# SurfShare: Lightweight Spatially Consistent Physical Surface and Virtual Replica Sharing with Head-mounted Mixed-Reality

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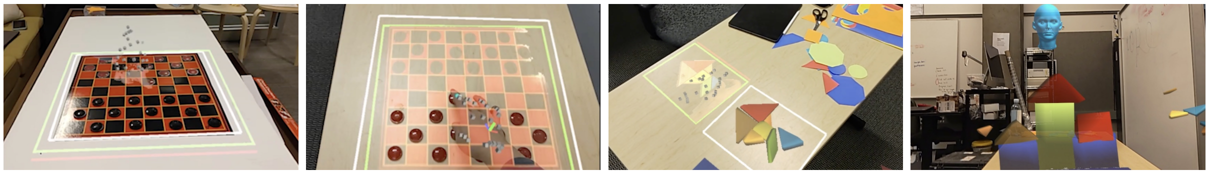

(a) (b) (c) (d)

Fig. 1. *SurfShare* enables remote mixed-reality shared communication by establishing spatial consistency and object sharing between two physical spaces. In (a) and (b), two geographically distributed users set up a merged view of their respective surfaces by overlapping the virtual portals (white and green frames). Such a setup can allow two remote users to participate in board games as if they are in person, as demonstrated in (a) and (b). *SurfShare* also enables the creation of shared virtual replicas of physical objects. In (c), an instructor shows a remote learner how to use tangram puzzles to construct a fish. Only the learner has the physical pieces of the tangram puzzles. Thus, the learner creates virtual replicas for the instructor to demonstrate. Using the same technique, two remote users can collaboratively author virtual AR content. In (d), two geographically distinct users collaboratively construct a virtual brick castle using virtual extrusions of physical shapes.

Shared Mixed Reality experiences allow two co-located users to collaborate on both physical and digital tasks with familiar social protocols. However, extending the same to remote collaboration is limited by cumbersome setups for aligning distinct physical environments and the lack of access to remote physical artifacts. We present *SurfShare*, a general-purpose symmetric remote collaboration system with mixed-reality head-mounted displays (HMDs). Our system shares a spatially consistent physical-virtual workspace between two remote users, anchored on a physical plane in each environment (e.g., a desk or wall). The video feed of each user's physical surface is overlaid virtually on the other side, creating a shared view of the physical space. We integrate the physical and virtual workspace through virtual replication. Users can transmute physical objects to the virtual space as virtual replicas. Our system is lightweight, implemented using only the capabilities of the headset, without requiring any modifications to the environment (e.g. cameras or motion tracking hardware). We discuss the design, implementation, and interaction capabilities of our prototype, and demonstrate the utility of *SurfShare* through four example applications. In a user experiment with a comprehensive prototyping task, we found that *SurfShare* provides a physical-virtual workspace that supports low-fi prototyping with flexible proxemics and fluid collaboration dynamics.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**.

Additional Key Words and Phrases: Mixed Reality, Remote Collaboration, Physical Surface Sharing, Virtual Replica, Proxemics

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## 1 INTRODUCTION

Mixed reality augments the physical environment with a layer of virtual space. As such, co-located, shared experiences [33, 45, 46, 52, 73] create a workspace where multiple users can communicate via both physical and virtual content. As co-located users retain access to the physical space, they can collaborate with familiar physical and social skills such as direct object manipulation and body language [2, 50]. Achieving the same in a remote setting enables remote users to collaborate on physical and virtual tasks more naturally and efficiently.

However, aligning heterogeneous remote spaces is challenging and often requires complex setup procedures and hardware. For example, projection-based systems [32, 35, 47] share a slice of the environment and are thus less dependent on environment homogeneity. However, they require cumbersome hardware and rigid configurations and lack the flexibility to transition between tasks and collaborative dynamics [21, 41]. Asymmetric remote collaborative systems [11, 30, 34, 65, 72] virtually bring all users to a single physical location, but incur differences in context and environment fidelity for users and are usually applied to more specialized application areas such as remote guidance [20, 25, 65, 72] and sightseeing [11, 12]. While symmetric remote collaborative systems are more general-purpose, contemporary systems align physical environments by merging their reconstructions [1, 39, 42], which requires detailed scans of the environment and substantially similar physical spaces.

Users in remote collaboration also lack access to physical objects from remote environments, thus hindering a seamless integration of the physical and virtual spaces. Systems that create virtual replicas from physical objects [15, 56] better connect the physical and virtual spaces, while requiring virtual replicas to be modeled with CAD tools. It is possible to rapidly create virtual content through hand sketching and paper prototyping [4, 7, 8], but the application of such capabilities in remote mixed-reality collaboration is not well-explored.

We present *SurfShare*, a general-purpose symmetric remote collaborative system with mixed reality HMDs. Our system is lightweight and requires only a pair of unmodified, commercial Microsoft HoloLens 2 devices and access to a wireless network. Our system creates a physical-virtual workspace between two remote users anchored on a physical plane in each environment while assuming minimal similarity between the users' respective physical environments. *SurfShare* establishes a spatially consistent shared space by allowing each user to create a portal (a rectangular content frame) on a physical surface (e.g., floors, desks, walls, whiteboards) of their environment, which defines both an anchoring point in the environment as well as a region of the surface that will be shared with the other user. To support physical collaborative tasks, our system captures and streams video of objects and annotations (e.g. pen marks) appearing on each surface using the HMD camera, creating a merged view of the physical surface. To better integrate the physical and virtual spaces and extend users' access to remote physical objects, our system allows users to create and extrude virtual replicas of planar physical objects in the portals. Users can directly manipulate the virtual replicas to demonstrate a physical task or edit the virtual replicas with free hand gestures for low-fidelity virtual content creation.

We demonstrate the utility of *SurfShare* with 4 example application scenarios in remote collaboration: surface sharing and annotation, collaborative puzzle building, physical gaming with user-defined virtual objects, and collaborative prototyping. To evaluate our system, we first conducted a 10-participant usability test with the four application scenarios. We then explored the implications of a lightweight configuration and ad-hoc virtual replicas in remote collaboration with a 12-participant dyadic user experiment.

*SurfShare* contributes a bi-directional symmetric remote collaborative system in Mixed Reality that 1) shares physical surfaces in a lightweight manner, and 2) extends physical surfaces with a virtual workspace that enables ad-hoc creation of virtual replicas. We also proposed the potential applications of the system and qualitatively evaluated it with a comprehensive user experiment.

## 2 BACKGROUND AND RELATED WORK

We situate our work in the domain of synchronized multi-user shared experiences with mixed reality. Here, we first lay the background by reviewing theoretical CSCW frameworks in workspace awareness and collaborative proxemics. Then, we overview existing remote mixed-reality collaborative systems. Finally, we discuss the integration of physical and virtual spaces with virtual replicas.

### 2.1 CSCW Workspace Awareness and Proxemics

Prior theoretical frameworks in remote CSCW have established the importance of workspace awareness. Gutwin and Greenberg [26] defined "WorkSpace Awareness" as the real-time understanding among collaborators regarding each other's 1) Who (e.g. n, user presence and identity), 2) What (e.g., actions, artifacts), and 3) Where (e.g., user location). Similarly, Buxton [10] proposed "person space", "task space", and "reference space" as the main communication channels in remote collaboration. In particular, "reference space" is the integration of users' presence and the tasks they perform. For contemporary remote collaborative systems, it has been common practice to combine Buxton's communication channels [10] in various ways. For example, prior research has integrated users' presence [31, 74], eye-gaze [3, 40] and gestures [19, 35, 64, 66] into the task space.

A related concept to workspace awareness is *proxemics* [41], which posits that the interaction between people is affected by the spatial distance between them and their physical surroundings. The spatial relationship between collaborators is related to what the environment provides (e.g., desks, walls, whiteboards, digital screens). Researchers have also proposed the idea of proxemic transitions [21], pointing out the fact that such spatial relationships are dynamic. During collaborative tasks, people are likely to change spatial formations (e.g., face-to-face, next to each other, or walking up to a whiteboard) to articulate their ideas and utilize resources in their environment [38, 44]. However, most prior work has only considered *proxemics* for co-located collaboration. Researchers have developed interactive mediums to support co-located proxemic transitions such as shape-changing furniture [22] and displays [63]. More recently, Grønbæk et. al [23] proposed Partially Blended Realities (PBR), which supports proxemic transition in remote collaboration. However, while PBR anchors each user's workspace on physical surfaces, it only supports virtual tasks.

### 2.2 Remote Mixed Reality Collaboration

Researchers have explored remote Mixed Reality collaboration systems with various symmetry, modalities, and placements on the reality-virtuality continuum [48, 49]. For example, asymmetric remote collaboration virtually brings remote guests into the same physical space. The remote guests can annotate the streamed environment [20, 25, 65, 72] and perform a real-time demonstration with an embodied avatar [62, 65]. Asymmetric remote collaboration has found rich applications in remote guidance in manufacturing [27], clinical operation [29], and sightseeing [12]. As asymmetric remote collaboration focuses on the local user's physical environment, it is more suitable for specialized applications in the domains of remote instruction [62, 65] or tourism [11, 12, 37].

Symmetric remote collaboration supports richer bi-directional interactions and generality. As such systems simultaneously consider more than one workspace, they face more challenges in establishing a common reference space. Prior research has explored projection-based surface sharing, which merges two remote desk areas together by overlapping real-time videos of them and enabling a shared physical workspace [35]. Further works have explored projection-based tabletop sharing without identical tabletop layouts [32, 47] and enabled projecting digital contents that align coherently with physical objects [68]. However, projection-based surface sharing has a heavy setup, making it hard to reconfigure as the task context changes. The rigid setup also assumes a static spatial relationship between the collaborators (e.g., sitting face-to-face with each other), thus lacking the flexibility for dynamic proxemic transitions [21] in user collaboration.

Researchers have also investigated symmetric remote collaboration in 3-dimensional space with spatial capture and reconstruction [28, 58, 71]. In the "person-space" [10] of remote communication, prior works have enabled users to place a life-scale projection or 3D reconstruction of a remote user into their physical [34, 58, 61] or virtual environments [17, 67], mimicking face-to-face communication. In the task-space [10], prior research has also studied creating a room-scale shared space by projecting and merging physical environments of remote users [1, 39, 42]. However, fully merging two remote 3D spaces with spatial consistency assumes substantial similarity between remote spaces, and often requires a cumbersome 3D reconstruction pipeline with external sensors. Utilizing similar physical elements in the environments, recent research has enabled spatial alignment [18, 69, 70] and proxemic transition [23] for remote users' virtual embodiment. Nevertheless, while such systems were anchored on physical space, they only focused on virtual tasks.

### 2.3 Integrating Physical and Virtual Space with Virtual Replicas

Gutwin and Greenberg [26] identified artifacts as important sources of awareness information. However, while users can access all the shared virtual content, a user cannot directly access physical artifacts in a remote environment. This disparity between the level of physical and virtual access makes it hard to integrate the physical and virtual spaces. As a result, contemporary remote mixed-reality collaborative systems focus on either physical or virtual tasks, thus limiting their generalizability. For example, most asymmetric remote instruction systems [20, 62, 65, 72] focus on physical tasks while only using virtual contents as annotations. On the other hand, systems such as virtual content authoring [53, 55, 67] often detach the physical space entirely.

To fully harness the potential of both physical and virtual space requires them to be better integrated. Jansen et al. [33] demonstrated a co-located physical-virtual board game with virtual proxies. Prior research [15, 56, 59] has also explored and demonstrated the effectiveness of virtual replicas in remote instruction, but they require the virtual replicas to be created in advance with CAD tools. Virtual objects can also be created dynamically via e.g. hand sketching and paper prototyping [4, 7, 8]. However, while such techniques can reduce the technical barrier for rapid prototyping mixed-reality applications [43, 53, 54], the potential of ad-hoc creation of virtual props in remote mixed-reality collaborations has not been well explored.

## 3 DESIGN GOALS AND CONCEPTUAL MODEL

Distilling the common considerations and gaps covered by the related works above, we identify 3 design goals and propose our conceptual model.

### 3.1 Design Goals

- **D1: Lightweight and Flexible System Configuration**: Our work is inspired by prior projection-based physical surface-sharing systems as described in Section 2.2. However, such systems are heavyweight and hard to reconfigure, and thus only support a static collaborative setting (e.g., face-to-face). Modern mixed-reality devices can perform inside-out environment sensing without static instrumentation. Therefore, our work sets out to contribute a lightweight mixed reality surface-sharing system that provides better flexibility and reconfigurability, enabling more fluid user dynamics in remote collaboration. The system should only rely on the sensing capability offered by off-the-shelf mixed-reality headsets, while stably tracking and streaming the surface area selected by the user despite the moving camera.
- **D2: Integrate Physical Surface and a Virtual Workspace**: Mixed reality seamlessly overlays a virtual space onto physical environments. Therefore, it is natural to extend the capabilities of shared physical surfaces to the virtual space. However, projection-based physical surface sharing systems [35, 47] are

limited to the physical space. Virtual replicas bridge the physical world with the virtual space while existing work [15, 33, 56, 59] require them to be pre-modeled in CAD software. Therefore, we explore 2D virtual replica creation from physical 2D objects (e.g., hand-drawn sketches and shapes cut from paper) shared on physical surfaces. The creation of such virtual replicas should be instantaneous. We hope such a system capability can support more direct remote instruction and collaborative low-fi prototyping.

- **D3: Spatially Consistent Object Sharing and Workspace Awareness**: All the content shared by our system, whether physical or virtual, should be anchored to a common reference space, such that the system maintains workspace awareness among users. While spatial awareness and workspace awareness are well-established in the CSCW literature, the approach to achieving them is system-specific. In particular, for our system, it is important to have simplicity in mind such that the effort for spatial awareness configuration is consistent with our system's lightweight nature (**D1**). Therefore, we include this design goal as it is the technical premise for our system to be usable.

## 3.2 Conceptual Model

We design our conceptual model revolving around the concept of "virtual portals". They are virtual rectangular frames snapped onto physical surfaces, sharing a sliced view of them. They are also spatial anchors that establish

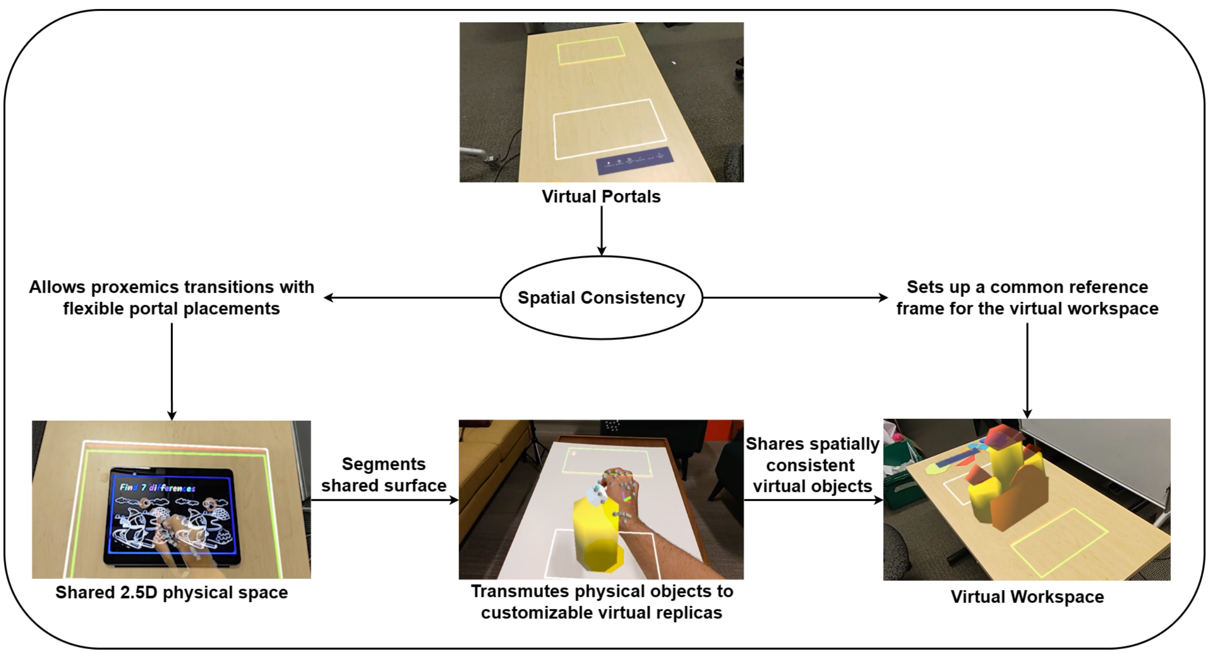


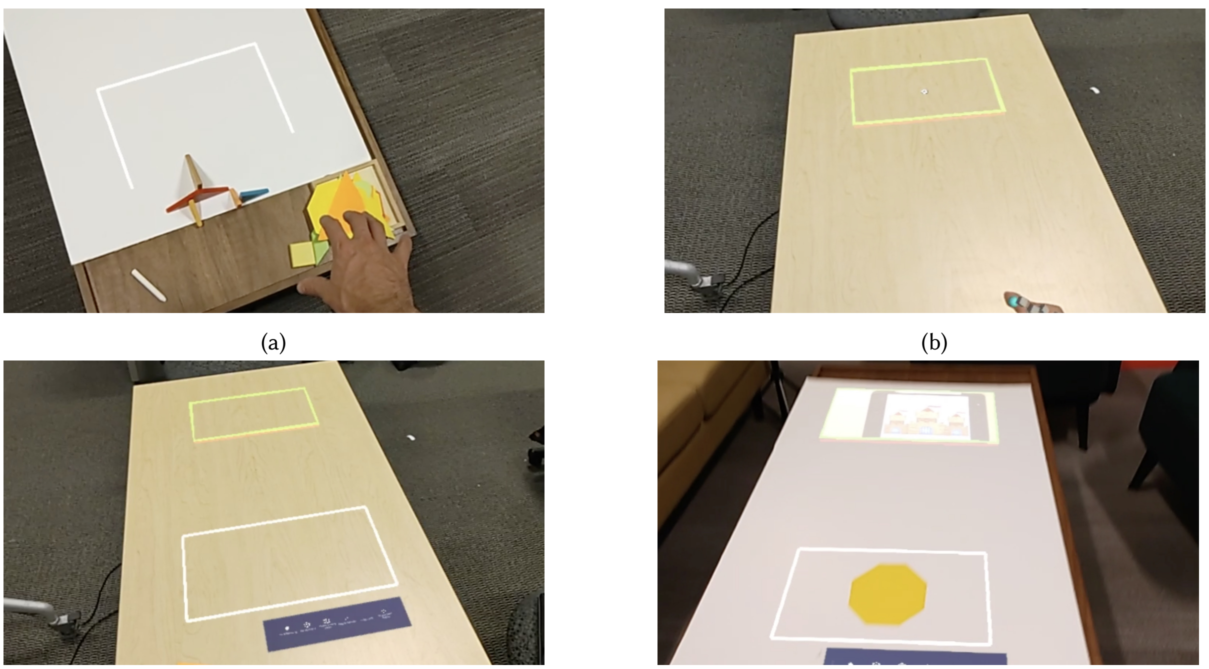

Fig. 2. The conceptual model of *SurfShare*. A key concept in our system is the *virtual portal*. Top: Each user sees a local portal (white) and a remote portal (green). These portals serve as spatial anchors that set up a common reference frame for remote users, as well as virtual displays that share a slice of their physical environments. Users can flexibly configure the positioning of the portals, allowing proxemic transitions. For example, they could overlap the virtual portals to create a merged view of their physical surfaces (left) or arrange the portals next to each other separately to have individual physical workspaces (top, bottom-center, bottom-right). Users can also use virtual portals to transmute physical objects to the virtual space (bottom center). All the shared virtual replicas are customizable and spatially synchronized between users (right).

spatial consistency and align the users' workspace awareness (**D3**). The virtual portals are easy to set up with common mixed-reality ray pointing gestures, and allow repositioning anytime during the remote collaboration (**D1**). In addition to sharing physical surfaces, the virtual portal segments 2D physical objects on the surface and allows users to virtually replicate them. Thus, our system extends the shared surfaces to a virtual space anchored to virtual portals and transmutes physical objects into their virtual twins (**D2**). We illustrate our conceptual model in Fig. 2 and detail how our system implements it in the following sections.

## 4 SURFSHARE SYSTEM DESIGN OVERVIEW

### 4.1 Virtual Portals and Spatial Consistency Initialization

To initialize the system, users start by defining the virtual portals. The first user uses a pointing gesture to select the corners of their local portal. This portal then becomes visible as a movable rectangle in the second user's view. The second user uses a pointing gesture to place the first user's portal in their environment, then uses pointing gestures to define their own portal. Placing this second portal defines the initial relative transform between the local and remote portals. To satisfy **D3**, this relative transform is then automatically applied to the first user's environment, thus initializing their remote portal. Our system attaches a 1x6 menu under the local portal, providing several functions: initiating physical surface sharing, creating virtual objects, toggling user avatars, enabling background subtraction, and repositioning portals. Finally, once both portals are established,

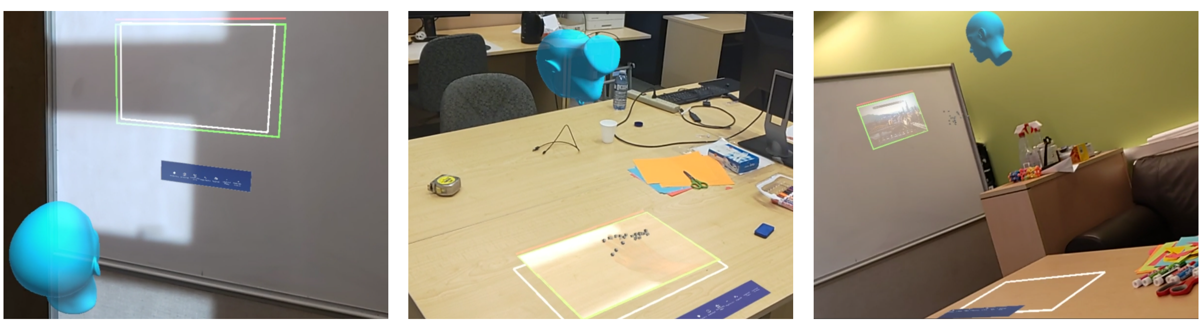


(a) (b) (c) (d)

Fig. 3. Users of *SurfShare* initialize their communication by setting up virtual portals. In (a), the first user uses pointing gestures to define the corners of their local portal. In (b), the second user places the first user's portal in their environment, then in (c) they use pointing gestures to define their own portal. In (d), the portal the second user defines appears automatically in the first user's view, placed at the same relative position.

the devices create an audiovisual link using WebRTC and then begin streaming the head-stabilized video of each surface to the other user. Crucially, to satisfy **D1**, we do not use any external camera to capture the physical portal contents, instead, we capture the video stream from the headset's front-facing camera and apply perspective rectification and head stabilization to extract the surface texture.

The lightweight setup of our system allows flexible configurations of the portals. Here we show 4 possible system setups. Fig. 1a, 1b and Fig. 3 demonstrate the two most typical setups, where users utilize the joint surfaces with the same orientation (i.e., both vertical or both horizontal) in their corresponding environments. In Fig. 1a and 1b, the users choose to overlap the two portals to work on a merged view. Alternatively in Fig. 3, the users may choose to place the portals separately. While the former setup allows physical annotation on each other's surface, the latter setup may be more suitable for divided labor or remote instruction, where each user maintains their own workspace while being aware of their collaborator's activities. In Fig. 4 we demonstrate two less typical cases which are supported with some trade-offs. In Fig. 4a and 4b, the users join surfaces that have different orientations (e.g., user A sets up on a vertical whiteboard while user B sets up on a horizontal desk). In this case, the user avatars would reflect such an orientation difference. For example, in Fig. 4a the remote user appears to look at the shared portals from a lower position at an angle. In Fig. 4b, the remote user appears above the shared surfaces. Although the avatars still provide accurate references (i.e., gaze, gestures), such positioning may be unnatural for users. We further investigated how much this impacts user experience as a part of user evaluation 9.4.2. Fig. 4c shows the configuration when users place their virtual portals separately on disjoint physical surfaces. Such a setting is useful for simulating presenter-audience interactions in remote communication. Note that in this case, our system is able to retain proper spatial awareness between the users despite using disjoint surfaces. Due to heterogeneity between environments, it may be challenging to guarantee that each other's remote portals are attached to physical surfaces (i.e., otherwise remote portals may be floating in the air) if the users reconfigure their portals during collaboration. However, as the remote portals are essentially virtual screens sharing the remote user's content, floating remote portals do not affect the system's functionality. Our system allows portal repositioning anytime during collaboration to satisfy **D1**, allowing them to set up the environment in a way that best suits their needs. We believe such flexibility fosters a more fluid experience that fits typical user collaboration dynamics.



(a) (b) (c)

Fig. 4. Here we show two non-typical system setups our system supports. In (a) and (b) users select surfaces with different orientations: a vertical whiteboard and a horizontal desk. In (c), the users set portals on disjoint surfaces.

## 4.2 Physical Surface Sharing

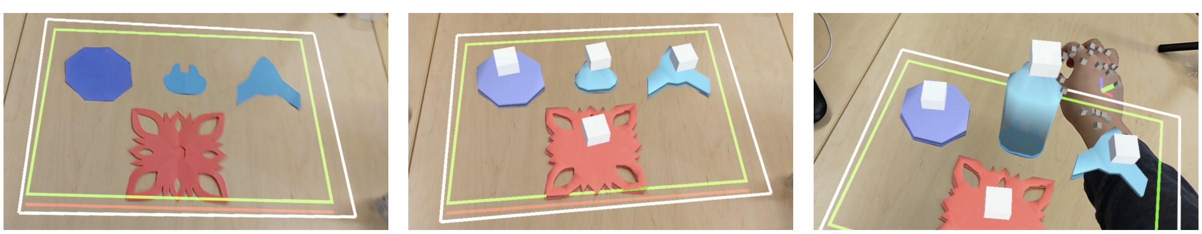
To support collaboration on physical tasks, *SurfShare* allows users to share physical surfaces with virtual portals (Fig. 1a and 1b). In line with **D1**, our system captures the physical surface in each user's local portal using the device's front camera and streams it the other user's remote portal, at a resolution of 760 × 428 and 30 FPS. To correct for head motion in the front camera, our system continually records the precise physical location and orientation of the headset and surface, and dynamically crops, rectifies, and perspective-corrects the outgoing video to capture only the surface contents. In the event of partial or missing captures (e.g. because the user looks away from the surface), we combine the observed pixels with previous frames to maintain a complete image. We implicitly assume that users will attend to the portal area while manipulating objects, thus ensuring fresh video content; if users look away while their local surface contents change, the cached video contents may become stale on the remote side.

By default, the video is background-subtracted such that the remote physical objects are seamlessly displayed over on the local physical surface, without including e.g. the texture of the underlying table or wall. In some usage scenarios such as screen- or document-sharing, users can choose to toggle off background subtraction on either side to view the entire surface (Fig. 6b). Note that we scope our system to share planar physical objects, and thus 3D physical objects appearing in the portal will have their height distorted. It is possible to share 3D objects through 3D scanning and reconstruction, although our current prototype does not support this.

## 4.3 Shared Virtual Object Creation and Manipulation

To extend the shared physical surfaces to a remote virtual workspace (**D2**), *SurfShare* allows users to create virtual replicas of nearly flat 2D physical objects in their local portals. As demonstrated in Fig. 5, users can create multiple virtual replicas with arbitrary shapes simultaneously. The replicas inherit the average color of the original physical objects and provide remote users "virtual" access to physical objects from the other space.

The virtual replicas are customizable after creation via extrusion and resizing. They are initialized with a default height of 1 cm, as anything less than that will make it more challenging for users to precisely manipulate them with hand gestures. The users can extrude and shear them by dragging the attached white handle (Fig. 5b and 5c), and scale with a two-handed pinch gesture. *SurfShare* enables the creation of two types of virtual objects: 1) floating objects, and 2) objects with physics (i.e., objects subject to gravity and collision). Floating objects are the most suitable for applications such as remote demonstration and prototyping, while objects with physics are more suitable for playing physical games (e.g., bowling, air hockey) in a remote shared experience. All virtual objects are shared networked objects, ensuring that their state is fully synchronized among participants. Our system ensures each virtual object can only be manipulated by one user at a time.



(a) (b) (c)

Fig. 5. *SurfShare* can create virtual replicas for planar physical objects with arbitrary shapes in two steps: (a) the user first puts the objects in their local portal. (b) the user then clicks "create object" or "create floating object" on the menu. A virtual replica with a default height of 1 cm will appear. (c) the user can extrude and shear the object by dragging the white cube.

### 4.4 User Avatars and Spatialized Voice Communication

To enhance the spatial awareness between users (D3), each user in *SurfShare* sees a virtual avatar of the other user (visible in Fig. 1d and 4). Each user avatar consists of a head and a pair of hands. As part of spatial consistency, the relative transform of the user avatar to the remote portal is synchronized with the actual remote user's relative position to their local portal. The user avatars facilitate the collaborative experience by bringing in the user's head direction and hand gesture to the collaboration, enriching the reference space [10] of remote communication. The system may render the users' 2D hand projections (as they appear on the portal surface) and 3D hand skeletons simultaneously (e.g. as seen in Figure 7). To avoid occlusion, we chose to render the hand skeletons as a set of cubes in a darker color, instead of the default bright blue solid appearance. This ensures that when a user's hands are close to the physical surface, the brighter 2D projection of them will stand out over the hand skeletons. *SurfShare* also implements a real-time audio connection for the two users to communicate verbally. Audio from the remote user is localized to their head avatar using spatial audio, providing sound direction as an additional cue for locating the other user in the shared space.

## 5 SURFSHARE IMPLEMENTATION

*SurfShare* has a symmetric hardware setting where the two users each wear a pair of Microsoft HoloLens 2[1]. Our system only relies on the sensing capability of the headset without any external sensors. We implemented our system with Unity3D [2] and Microsoft Mixed Reality Toolkit (MRTK) [3]. The devices stream audio and video using MixedReality-WebRTC [4] and synchronize networked virtual objects with Mirror [5]. Our system implementation is open-sourced at https://github.com/UBC-X-Lab/SurfShare.

### 5.1 Spatial Consistency

Since *SurfShare* only shares physical objects in the virtual portal, the spatial consistency for the shared physical surfaces is established by synchronizing the relative transformation between each user's portals. For establishing spatial consistency for the virtual objects and user avatars, *SurfShare* uses the virtual portals as spatial anchors to align a user's local world coordinate system to the environment of the other user. As a room-scale application, when *SurfShare* starts, Hololens 2 sets up a world coordinate system with the world origin at the user's head level. After the users set up the virtual portals, we first calculate the relative transformation from the center point of User 1's local portal to their world origin. We then apply the same transformation to the center point of the local portal's remote twin (i.e. User 2's remote portal) to place User 1's world coordinate system into User 2's environment. We then repeat the same process to place User 2's world coordinate system in User 1's environment. To achieve spatial consistency for virtual replicas/objects (including a user's avatar head and hand skeleton), our system synchronizes a virtual object's coordinate in the owner's world coordinate system with its coordinate in the other user's remote coordinate system.

### 5.2 Holographic-Projective Video Masking

With Hololens' forward-facing video camera, *SurfShare* captures a real-time video of the physical surface in a user's local portal and streams it to the other user's remote portal. Because we allow users to naturally move while they are collaborating with each other, the portal contents will occupy a constantly changing region of the raw video. One naive way to play the cropped video in the rectangular remote portal is to stretch it to fit.

[1] https://www.microsoft.com/en-ca/hololens/hardware
[2] https://unity.com/
[3] https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2021-05
[4] https://microsoft.github.io/MixedReality-WebRTC/
[5] https://mirror-networking.com/

However, this approach will lead to distortion due to the parallax effect. Therefore, our system crops the video and stabilizes it to counter head movements and parallax effects with projective transformation, which we term "holographic-projective video masking".

The first step of projective transformation is to calculate the world coordinates (in Unity coordinates) that correspond to the 720×428 pixels of video we would like to stream. We obtain these coordinates by linearly interpolating them for the physical area in the local portal. Next, we transform the world coordinates of the pixels into the coordinate system of the video camera, which is a right-handed coordinate system with the z-axis pointing in the user's head direction. Knowing the video camera's intrinsic distortion parameters, we can transform these 3D coordinates to the 2D position on the frames captured by the camera. We apply bilinear interpolation to obtain the corresponding pixel colours, forming the transmitted frame.

With holographic-projective video masking, we obtain a video as if it is captured with a static orthographic camera above the surface despite an always-moving camera mounted to the user's head. Although we expect users will target their heads towards the shared physical surface as they collaborate, the head-mounted camera won't necessarily capture the entire physical surface in the local portal all the time. To mitigate this, at each frame, our system dynamically updates the pixels for the part of the physical surface within the camera's field of view, while the areas falling outside of the camera's field of view remain unchanged.

### 5.3 Video Background Subtraction with HSV Thresholding

By default, our system applies background subtraction to the video played in each user's remote portal such that the virtual image of shared physical objects overlays seamlessly on the user's physical surface, which is particularly crucial for overlapping portals. Without background subtraction, the color of the surface itself (e.g. table, wall) would overlay the entire portal. Classic background subtraction algorithms [36, 75] are more suitable for detecting moving foreground objects, which does not apply to our system. Furthermore, we observed that video captured from a moving head-mounted camera leads to dynamic lighting conditions, as the intensity of light reflected from a surface can change drastically as the camera moves. Thus, we chose to implement a background subtraction technique based on color-channel thresholding in the Hue-Saturation-Value (HSV) color space. Note that the hue channel represents the "pure color" and disregards shade and lighting, whereas the saturation and value channels are related to lighting conditions. Therefore, by setting a tight threshold range on the hue and loosened threshold ranges on saturation and value, our thresholding approach is made more robust against lighting and shade variation.

To implement our background subtraction with HSV thresholding, our system stores the first frame of a user's local portal as the background. For subsequent frames, we calculate how much each pixel varies from the first frame. If the variation exceeds the threshold on any channel, we mark the pixel as foreground. Thresholds were set via experimentation (all channels in the range 0-1): for black or white backgrounds (Saturation < 0.2 or Value < 0.2), foreground pixels are any pixels that no longer appear black or white; for colored backgrounds, foreground pixels are any pixels that differ from the background in Hue by at least 0.04, in Saturation by at least 0.5, or in Value by at least 0.6. Our background subtraction algorithm is implemented as a custom Unity shader. We verified that our background subtraction technique works well on common textures such as plain walls, white/black boards, and wooden desks (with grain patterns) under typical indoor office lighting.

### 5.4 Virtual Object Creation and Manipulation

*SurfShare* enables virtual object creation from physical objects. To give users a clear sense of initial ownership of objects, our system only allows users to create virtual replicas from the actual physical objects (i.e., not the projected remote image) in their local portal.

We used Unity's Mesh API [6] for runtime custom mesh creation. When a user clicks on "Create Object" or "Create Floating Object" on the menu, our system takes the newest background-subtracted frame captured for the local portal and attempts to create virtual replicas for all foreground objects identified in the frame. We use OpenCV [9] to find the contours of each foreground object. We ignore external contours containing less than 1600 pixels (equivalent to a 40x40 area) and holes containing less than 225 pixels (equivalent to a 15x15 area) to reduce noise. We transform the contour points from the video's 2D coordinates to the Hololens' 3D coordinates to obtain the mesh bottom polygon, which is then extruded 1 cm perpendicular to the surface to form the mesh sides. We then triangulate the polygon using constrained Delaunay triangulation [13, 51, 60] to form the top and bottom faces. Finally, we construct a Mesh from the resulting vertices and triangles.

It is important to note that we do not use depth information to create virtual replicas. We opted out of using RGB+D images because it requires users to carefully rotate and scan the objects and clean up the floaters in point clouds through post-processing. We consider such a process to be too tedious for real-time remote collaboration. In contrast, our system demonstrates a technique for the instantaneous creation of virtual replicas.

To enable mesh extrusion and shearing, we present an extrusion handle (the white cube in Fig. 5b and 5c) above the top of each mesh. We track an extrusion handle's position translation as a user drags it, and apply the translation to the mesh's top vertices at runtime. We relied on MRTK's object manipulation components to enable freehand manipulation of the virtual objects including movement, rotation, and scaling.

"Create Floating Object" creates objects without any physics system, allowing them to be freely placed and rotated in mid-air. "Create Object" creates objects with physics (a Unity RigidBody component), which are subject to gravity and collisions with the shared surface plane and other objects.

Positions, rotations, and vertices of all objects are constantly synchronized using Mirror to maintain spatial consistency. Objects are additionally assigned an owner (either one of the users) to ensure that only one user can manipulate the object at a time. Objects are initially owned by the creator (i.e. the user who clicked "Create"). If the user stops manipulating an object, it becomes free to be claimed; either user can then gain ownership simply by starting to manipulate it.

## 6 APPLICATION SCENARIOS

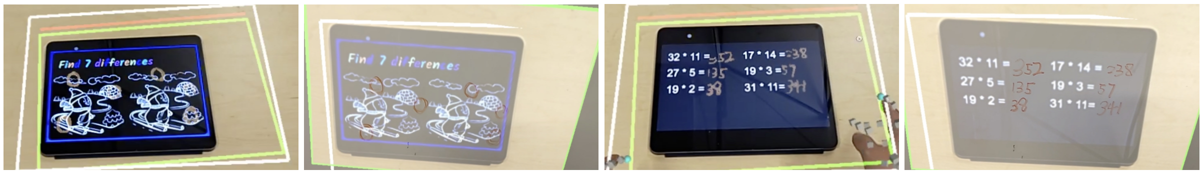
We design *SurfShare* to be a general-purpose collaborative system. Here, we show that our system can be applied to various domains of tasks with four example application scenarios.

### 6.1 Shared Physical Surfaces

During daily in-person interactions, people often gather around a physical surface (e.g., whiteboard, desks) and collaborate on documents, puzzles, or screens. In this application scenario, we demonstrate how *SurfShare* empowers users to easily set up shared physical surfaces, on which they can conduct common tabletop activities such as playing chess, working on math problems, and sketching designs together. Such a technique can also add tangibility to on-screen digital interactions, which proves to be effective for educational scenarios [14].

Here we show an example task where one user shares a "finding difference" game (Fig. 6a and Fig. 6b) and a set of math problems (Fig. 6c and Fig. 6d) with the other user. To set up *SurfShare* for this application scenario, one user can anchor their virtual portals on a whiteboard, while the other user anchors the portals on a desk. The users overlap their virtual portals to create a merged view of each other's surface. One user then shares a document (presented on a tablet) for the other user to remotely annotate. In this case, the user receiving the document turns the background-subtraction off to get a full view of the other user's surface. The user sharing the document can see the other user's background-subtracted image of annotations overlaid on the documents.

[6]https://docs.unity3d.com/ScriptReference/Mesh.html




(a) (b) (c) (d)

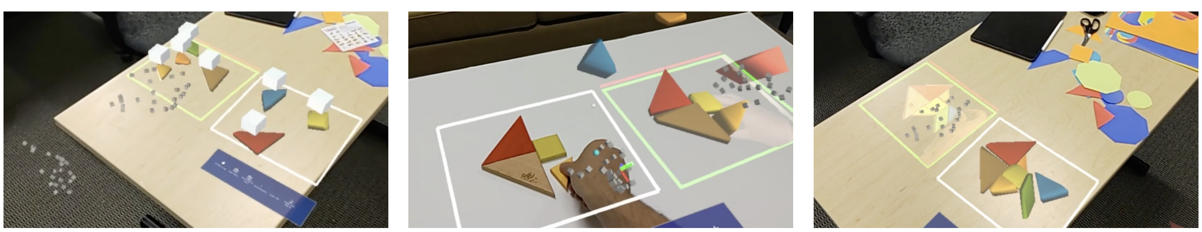
Fig. 6. *SurfShare* allows users to create a shared physical surface. The first user, in (a) and (c), is sharing a tablet on their desk while the second user in (b) and (d) shares a vertical whiteboard, using a marker for annotation. The second user's pen marks are made visible in the first user's virtual view through background subtraction. In (a) and (b), one user shares a "find difference" game with the other. Similarly, in (c) and (d), the users can work on math problems.

Allowing users to annotate with natural handwriting enables them to write math equations or draw patterns using a pen, which may be inconvenient with conventional digital screen sharing.

## 6.2 Demonstration with Virtual replicas for Remote Instruction

Prior research has investigated using remote collaboration tools for remote instruction on physical tasks [20, 25, 35, 65, 66, 72]. However, since users can only physically manipulate objects that actually exist in their environment, enabling the direct demonstration of physical tasks requires both the learner and the instructor to possess the physical assets required for the task. This application scenario shows how *SurfShare* alleviates such a restriction by allowing a learner to create virtual replicas of physical objects for an instructor to demonstrate with. Such an application can be useful for remote instruction for physical tasks as well as education.

Here we show a simple physical task with tangram puzzles (i.e., a set of geometrical pieces that can be constructed into shapes such as trees, fish, or chickens) supported by *SurfShare* (Fig. 7). The learner who possesses a set of tangram puzzles would like the instructor to show him or her how to construct a fish. The learner can bring the physical tangram puzzles into their local portal and create virtual replicas of them by clicking "create floating objects". Floating objects do not have physics properties (e.g., collision, gravity) attached to them and are easier to manipulate. The instructor then starts demonstrating with the virtual set of tangrams for the learner to follow along. Here we show a side-by-side workspace with the virtual portals arranged next to each other.



(a) (b) (c)

Fig. 7. This application scenario shows how an instructor (a, c) can remotely teach a learner (b) by demonstrating with virtual replicas. Here, one user shows the other how to construct a fish with tangram puzzles. In (a), the learner creates virtual replicas of the tangram pieces for the instructor to use. In (b), the instructor grabs the virtual replicas and demonstrates the solution by directly manipulating the replicas as the learner follows along. Finally, in (c) the learner has successfully constructed the fish (in the green portal) following the instructor's demonstration (in the white portal).

### 6.3 Shared Room-Scale Mixed-Reality Recreational Activities

People enjoy recreational activities to socialize and stay healthy. By creating virtual objects with physics properties, *SurfShare* has the potential to enable room-scale recreational activities (e.g., mini-bowling, air hockey) for remote users. Here, two users configure a shared mini-bowling alley by arranging their virtual portals apart at the ends of a horizontal on a physical surface such as a desk. In this scenario, users click on "create objects" to spawn virtual replicas with physics properties. The user at one end of the desk can cut colored circles and put them into their local portals. The colored circles are used as bowling pin generators from which the user can create and extrude cylinders as new bowling pins. The user at the other end of the desk can create virtual replicas of octagons and use them as bowling balls. Fig. 8 shows such a mini-bowling game between two remote players.

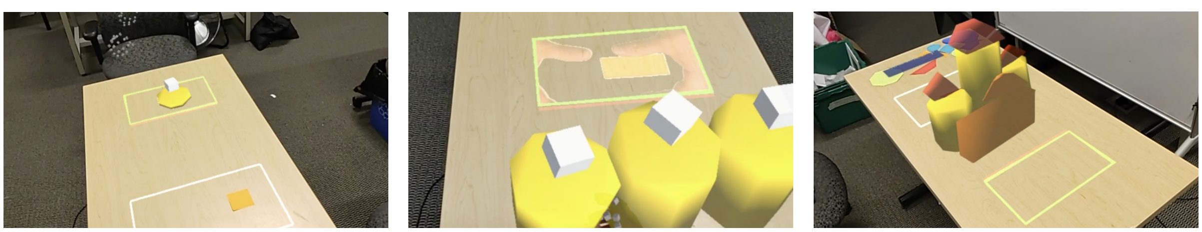
(a) (b) (c) (d)

Fig. 8. Here we show a mini-bowling game *SurfShare* enables by allowing users to create virtual objects with physics. (a) The user creates an octagon as a bowling ball. (b) The other user extruded three bowling pins. (c) The user with the virtual bowling ball throws it towards the bowling pins and knocks them off in (d).

### 6.4 Collaborative Virtual Content Authoring

In-situ AR content authoring [5, 24, 43] allows users to create virtual assets immersively in the AR scene. Prior research has investigated extruding virtual objects from paper sketches [7, 8], which allows users to create custom content rather than just pre-defined assets. In this application scenario, we demonstrate *SurfShare*'s potential in combining sketch-based content creation and in-situ authoring for remote shared experiences.

Here, two users of *SurfShare* are trying to prototype a virtual brick castle. They arrange their virtual portals into a face-to-face workspace while leaving an area between them for the castle building. The users can cut colored papers into desired shapes and put them into their local portal. They then create floating virtual replicas of the shapes and extrude them into 3D bricks. Fig. 9 shows a brick castle collaboratively built with *SurfShare*.



(a) (b) (c)

Fig. 9. By creating the floating virtual replicas, *SurfShare* can enable remote collaborative AR content authoring. Here, two users collaboratively build a virtual brick castle. In (a), the users start by creating virtual objects from shapes cut from colored paper. In (b), one user aligns yellow octagons as the body of the castle while the other continues to create more virtual objects. (c) shows the completed virtual castle.

## 7 STUDY 1: USABILITY TEST

To evaluate our system's usability, we recruited 10 participants (6 male, 4 female, aged from 18 to 32) to interact with our system in the 4 application scenarios described above. Our study design was approved by the institution's ethics review board. All participants read and signed an institutionally-approved consent form prior to the studies. All participants are frequent users (at least once a week) of common remote collaborative software (e.g., video conferences, shared documents). Most of our participants are novices in augmented reality: 5 of them reported that they have never interacted with mobile or head-mounted augmented reality, and the rest of the participants have only used them a few times in the past. As we are mainly evaluating the usability of our system in this study, recruiting participants with less experience in augmented reality allows us to evaluate whether our lightweight setup leads to higher learnability.

### 7.1 Procedure

Each user study session took approximately 1.5 hours, and we compensated each participant 8 dollars for every 30 minutes of their time. At the beginning of each session, we invite the participants to go through the built-in tutorial of Microsoft Hololens 2. We then show them a 30-second video demonstrating how to set up the *SurfShare* system with virtual portals. Once the participant confirms that they are familiarized with Hololens and how to set up *SurfShare* virtual portals, the participant and the experimenter then collaborate on the same four application scenarios described in Section 6, where each scenario tasks approximately 10 minutes. To reduce the author's impact on the experiment, the authors and the participants completed the tasks in separate rooms and maintained communication only through our system. After completing the tasks, the participant reflects on the system's general usability and fills out a 5-Likert version of the System Usability Scale (SUS).

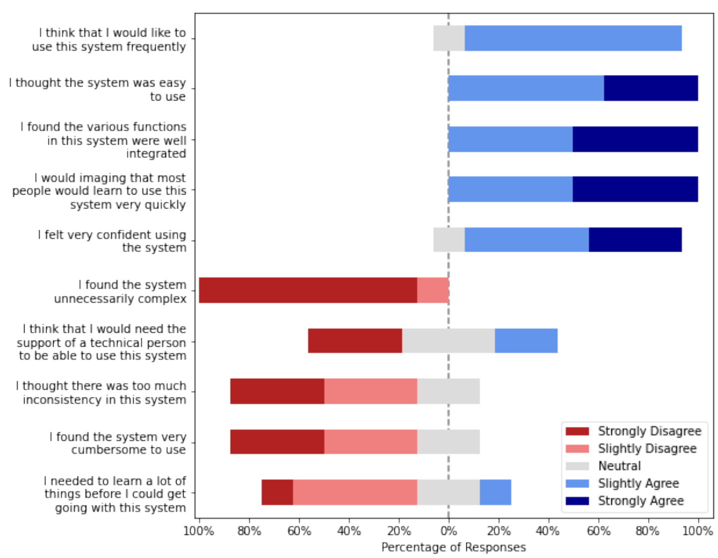



Fig. 10. The response to the System Usability Scale shows that the participants found *SurfShare* to be mostly easy to use. Note that for questions 6 - 10, a lower score indicates a better performance. We calculated an average SUS score of 3.76 by inverting the scores from the last 5 questions, corresponding to 75.2 ("good") on the adjective rating scale [6]

## 7.2 Results

All the participants successfully completed all tasks in our study. In general, the participants found the system's functionality effective and easy to understand. Most of the participants acknowledged the system is straightforward to set up. The majority of difficulties participants experienced came from unfamiliarity with Hololens' hand gestures (e.g., pressing buttons, grabbing or scaling objects). In these cases, the author helped them by demonstrating in the *SurfShare* scene. The results from the SUS (Fig. 10) show that most users found our system easy to use. Note that for questions 6 - 10 in the SUS, a lower score indicates a better performance. To obtain an average SUS score, we inverted the scores for the last 5 questions and uniformly averaged all the scores. The average score of *SurfShare* is 3.76, which corresponds to 75.2 ("good") on the adjective rating scale [6].

# 8 STUDY 2: USER EVALUATION TASK AND PROCEDURE

To further evaluate how well our system has achieved the design goals, we applied *SurfShare* to a more comprehensive low-fidelity prototyping scenario with dyads of users. We derived 2 research questions from **D1** and **D2** that we hoped to answer with this study:

- ***RQ1***: *How does lightweight physical surface sharing impact proxemics in remote mixed reality collaboration?*
- ***RQ2***: *Can ad-hoc 2D virtual replicas enhance remote collaboration and low-fi prototyping?*

We recruited 12 participants (aged 20 to 28, 6 male, 6 female) from the local campus for this study. The participants worked in pairs, brainstormed an idea, sketched their design, and completed a prototype. We will refer to participants as P1A/B to P6A/B in the following sections.

At the beginning of each dyad session, we welcomed both participants into the lab. We first briefed the participants on the task and asked them to read and sign the consent forms. We then asked the participants to go through the HoloLens 2 built-in tutorial, then demonstrate the SurfShare system setup, portal repositioning, and main collaboration functionality. This training process takes approximately 10 minutes.

After the participants confirmed that they had sufficient familiarity with the system, we situated the 2 participants in the corners of a large lab (14 meters apart and separated with blinds), simulating a remote collaborative scenario. In Fig. 11 we show the two areas the participants worked in. The two spaces had different

(a) (b)

Fig. 11. The spaces where we conducted the dyad sessions in. Both environments have a desk, colored markers, and colored sheets of paper, While space (a) has a small (30cm x 40cm) whiteboard, space (b) has a vertical large whiteboard. We hope such a difference in spatial arrangement can encourage participants to communicate and decide on their idea system setup.

spatial arrangements, which encouraged users to communicate and decide on their ideal system setup. We then asked the participants to wear and launch the SurfShare application in their respective HoloLens 2 headsets.

The study then proceeded in two phases. In the first phase, we instructed the participants to brainstorm and design what they would like to prototype. We prompted the participants with broad themes including building construction, vehicles, and toys. To start, the participants discussed through the system's audio link to agree on the optimal portal configuration and set up the system accordingly. Participants were able to reposition their portal anytime during the study. The participants then used the materials given to them (e.g., whiteboards, sheets of paper) to agree on an idea and sketch their design. In the second phase, the participants worked on prototyping their design. Here, we prompt the participants that they can choose to keep or alter the system configuration to better suit their new task. We then instructed the participants to prototype their designs by creating virtual objects from hand-drawn sketches or shapes cut from paper. During both phases, we instructed the participants to think aloud and only intervened if they requested help. At the end of the study, each participant filled out a questionnaire where they rated and explained their level of agreement (5-Likert scale) on 6 statements regarding the system (Fig. 12), and answered what they liked and did not like about the system in each of the two phases.

## 9 USER EVALUATION RESULTS

In Fig. 12, we report the level of agreement on our system's flexibility, spatial consistency, and low-fi prototyping. The result shows the effectiveness of our system design. We then analyzed the participants' feedback from the questionnaire with affinity diagrams, grouping them under themes related to our research questions. We report the findings as follows.

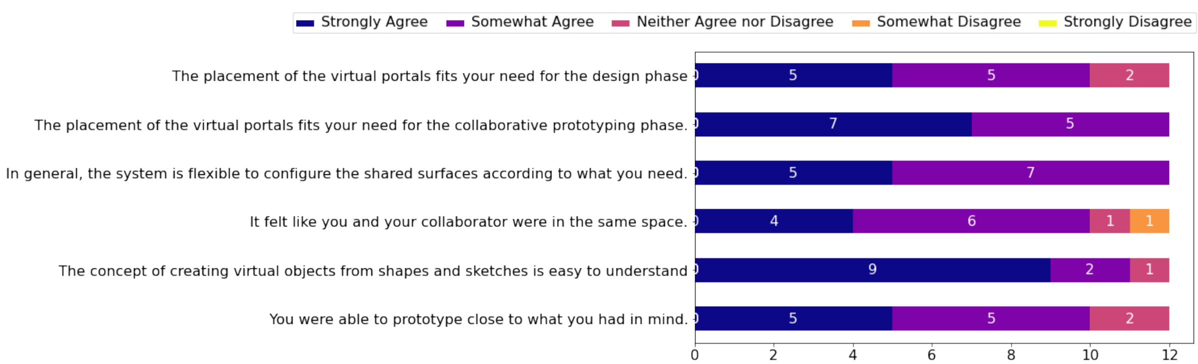



Fig. 12. We gather the 6 statements we asked participants to rate their level of agreements on and report the results. The results show that participants generally appreciate the flexibility of our system and acknowledge its usage. In addition, most participants perceives a sufficient level of spatial consistency. Lastly, ad-hoc 2D virtual replica creation is easy to understand and effective in the context of low-fi prototyping.

### 9.1 The Usage of Overlapped and Separated Portal Configurations

For **RQ1**, our study shows that users overlap or separate the portals for different kind of tasks. In general, overlapped portals are better suitable for collaboration on the same content:

> *P6A: Overlapping portals allowed us to collaborate and iterate on the same design. this is much improved over having two separate portals since that resulted in us repeating each other's drawings*

The participants also found that separated portals help split work between them:

> *P4B: The two portal designs made it easy for us to divide the task to each individual and work more efficiently.*

> *P2B: Having two separate portals... we could independently draw and spawn objects without affecting the others' work*

Echoing the participant feedback, we also observed that 5 out of the 6 pairs of participants set up or repositioned their portals to a merged view during the design phase, while all of them chose to configure the portals separately for the prototyping phase.

## 9.2 The Change of Portal Configurations

Further digging into **RQ1**, we found that users may change the configuration of their portals during the collaboration for various reasons:

*9.2.1 Matching spatial resource to tasks.* The concept of Proxemic Transitions [21] suggests that users tend to rearrange themselves to best utilize the physical environment for their tasks. This is echoed by our study when participants reconfigure the portals when they switch from the design phase to the prototyping phase:

> *P2A: [We conducted] the design phase on a vertical whiteboard, and the prototype phase on a horizontal desk. I appreciated this ability to relocate the portals regarding different tasks.*

*9.2.2 Adapting to virtual contents.* As our system provides a physical shared surface and a virtual workspace anchored to them, we observed participants reposition the virtual portals to adapt to virtual contents as well. We observed that several pairs of participants used the space between their virtual portals to build the prototype. As the prototypes get larger, they reposition the portals:

> *P2B: further separating portals gave us extra scratch space for creating objects*

*9.2.3 Optimizing collaboration.* We found that a reconfiguration also happens as users optimize their collaborative experience. In our study, the participants may not start with an optimal configuration and tend to adjust it later:

> *P6B: We started with the side-by-side placement but then moved to the overlapping placement and I much preferred the overlapping placement because my partner and I could annotate each other's work, it promoted better collaboration that way.*

## 9.3 Prototyping with Virtual Replicas

Participants also reflected on low-fi prototyping with ad-hoc virtual replica creation (**RQ2**).

*9.3.1 Intuitive Design Technique.* Participants found the concept of ad-hoc virtual replica creation intuitive:

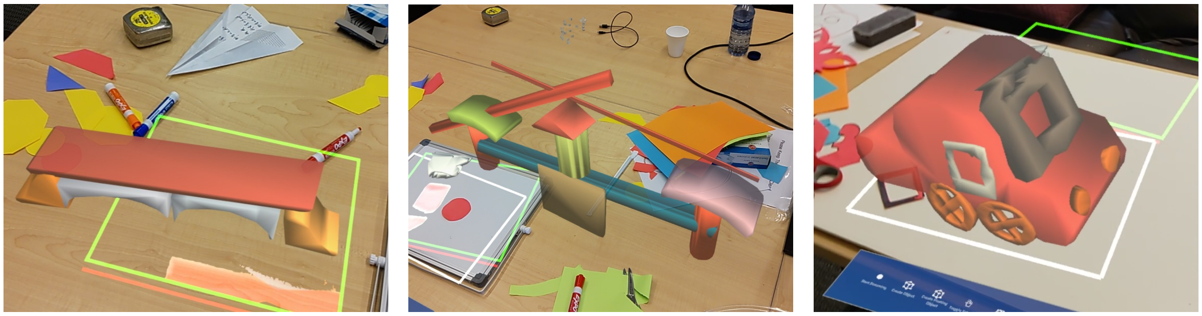
> *P6A: [There is] not much thinking I had to do for this. Just had to click a button and *boom* the shapes were made. Quite easy actually.*

> *P1B: The feature is very intuitive and the method is easy to learn, even for people who are new to AR/VR facilities like me.*

*9.3.2 Reaching a sufficient level of prototyping freedom.* We found that the idea of extruding 3D objects from 2D shapes already provides a sufficient level of prototyping freedom for low-fi prototyping. By drawing and extruding from the side view of desired 3D objects, some participants created prototypes with a high amount of detail. In Fig. 13, we show 3 of the final prototypes from our sessions with participants' consent.

## 9.4 Spatial Consistency

Our study showed how spatial consistency (**D3**) was perceived by users.



(a) (b) (c)

Fig. 13. The participants were able to realize their creativity with our low-fi prototyping functionalities. The participants built a traditional stone bridge in (a), a suspension bridge in (b), and a cartoon car in (c).

*9.4.1 Different tasks require different levels of spatial awareness.* Our study involves both physical surface sharing (i.e., the design phase) and prototyping with virtual replicas (i.e., the prototyping phase). We found that the levels of spatial awareness required differ between the two phases. While the head avatar indicates where the remote collaborator is in the virtual space, some participants found it redundant in the design phase as they are engaged in the physical surfaces:

> *P5A: However, I found the human head not really necessary, since it does not really contribute to the design process.*

*9.4.2 Spatial awareness when matching surfaces with different orientations.* Due to the spatial arrangement of the two spaces, the participants often paired the vertical whiteboard in space B with the desk in space A in the design phase, leading to the example configuration we discussed in Section 4.1 and showed in Fig. 4a and 4b. For the physical task (i.e., the design phase), none of the participants experienced confusion due to the different spatial orientations. However, we discovered that with our current system, matching surfaces with different orientations is less suitable for virtual tasks. P6A and P6B kept using the whiteboard-desk setup for the prototyping phase. For example, while P6A built their prototype naturally from low to high on their desk, P6B saw objects building out from the whiteboard towards them.

## 10 DISCUSSION

*SurfShare* contributes a bi-directional symmetric remote collaborative system in mixed reality. It shares physical surfaces in a lightweight manner, and extends physical surfaces with a virtual workspace that enables ad-hoc creation of virtual replicas. Here we discuss the main contributions of our system, what *SurfShare* has made possible, and future work. Where relevant, we refer to the dimensions outlined by Olsen's framework [57].

The user evaluations show that our system achieves all three design goals we set in Section 3.1. In particular, **D1** and **D2** point to the main novel components of *SurfShare*: 1) the lightweight system configuration and 2) the integration of physical and virtual workspace. As we achieve **D1**, our system improves upon prior projector-based physical surface-sharing systems [16, 32, 35, 47], by eliminating the need to instrument the environment. To fulfill **D1**, we made 2 technical contributions: 1) stably track and stream the surface area selected by users despite using the moving head-mounted camera and 2) a simplistic way to construct a common reference space that only requires a single planar surface in each physical environment. We achieved **D2** with ad-hoc virtual replica creation, which extends shared physical surfaces to remote virtual collaboration. While we only support 2D virtual replicas, our system creates them on demand during collaboration. With **RQ1** and **RQ2**, our user evaluation further looked into the implications of the lightweight setup and the hybrid physical-virtual workspace in remote collaboration, and we discuss them as follows.

The lightweight nature of *SurfShare* leads to *flexibility*, a factor of Olsen's *Reduce solution viscosity* dimension, at the system setup and throughout the collaboration. By answering **RQ1**, we found that such *flexibility* aligns well with the dynamic proxemics during remote collaboration. Through the user evaluation, we found that proxemic changes occur at different levels with different implications. Users make proxemic transitions as they adapt the system configuration to their specific spatial patterns (see Section 9.2.1). Such proxemic transitions are more drastic and usually happen when users initialize their collaboration or transition between task contexts. Proxemic transitions occurring during the same task are more subtle. When users change portals between overlapped or separated patterns, they are essentially changing their collaborative modes (see Section 9.1). While the portals remain on the same surface, overlapping portals stimulate more discussions while separated portals divide work between users. The most subtle proxemic adjustment we observed happens when users adapt to virtual content creation (see Section 9.2.2). The users are actually repositioning the portals to define and adjust their virtual workspace. During the prototyping phase, we observe that the users tend to use the virtual space e between them (i.e., as defined by the positioning of the portals) to build the virtual model. As the virtual model grows, they make minor adjustments to the positioning of the portals to resize their virtual workspace. *SurfShare*'s flexibility provides users high freedom in adjusting the configurations by allowing continuous repositioning of the portals anytime during the collaboration, thus supporting the above proxemic changes across all levels.

The combination of physical surface sharing and the anchored virtual workspace demonstrates *power in combination* [57]. Both physical and virtual object sharing [35, 67] have been well explored in prior research. However, *SurfShare* combines the two sharing modalities with ad-hoc virtual replica creation, allowing users to rapidly create virtual objects that are seamlessly referenced to the physical environment in both spaces. By answering **RQ2**, we verified the effectiveness of ad-hoc creation of virtual replicas. Despite only supporting planar virtual replicas (customizable thereafter in the virtual space), *SurfShare* is already applicable to basic low-fi 3D modeling. Rapidly creating virtual content and objects is a well-investigated topic to lower the technical barrier for designers [43, 53, 54]. Therefore, our system also *empowers new design participants* [57], allowing non-technical designers to rapidly create virtual content from sketches and shapes cut from paper.

Both the lightweightness and the hybrid physical-virtual workspace contribute to the *generality* dimension of Olsen's framework [57]. The lightweightness brings the generality of configuration, allowing users to utilize any physical surface (e.g., screen, whiteboard, desks) available to them in their environment. The hybrid physical-virtual workspace allows a large application space, making *SurfShare* a general-purpose remote collaborative system. We demonstrated *SurfShare*'s potential application with four example scenarios. Here, we discuss the application domains they correspond to. Our first example application (Section 6.1), which enables physical annotations on remote surfaces, can be extended to collaborative sketching with natural handwriting or drawing on documents or even digital screens shared with our system. Our second example application (Section 6.2) corresponds to the application domain of remote instruction, where demonstration with virtual props can enhance verbal instructions. The third example application (Section 6.3) looks into the application domain of remote sports and games, by attaching physics to the virtual props created by our system. Existing online sports instruction is mostly based on asynchronous videos. Future work can extend our system to enable a sports coach and a coachee to participate in recreational sessions regardless of distance. Our last example application (Section 6.4) points to remote collaborative prototyping with ad-hoc virtual replicas, which we further evaluated with the user experiment and have already discussed above. In the future, we will look into rapid 3D reconstruction methods, extending the ad-hoc creation of virtual replicas to 3D, with higher reality and fidelity.

The dimension of *Can it scale up* in Olsen's framework [57] points to a future direction. The presented *SurfShare* prototype only supports two physical endpoints in a shared experience. Although it is easy to add virtual portals as spatial anchors for each additional physical space, such a naive approach may lead to a messy shared workspace and confusing object ownership. We expect that our current approach could scale to 3-4 merged physical spaces before requiring a more nuanced approach. Therefore, enabling remote shared mixed reality that can enable several users to synchronously collaborate efficiently is an interesting topic for future work.

## 11 CONCLUSION

In this work, we presented *SurfShare*, a system that enables symmetric shared mixed-reality collaboration and communication for remote users. *SurfShare* allows users to establish a spatially consistent connection between two remote spaces with minimal requirements on the similarity between them. *SurfShare* has a lightweight hardware setup, which enables users to flexibly turn any physical surface into a shared area without relying on any external sensors other than an off-the-shelf head-mounted mixed-reality display. Users gain a better awareness of each other through avatars and hand skeletons. *SurfShare* can share images and virtual replicas of physical objects, thus supporting collaborative physical tasks. Through a series of application scenarios, we demonstrated *SurfShare*'s potential in remote instruction, collaborative prototyping, as well as remote mixed-reality recreational activities. We validated *SurfShare*'s functionality with a usability test. We further evaluated the system in a comprehensive prototyping task with ad-hoc virtual replica creation. We found that *SurfShare*'s lightweightness allows for flexible and fluid proxemic transitions. We hope *SurfShare* blurs the boundary between remote spaces and provides insights for bringing the remote collaborative experience closer to natural in-person interaction.

## ACKNOWLEDGMENTS

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## REFERENCES

[1] Matt Adcock, Stuart Anderson, and Bruce Thomas. 2013. RemoteFusion: real time depth camera fusion for remote collaboration on physical tasks. In *Proceedings of the 12th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry* (Hong Kong, Hong Kong) *(VRCAI '13)*. Association for Computing Machinery, New York, NY, USA, 235–242.

[2] Maneesh Agrawala, Andrew C Beers, Ian McDowall, Bernd Fröhlich, Mark Bolas, and Pat Hanrahan. 1997. The two-user Responsive Workbench: support for collaboration through individual views of a shared space. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques (SIGGRAPH '97)*. ACM Press/Addison-Wesley Publishing Co., USA, 327–332.

[3] Deepak Akkil, Jobin Mathew James, Poika Isokoski, and Jari Kangas. 2016. GazeTorch: Enabling Gaze Awareness in Collaborative Physical Tasks. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 1151–1158.

[4] Rahul Arora, Rubaiat Habib Kazi, Tovi Grossman, George Fitzmaurice, and Karan Singh. 2018. SymbiosisSketch: Combining 2D & 3D Sketching for Designing Detailed 3D Objects in Situ. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18, Paper 185)*. Association for Computing Machinery, New York, NY, USA, 1–15.

[5] Rahul Arora, Rubaiat Habib Kazi, Danny M Kaufman, Wilmot Li, and Karan Singh. 2019. MagicalHands: Mid-Air Hand Gestures for Animating in VR. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 463–477.

[6] Aaron Bangor, Philip Kortum, and James Miller. 2009. Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale. *J. Usability Studies* 4, 3 (may 2009), 114–123.

[7] Simona Maria Banu. 2012. Augmented Reality system based on sketches for geometry education. In *2012 International Conference on E-Learning and E-Technologies in Education (ICEEE)*. 166–170.

[8] Sukanya Bhattacharjee and Parag Chaudhuri. 2020. A survey on sketch based content creation: From the desktop to virtual and augmented reality. *Comput. Graph. Forum* 39, 2 (May 2020), 757–780.

[9] G. Bradski. 2000. The OpenCV Library. *Dr. Dobb's Journal of Software Tools* (2000).

[10] Bill Buxton. 2009. Mediaspace – Meaningspace – Meetingspace. In *Computer Supported Cooperative Work*. Springer London, London, 217–231.

[11] Minghao Cai, Soh Masuko, and Jiro Tanaka. 2018. Shopping Together: A Remote Co-shopping System Utilizing Spatial Gesture Interaction. In *Human-Computer Interaction. Interaction Technologies*. Springer International Publishing, 219–232.

[12] Minghao Cai and Jiro Tanaka. 2017. Trip Together: A Remote Pair Sightseeing System Supporting Gestural Communication. In *Proceedings of the 5th International Conference on Human Agent Interaction* (Bielefeld, Germany) *(HAI '17)*. Association for Computing Machinery, New York, NY, USA, 317–324.

[13] Long Chen and Jin-Chao Xu. 2004. OPTIMAL DELAUNAY TRIANGULATIONS. *J. Comput. Math.* 22, 2 (2004), 299–308.

[14] Tobias Drey, Jessica Janek, Josef Lang, Dietmar Puschmann, Michael Rietzler, and Enrico Rukzio. 2022. SpARklingPaper: Enhancing Common Pen- And Paper-Based Handwriting Training for Children by Digitally Augmenting Papers Using a Tablet Screen. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 3, Article 113 (sep 2022), 29 pages. https://doi.org/10.1145/3550337

[15] Carmine Elvezio, Mengu Sukan, Ohan Oda, Steven Feiner, and Barbara Tversky. 2017. Remote collaboration in AR and VR using virtual replicas. In *ACM SIGGRAPH 2017 VR Village* (Los Angeles, California) *(SIGGRAPH '17, Article 13)*. Association for Computing Machinery, New York, NY, USA, 1–2.

[16] Barrett Ens, Sarah Goodwin, Arnaud Prouzeau, Fraser Anderson, Florence Y Wang, Samuel Gratzl, Zac Lucarelli, Brendan Moyle, Jim Smiley, and Tim Dwyer. 2021. Uplift: A Tangible and Immersive Tabletop System for Casual Collaborative Visual Analytics. *IEEE Trans. Vis. Comput. Graph.* 27, 2 (Feb. 2021), 1193–1203.

[17] Allen J Fairchild, Simon P Campion, Arturo S García, Robin Wolff, Terrence Fernando, and David J Roberts. 2017. A Mixed Reality Telepresence System for Collaborative Space Operation. *IEEE Trans. Circuits Syst. Video Technol.* 27, 4 (April 2017), 814–827.

[18] Daniel Immanuel Fink, Johannes Zagermann, Harald Reiterer, and Hans-Christian Jetter. 2022. Re-Locations: Augmenting Personal and Shared Workspaces to Support Remote Collaboration in Incongruent Spaces. *Proc. ACM Hum.-Comput. Interact.* 6, ISS, Article 556 (nov 2022), 30 pages. https://doi.org/10.1145/3567709

[19] Susan R Fussell, Leslie D Setlock, Jie Yang, Jiazhi Ou, Elizabeth Mauer, and Adam D I Kramer. 2004. Gestures over video streams to support remote collaboration on physical tasks. *Hum.-Comput. Interact.* 19, 3 (Sept. 2004), 273–309.

[20] Danilo Gasques, Janet G Johnson, Tommy Sharkey, Yuanyuan Feng, Ru Wang, Zhuoqun Robin Xu, Enrique Zavala, Yifei Zhang, Wanze Xie, Xinming Zhang, Konrad Davis, Michael Yip, and Nadir Weibel. 2021. ARTEMIS: A Collaborative Mixed-Reality System for Immersive Surgical Telementoring. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21, Article 662)*. Association for Computing Machinery, New York, NY, USA, 1–14.

[21] Jens Emil Grønbæk, Henrik Korsgaard, Marianne Graves Petersen, Morten Henriksen Birk, and Peter Gall Krogh. 2017. Proxemic Transitions: Designing Shape-Changing Furniture for Informal Meetings. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 7029–7041. https://doi.org/10.1145/3025453.3025487

[22] Jens Emil Grønbæk, Majken Kirkegaard Rasmussen, Kim Halskov, and Marianne Graves Petersen. 2020. KirigamiTable: Designing for Proxemic Transitions with a Shape-Changing Tabletop. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3313831.3376834

[23] Jens Emil Sloth Grønbæk, Ken Pfeuffer, Eduardo Velloso, Morten Astrup, Melanie Isabel Sønderkær Pedersen, Martin Kjær, Germán Leiva, and Hans Gellersen. 2023. Partially Blended Realities: Aligning Dissimilar Spaces for Distributed Mixed Reality Meetings. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 456, 16 pages. https://doi.org/10.1145/3544548.3581515

[24] Anhong Guo, Ilter Canberk, Hannah Murphy, Andrés Monroy-Hernández, and Rajan Vaish. 2019. Blocks: Collaborative and Persistent Augmented Reality Experiences. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 3, 3 (Sept. 2019), 1–24.

[25] Pavel Gurevich, Joel Lanir, Benjamin Cohen, and Ran Stone. 2012. TeleAdvisor: a versatile augmented reality tool for remote assistance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 619–622.

[26] Carl Gutwin and Saul Greenberg. 2002. A Descriptive Framework of Workspace Awareness for Real-Time Groupware. *Comput. Support. Coop. Work* 11, 3 (Sept. 2002), 411–446.

[27] Steven Henderson and Steven Feiner. 2011. Exploring the benefits of augmented reality documentation for maintenance and repair. *IEEE Trans. Vis. Comput. Graph.* 17, 10 (Oct. 2011), 1355–1368.

[28] Jaylin Herskovitz, Yi Fei Cheng, Anhong Guo, Alanson P. Sample, and Michael Nebeling. 2022. XSpace: An Augmented Reality Toolkit for Enabling Spatially-Aware Distributed Collaboration. *Proc. ACM Hum.-Comput. Interact.* 6, ISS, Article 568 (nov 2022), 26 pages. https://doi.org/10.1145/3567721

[29] Donald M Hilty, Karan Randhawa, Marlene M Maheu, Alastair J S McKean, Richard Pantera, Matthew C Mishkind, and Albert "skip" Rizzo. 2020. A Review of Telepresence, Virtual Reality, and Augmented Reality Applied to Clinical Care. *Journal of Technology in Behavioral Science* 5, 2 (June 2020), 178–205.

[30] Xincheng Huang, James Riddell, and Robert Xiao. 2023. Virtual Reality Telepresence: 360-Degree Video Streaming with Edge-Compute Assisted Static Foveated Compression. *IEEE Transactions on Visualization and Computer Graphics* 29, 11 (2023), 4525–4534. https://doi.org/10.1109/TVCG.2023.3320255

[31] Hiroshi Ishii and Minoru Kobayashi. 1992. ClearBoard: a seamless medium for shared drawing and conversation with eye contact. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Monterey, California, USA) *(CHI '92)*. Association for Computing Machinery, New York, NY, USA, 525–532.

[32] Daisuke Iwai, Ryo Matsukage, Sota Aoyama, Tsuyoshi Kikukawa, and Kosuke Sato. 2018. Geometrically Consistent Projection-Based Tabletop Sharing for Remote Collaboration. *IEEE Access* 6 (2018), 6293–6302.

[33] Pascal Jansen, Fabian Fischbach, Jan Gugenheimer, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. 2020. ShARe: Enabling Co-Located Asymmetric Multi-User Interaction for Augmented Reality Head-Mounted Displays. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 459–471.

[34] Michal Joachimczak, Juan Liu, and Hiroshi Ando. 2017. Real-time mixed-reality telepresence via 3D reconstruction with HoloLens and commodity depth sensors. In *Proceedings of the 19th ACM International Conference on Multimodal Interaction* (Glasgow, UK) *(ICMI '17)*. Association for Computing Machinery, New York, NY, USA, 514–515.

[35] Sasa Junuzovic, Kori Inkpen, Tom Blank, and Anoop Gupta. 2012. IllumiShare: sharing any surface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 1919–1928.

[36] P KaewTraKulPong and R Bowden. 2002. An Improved Adaptive Background Mixture Model for Real-time Tracking with Shadow Detection. , 135–144 pages.

[37] Shunichi Kasahara and Jun Rekimoto. 2015. JackIn head: immersive visual telepresence system with omnidirectional wearable camera for remote collaboration. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology* (Beijing, China) *(VRST '15)*. Association for Computing Machinery, New York, NY, USA, 217–225. https://doi.org/10.1145/2821592.2821608

[38] Adam Kendon. 2010. Spacing and Orientation in Co-present Interaction. In *Development of Multimodal Interfaces: Active Listening and Synchrony: Second COST 2102 International Training School, Dublin, Ireland, March 23-27, 2009, Revised Selected Papers*, Anna Esposito, Nick Campbell, Carl Vogel, Amir Hussain, and Anton Nijholt (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 1–15. https://doi.org/10.1007/978-3-642-12397-9_1

[39] Dooyoung Kim, Jae-Eun Shin, Jeongmi Lee, and Woontack Woo. 2021. Adjusting Relative Translation Gains According to Space Size in Redirected Walking for Mixed Reality Mutual Space Generation. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. 653–660.

[40] Joel Lanir, Ran Stone, Benjamin Cohen, and Pavel Gurevich. 2013. Ownership and control of point of view in remote assistance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 2243–2252.

[41] Paulett Lara. 2020. The Hidden Dimension - Edward hall. (Aug. 2020). https://www.academia.edu/43785083/The_Hidden_Dimension_Edward_Hall

[42] Nicolas H Lehment, Daniel Merget, and Gerhard Rigoll. 2014. Creating automatically aligned consensus realities for AR videoconferencing. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 201–206.

[43] Germán Leiva, Cuong Nguyen, Rubaiat Habib Kazi, and Paul Asente. 2020. Pronto: Rapid Augmented Reality Video Prototyping Using Sketches and Enaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13.

[44] Paul Luff and Christian Heath. 1998. Mobility in Collaboration. In *Proceedings of the 1998 ACM Conference on Computer Supported Cooperative Work* (Seattle, Washington, USA) *(CSCW '98)*. Association for Computing Machinery, New York, NY, USA, 305–314. https://doi.org/10.1145/289444.289505

[45] Mille Skovhus Lunding, Jens Emil Sloth Grønbæk, Karl-Emil Kjær Bilstrup, Marie-Louise Stisen Kjerstein Sørensen, and Marianne Graves Petersen. 2022. ExposAR: Bringing Augmented Reality to the Computational Thinking Agenda through a Collaborative Authoring Tool. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22, Article 131)*. Association for Computing Machinery, New York, NY, USA, 1–14.

[46] Yuhao Ma, Joshua Ferguson, Kevin Jonaitis, Kyle Boos, and Donald Patterson. 2014. Collaborative Geometry-Aware Augmented Reality with Depth Sensors. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication* (Seattle, Washington) *(UbiComp '14 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 251–254. https://doi.org/10.1145/2638728.2638765

[47] Ryo Matsukage, Daisuke Iwai, and Kosuke Sato. 2015. Consistent desktop sharing based on document coordinate system for face-to-face online meeting. In *SIGGRAPH Asia 2015 Emerging Technologies* (Kobe, Japan) *(SA '15, Article 6)*. Association for Computing Machinery, New York, NY, USA, 1–2.

[48] Paul Milgram and Fumio Kishino. 1994. A Taxonomy of Mixed Reality Visual Displays. *IEICE Trans. Information Systems* vol. E77-D, no. 12 (12 1994), 1321–1329.

[49] Paul Milgram, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1994. Augmented reality: A class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies* 2351 (01 1994). https://doi.org/10.1117/12.197321

[50] Meredith Ringel Morris, Jarrod Lombardo, and Daniel Wigdor. 2010. WeSearch: supporting collaborative search and sensemaking on a tabletop display. In *Proceedings of the 2010 ACM conference on Computer supported cooperative work* (Savannah, Georgia, USA) *(CSCW '10)*. Association for Computing Machinery, New York, NY, USA, 401–410.

[51] Oleg R Musin. 1997. Properties of the Delaunay triangulation. In *Proceedings of the thirteenth annual symposium on Computational geometry* (Nice, France) *(SCG '97)*. Association for Computing Machinery, New York, NY, USA, 424–426.

[52] Michael Nebeling, Katy Lewis, Yu-Cheng Chang, Lihan Zhu, Michelle Chung, Piaoyang Wang, and Janet Nebeling. 2020. XRDirector: A Role-Based Collaborative Immersive Authoring System. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–12.

[53] Michael Nebeling and Katy Madier. 2019. 360proto: Making Interactive Virtual Reality & Augmented Reality Prototypes from Paper. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13.

[54] Michael Nebeling, Janet Nebeling, Ao Yu, and Rob Rumble. 2018. ProtoAR: Rapid Physical-Digital Prototyping of Mobile Augmented Reality Applications. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–12.

[55] Michael Nebeling, Shwetha Rajaram, Liwei Wu, Yifei Cheng, and Jaylin Herskovitz. 2021. XRStudio: A Virtual Production and Live Streaming System for Immersive Instructional Experiences. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21, Article 107)*. Association for Computing Machinery, New York, NY, USA, 1–12.

[56] Ohan Oda, Carmine Elvezio, Mengu Sukan, Steven Feiner, and Barbara Tversky. 2015. Virtual Replicas for Remote Assistance in Virtual and Augmented Reality. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 405–415. https://doi.org/10.1145/2807442.2807497

[57] Dan R. Olsen. 2007. Evaluating User Interface Systems Research. In *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology* (Newport, Rhode Island, USA) *(UIST '07)*. Association for Computing Machinery, New York, NY, USA, 251–258. https://doi.org/10.1145/1294211.1294256

[58] Sergio Orts-Escolano, Christoph Rhemann, Sean Fanello, Wayne Chang, Adarsh Kowdle, Yury Degtyarev, David Kim, Philip L Davidson, Sameh Khamis, Mingsong Dou, Vladimir Tankovich, Charles Loop, Qin Cai, Philip A Chou, Sarah Mennicken, Julien Valentin, Vivek Pradeep, Shenlong Wang, Sing Bing Kang, Pushmeet Kohli, Yuliya Lutchyn, Cem Keskin, and Shahram Izadi. 2016. Holoportation: Virtual 3D Teleportation in Real-time. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 741–754.

[59] Riccardo Palmarini, Iñigo Fernández Del Amo, Dedy Ariansyah, Samir Khan, John Ahmet Erkoyuncu, and Rajkumar Roy. 2023. Fast Augmented Reality Authoring: Fast Creation of AR step-by-step Procedures for Maintenance Operations. *IEEE Access* (2023), 1–1.

[60] L Paul Chew. 1989. Constrained delaunay triangulations. *Algorithmica* 4, 1 (June 1989), 97–108.

[61] Tomislav Pejsa, Julian Kantor, Hrvoje Benko, Eyal Ofek, and Andrew Wilson. 2016. Room2Room: Enabling Life-Size Telepresence in a Projected Augmented Reality Environment. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing* (San Francisco, California, USA) *(CSCW '16)*. Association for Computing Machinery, New York, NY, USA, 1716–1725.

[62] Thammathip Piumsomboon, Gun A Lee, Andrew Irlitti, Barrett Ens, Bruce H Thomas, and Mark Billinghurst. 2019. On the Shoulder of the Giant: A Multi-Scale Mixed Reality Collaboration with 360 Video Sharing and Tangible Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–17.

[63] Kazuki Takashima, Takafumi Oyama, Yusuke Asari, Ehud Sharlin, Saul Greenberg, and Yoshifumi Kitamura. 2016. Study and Design of a Shape-Shifting Wall Display. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 796–806. https://doi.org/10.1145/2901790.2901892

[64] Franco Tecchia, Leila Alem, and Weidong Huang. 2012. 3D helping hands: a gesture based MR system for remote collaboration. In *Proceedings of the 11th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry* (Singapore, Singapore) *(VRCAI '12)*. Association for Computing Machinery, New York, NY, USA, 323–328.

[65] Balasaravanan Thoravi Kumaravel, Fraser Anderson, George Fitzmaurice, Bjoern Hartmann, and Tovi Grossman. 2019. Loki: Facilitating Remote Instruction of Physical Tasks Using Bi-Directional Mixed-Reality Telepresence. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 161–174.

[66] Peng Wang, Shusheng Zhang, Xiaoliang Bai, Mark Billinghurst, Weiping He, Mengmeng Sun, Yongxing Chen, Hao Lv, and Hongyu Ji. 2019. 2.5DHANDS: a gesture-based MR remote collaborative platform. *Int. J. Adv. Manuf. Technol.* 102, 5 (June 2019), 1339–1353.

[67] Haijun Xia, Sebastian Herscher, Ken Perlin, and Daniel Wigdor. 2018. Spacetime: Enabling Fluid Individual and Collaborative Editing in Virtual Reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 853–866.

[68] Robert Xiao, Scott Hudson, and Chris Harrison. 2017. Supporting Responsive Cohabitation Between Virtual Interfaces and Physical Objects on Everyday Surfaces. *Proc. ACM Hum.-Comput. Interact.* 1, EICS (June 2017), 1–17.

[69] Leonard Yoon, Dongseok Yang, Choongho Chung, and Sung-Hee Lee. 2021. A Full Body Avatar-Based Telepresence System for Dissimilar Spaces. arXiv:2103.04380 [cs.HC]

[70] Leonard Yoon, Dongseok Yang, Jaehyun Kim, ChoongHo Chung, and Sung-Hee Lee. 2022. Placement Retargeting of Virtual Avatars to Dissimilar Indoor Environments. *IEEE Transactions on Visualization and Computer Graphics* 28, 3 (2022), 1619–1633. https://doi.org/10.1109/TVCG.2020.3018458

[71] Jacob Young, Tobias Langlotz, Steven Mills, and Holger Regenbrecht. 2020. Mobileportation: Nomadic Telepresence for Mobile Devices. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 2, Article 65 (jun 2020), 16 pages. https://doi.org/10.1145/3397331

[72] Kevin Yu, Alexander Winkler, Frieder Pankratz, Marc Lazarovici, Dirk Wilhelm, Ulrich Eck, Daniel Roth, and Nassir Navab. 2021. Magnoramas: Magnifying Dioramas for Precise Annotations in Asymmetric 3D Teleconsultation. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. 392–401.

[73] Fengyuan Zhu and Tovi Grossman. 2020. BISHARE: Exploring Bidirectional Interactions Between Smartphones and Head-Mounted Augmented Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–14.

[74] Jakob Zillner, Christoph Rhemann, Shahram Izadi, and Michael Haller. 2014. 3D-board: a whole-body remote collaborative whiteboard. In *Proceedings of the 27th annual ACM symposium on User interface software and technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 471–479.

[75] Z Zivkovic. 2004. Improved adaptive Gaussian mixture model for background subtraction. In *Proceedings of the 17th International Conference on Pattern Recognition, 2004. ICPR 2004.*, Vol. 2. 28–31 Vol.2.