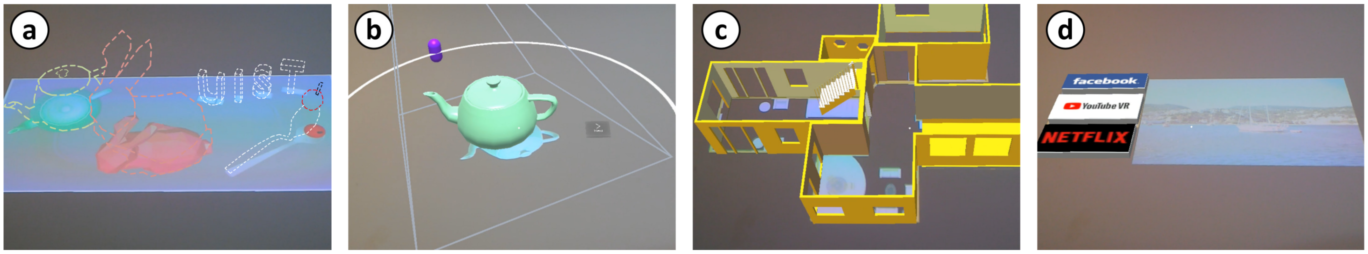

Figure 8. An overview of the exploratory applications: (a) Orthographic projection of various 3D models. Dotted lines indicate model orientation in 3D space. (b) Perspective projection underneath a 3D model in the model viewer application, creating a shadow-like effect. (c) Orthographic projection of a floor plan being virtually overlaid by its 3D model in the floor planner application. (d) Projection of a video next to a menu overlay in the video player application.

Observations and Insights

We conducted a preliminary use exposure of our collaborative, competitive, and exploratory applications amongst the authors. Each application was tested by two authors acting as users (*HMD User* and *Non-HMD User*) and two authors as passive observers in two rounds, with different visualization surfaces (sitting at a table and standing in front of a wall), and swapped roles. We report our observations of the use of *ShARe* regarding its performance, robustness, visualization quality, system interaction, and social interaction.

System performance and robustness: In the game applications, the projection area was sometimes too small to see the entire game board. Therefore, the *HMD User* has to maintain a suitable distance to the surface (at least one meter) to enable a display size (30 centimeters width) that fits the content sufficiently. In the future, a short-throw projector can be used for a large display at small distances. As the used DLP projector has a focal range of 0.5 to 3.2 meters and does not support auto-focus, we set the focus to a fixed distance of one meter in the table scenario and two meters in the wall scenario. Besides, there was a noticeable offset of approximately two centimeters between the marker position and the actual touch position on the surface.

Visualization quality: HMD User head movements seemed to lead to shaking of projected content, which was unexpected for the *Non-HMD Users*, but not apparent to themselves, as they had control over the visualization. This implies that the *HMD User* cannot look away if shared content should also be visible for *Non-HMD Users*. Alternatively, future work could benefit from an implementation consisting of multiple projectors facing in different directions (for the same reason, multiple displays were used in *FaceDisplay* [22]). The orthographic mode depicted both game applications quite accurately, resulting in a real understanding of the form and size of the virtual objects. The perspective mode was challenging to interpret for the *Non-HMD User*, although the user was nearly in the same position and orientation as the virtual camera. We assume that this is caused by the lack of shadows and the uniform object color (see Fig. 8b), but this needs further investigation.

System interaction: As the *HMD User*, it can be difficult to ensure tracking of the *Non-HMD User*'s finger marker because it was hard to determine where the camera field of view (FoV) ends and when the HMD device had to be moved to follow the finger. To provide such information, we could imagine a concept to indicate the current FoV of the marker tracking camera and to visually highlight a direction in which the HMD needs to be moved to keep the marker in view (e.g., directional arrows, and glowing FoV borders). From the *Non-HMD User* point of view, the marker tracking was useful to interact with the projection.

Social interaction: In addition to physical interaction (e.g., touch, or *airtap*), *ShARe* seemed to facilitate social interactions. Due to the *HMD User* having full control over the visualization, they can intentionally look away to annoy or disrupt *Non-HMD Users* in their experience. This could be a valid strategy in a competitive application. Encouraged by our collaborative application, the active users mainly used voice commands to communicate with each other (e.g., "Touch the left-most field," or "Move your head here"). In our collaborative application, this worked well since both users can agree on a specific way to describe the intended interaction. However, it needs further investigation on how precise this voice communication is, especially concerning other application types (e.g., *Floor Planner*).

AR HMD + Projection Specific Challenges

While developing and testing *ShARe*, we discovered various challenges specific to the combination of AR HMD and projector. We summarized these challenges into three different categories: perspective, control of visualization, and distribution of information.

Perspective

Due to the asymmetry of *ShARe*, there are generally more options to visualize object details for *HMD Users* than for *Non-HMD Users*. For example, a 3D model projected in orthographic mode does not contain any three-dimensional information, such as height and vertical details (see Fig. 8a). We addressed this by using the perspective mode for the *Non-HMD View*. This allowed us to convey more information about height and vertical details (see Fig. 8b) than using the orthographic mode. Another problem is to match the Unity camera's perspective with the *Non-HMD User* perspective that changes with movement, so that objects are rendered, enabling the correct perspective impression. For this, the *Non-HMD User* can set the perspective camera position by using the aforementioned forehead marker. A future solution could be a system that recognizes the *Non-HMD User* viewing position and adjusts the perspective projection accordingly. Besides, there are related projections that are worth exploring.

For example, a military perspective or a shear transformation applied to an orthogonal projection. Those would not cause problems for more than one *Non-HMD User*, i.e. having more than one viewpoint.

Control of Visualization

As AR content leverages the environment around the HMD, the *HMD User* may not always look at the same projection spot and could avert their gaze. In such cases, the projection is no longer visible to *Non-HMD Users*, and the *HMD User* has full control over the visualization. Our servo rig can only move the projector in a vertical direction, which means that the *HMD User* is still able to look away in a horizontal direction. Using a fully controllable gimbal mount system in future iterations would enable to project content only visible to *Non-HMD Users* independent of the *HMD User*'s viewing direction and enable a new form of asymmetry in which both users (*HMD User* and *Non-HMD User*) see different content displayed by one device. Due to intentional or unintentional head movements of the *HMD User*, the projected image is jittering. We acknowledge that such limitations can be overcome with existing technologies. Our solution for stabilization is to use a servo-controlled hardware alignment, which counteracts head movements within the available servo tilt range (see Fig. 3b). Besides, we used the *1Euro Filter* [7] to filter any movement of our virtual rig. In the future, a gimbal setup could be used for automatic 3DoF projector stabilization and to support the motion filtering currently only existing on the software side.

Distribution of Information

The HoloLens cannot render the virtual augmentation completely opaque. As such, the *HMD User* may perceive a mixture of *HMD View* and *Non-HMD View*. This mix of information can be distracting for the *HMD User* and disruptive for the experience. Therefore, developers have to determine which virtual content to show to individual users and when to display an object in *HMD View*, *Non-HMD View*, or in both views. The distribution of information has a major impact on the perception of the application by *Non-HMD Users* because having enough information is critical to understand the current state of an application. A straight forward solution is to use one of the views (e.g., only projection). Because this solution does not use the full potential of *ShARe* (using both views) and users might miss information, we combined the perspective rendering of the AR HMD with an orthographic projection of all currently visible objects. Regardless of the visualization mode, our goal in designing the applications was to show specific objects that are relevant for the user in each visualization (e.g., showing furniture only via projection in *Floor Planner*). In the future, any application running on a system combining AR HMD and projector will have to take the distribution of information into account when designing the experience. A future solution to overcome this challenge could be the usage of polarization filtering see-through displays in AR HMDs [28]. The projection could have a particular polarization, which is filtered out by the glasses and is therefore not visible to the *HMD User*.

Limitations and Future Work

The applications used marker-based tracking for *Non-HMD Users* to create an overall enjoyable experience. Due to the limited interaction capabilities of our prototype (unstable marker tracking, needing a marker, gestures only working for the *HMD User*), it is difficult to explore the impact of the interaction concept on the experience. Our findings are currently based solely on observations of the preliminary use exposure. More research in the form of a study has to be conducted to assess if our observations translatable to generalized findings and to understand the social dynamics happening in this asymmetric setup entirely.

In the future, we are planning to extend *ShARe* with a system for reliable *Non-HMD User* hand tracking, which should improve our current interaction concept and make the use of markers obsolete. We also plan to reduce the overall weight of our hardware setup by using a smaller projector. We further want to improve the head movement compensation by using a pan-tilt unit or a gimbal mount. Finally, we plan a consecutive user study to investigate the novel design space of co-located asymmetric AR experiences and their impact on social dynamics.

CONCLUSION

In this work, we presented *ShARe*, a proof-of-concept prototype using an AR HMD with a servo-controlled projector to visualize the virtual world for *Non-HMD Users* and enable them to interact with the *HMD User* and become part of the AR experience. We presented three applications (*Labyrinth*, *Treasure Hunt*, and *Floor Planner*), each focusing on one specific aspect of the asymmetric co-located interaction and leveraging our visualization concepts (*orthographic* and *perspective*). We further conducted a preliminary use exposure amongst the authors that helped us discover several challenges specific to the combination of AR HMD and projector. In a final step, we used these insights to formulate future design solutions addressing those challenges for co-located asymmetric AR experiences. We argue that AR HMDs are currently designed to have only the *HMD User* in mind but should also include the people in the environment to reduce the isolation of *HMD Users* when using AR HMDs.

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