Mini-Me: An Adaptive Avatar for Mixed Reality Remote Collaboration

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Figure 1. Mini-Me Concept: (a) MR view through the HoloLens of a remote VR user's Mini-Me avatar standing on a table and a life-size avatar standing on the right, both avatars gaze toward the same place and point at the same target with gaze and pointing of the Mini-Me avatar redirected, (b) A male (VR user) and a female (AR user) avatars in VR, (c) Design features of the Mini-Me avatar, (d) The local AR user moving a tea box, (e) + (f) The remote VR user is pointing at a box and the Mini-Me in the AR user's FOV has its gaze and pointing gesture redirected to the same box (g) A remote VR user is pointing.

ABSTRACT
We present Mini-Me, an adaptive avatar for enhancing Mixed Reality (MR) remote collaboration between a local Augmented Reality (AR) user and a remote Virtual Reality (VR) user. The Mini-Me avatar represents the VR user's gaze direction and body gestures while it transforms in size and orientation to stay within the AR user's field of view. A user study was conducted to evaluate Mini-Me in two collaborative scenarios: an asymmetric remote expert in VR assisting a local worker in AR, and a symmetric collaboration in urban planning. We found that the presence of the Mini-Me significantly improved Social Presence and the overall experience of MR collaboration.

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INTRODUCTION
This paper explores how adaptive avatars can improve Mixed Reality (MR) remote collaboration. MR is a technology that seamlessly bridges real and virtual worlds. In the near future, MR collaboration between users in the real world using Augmented Reality (AR) and remote users in Virtual Reality (VR) may be commonplace. A MR remote collaboration involves a local AR user sharing their real-world information with a remote VR user, such as the reconstructed task space necessary for spatial awareness and understanding. Like any remote collaborative systems, one of the main goals of MR collaboration is to enable people to feel co-present. AR and

VR technology naturally immerse the users in three-dimensional spaces, bringing us closer to achieving this goal. However, MR technology has the potential to enhance collaboration beyond what people can normally do face-to-face. This is the primary motivation of our research.

In a virtual environment, the user's remote embodiment is commonly represented by a graphical persona, or avatar, which creates an illusion to both the user and the collaborator of being present in the environment and co-present with their partner. In MR systems, remote collaborators have been represented in the local user's real space, as 2D video avatars [22], virtual characters[5, 38], volumetric video [18, 35, 36, 52], or 3D reconstructions [27, 34]. We are interested in exploring novel methods for representing the user in MR that deviates from these virtual embodiments of past research. In this paper, our focus is to improve the local AR user's experience of collaborating with a remote VR user.

We propose Mini-Me, an adaptive avatar, which dynamically pursues the AR user's gaze, adapts to the surface geometry being projected on in the AR user's field of view (FOV), and mimics the VR user with redirected gaze and gestures to consistently gaze and point at the same location in shared space. It is an extension to the common representation of a VR user's life-size avatar, of which the life-size avatar is statically fixed to the VR user's position in space. We demonstrate that Mini-Me can enhance MR collaboration supporting shoulder to shoulder collaboration with better shared perspective and improving the sense of co-presence. It also alleviates some of the main issues of AR users in MR collaboration, such as keep tracking of a VR user's movement when they use teleportation as a travel method, and being aware of VR user's communication cues when they are out of the limited FOV, which is an important problem of AR optical see-through head mounted displays (OST-HMD) such as the Microsoft HoloLens, whose FOV is approximately 30x17º.

The main novel contributions of the paper are:

- Concept, design, and implementation of the Mini-Me, a novel adaptive avatar with redirected gaze and gestures for enhancing remote MR collaboration.
- Findings from a user study (n=16), evaluating the impact of the Mini-Me on Social Presence, task difficulty, and mental effort for two collaborative scenarios.
- Discussion of the implications for future MR collaborative interface design.

RELATED WORK

Our work combines and extends earlier research in MR collaboration, remote embodiment in collaborative systems, and gaze redirection for virtual embodiment. In this section, we review key papers from this earlier work and describe the novel research contribution we are making.

Collaboration in Mixed Reality

MR collaborative systems combine AR and VR technologies to leverage the strengths of each platform [37]. Collaborative experiences in AR or VR are relatively common, but there are fewer interfaces that support collaboration between both AR and VR views. One of the earliest was Kiyokawa's system [21] which allowed users to easily move between VR and AR views. The MagicBook interface [7] allowed a user to fly inside a 3D scene and experience it from an ego-centric view in immersive VR, while a second user provided guidance from an AR version of the scene using an exo-centric viewpoint. Similarly, Grasset et al. [14] reported on a navigation task where one user looks down upon a virtual maze from an AR exocentric viewpoint, and helps a partner, in a VR egocentric view, finding their way out. They found that navigation assistance improved task performance, but no benefit of AR over VR for the exocentric view. The Vishnu interface [25] supported collaboration between an expert in a VR display and a local worker in a video see-through AR system, where the expert uses virtual gestures to help the AR user complete a real world task. Oda et al. [32] developed a system in which an expert user in VR could use pointing and virtual object manipulation to help an AR user complete an object assembly task

In these examples both the AR and VR users were using head mounted displays (HMDs). However, there are also other display configurations that support MR collaboration. For example, Stafford et al. [44] used a tabletop display to provide an exo-centric view for collaboration with an AR user in an outdoor setting. The tabletop user could add virtual cues to guide the AR's user navigation. Sun et al. [5] developed a system where a remote expert using desktop VR could similarly provide virtual cues to a second user wearing a see-through AR display. Tait and Billinghurst [45] developed another similar system where a desktop user placed 3D copies of real objects in a remote user's AR view to help complete an object placement task. In this previous work, we found several systems that use AR or VR viewpoints to support different collaborative roles, often a remote expert supervising another user performing a real-world task.

Previous systems also showed the importance of awareness cues, such as virtual pointers [12, 15, 32], and hand gestures [42] to support effective communication. For example, the MagicBook interface [7] represented the perspective of each collaborator with a virtual head.

Recently, several researchers have explored sharing richer cues in collaboration between MR spaces. Le Chénéchal et al. [24] developed a MR system in which an expert user in VR shares viewpoint and gesture cues with an AR user in order to help them complete a real world task. Similarly, the work of Oda et al. [32] uses shared gesture and pointing cues between an expert in VR and worker in AR to help with assembly tasks. Holoportation [34] uses a real-time capture technique to render reconstructed people or objects that can be visualized in MR, and Room2Room [36] uses projected AR to recreate a life-size virtual person into the remote space. There is also research that focuses on enhancing the collaboration through highlighting the visual and audio cues that catch AR user's attention to improve the task performance, such as Halo [4] and CoVAR [39]. However, it was found that these awareness cues could also alter user's social behavior and possibly lost some of the important social cues such as facial expression or body gestures [37]. On the contrary, our research focuses on developing an adaptive avatar to enhance a room scale MR collaboration. We designed our avatar in such a way that it can be used in conjunction with the other awareness cues yet help maintain these natural social cues.

Remote Embodiment

Embodiments are virtual representations that provide awareness [16] of a collaborator's activities by representing physical states, such as location, pose, movement or hand gestures. An early example is the Telepointer [15] which replicated the motions of a remote user's cursor in a shared desktop workspace. Several techniques were developed for sharing information about the state of users' limbs (arms [11, 46, 47], hands [42, 48, 50] or feet [1]) in various remote collaboration platforms.

In order to convey gesture over distance, Tang et al. [46] captured live images of arms working above a touch surface, and displayed them on a remote shared tabletop display. Although providing gesture in remote collaboration, one limitation of such systems is that the captured hands or arms are 2D, and so appear flat without any depth information. Several systems have captured users' hands in 3D, to provide information about depth and spatial relationships, and share hand embodiments through mobile AR [42], or a HMD in AR [50] or VR [3, 48]. Virtual embodiments have also been applied in MR collaborative systems using tabletop displays combined with AR [44] or VR [43]. In cases where objects cannot easily be indicated by hand gestures, researchers have explored alternative object referencing techniques such as raycasting [12], or virtual reconstruction of a selected scene region [33]. Also, recent work in telepresence has demonstrated lifelike full-body reconstructions of distant persons, placed in a local environment, and viewed through AR [27, 34, 36].

This previous research shows that adding a representation of the user's body can improve collaboration in shared AR and VR experiences. They increase Social Presence, enable people to use natural non-verbal communication cues, and support shared interaction with the virtual content in the space. Our research builds on this work by using the remote embodiment in the MR collaboration and applying these cues such as a pointing ray.

Re-directed Gaze and Miniaturization for Virtual Embodiment

Borland et al. [8] proposed a technique for animating self-avatar eye movements in an immersive virtual environment without the use of eye-tracking hardware. This work inspired us to consider redirected gaze for our adaptive avatar. Recent research [20], explored methods for redirecting gaze of virtual avatars in distributed augmented reality (AR) meetings. In terms of miniaturization, Prince et al. [40] demonstrated the use of a miniature avatar fixed in the real world to represent the remote collaborator to the AR user in an MR collaboration. Compared to earlier work, our research has the following novel aspects:

- We propose the Mini-Me, an adaptive avatar with redirected gaze and gestures, designed to maintain non-verbal communication cues in a remote MR collaboration.
- We present a user study that evaluates our adaptive avatar in both asymmetric and symmetric remote MR collaboration scenarios with a room scale reconstruction.

The focus of our research is on the benefits of presenting an adaptive avatar in a MR collaboration to provide non-verbal communication cues of the collaborator. In the next section, we describe the concept, design, and implementation of the Mini-Me and then report on a user study evaluating the benefits of the Mini-Me.

MINI-ME: DESIGN AND IMPLEMENTATION

From past research, a number of problems had been identified. To address some of the issues that the AR user faces in a remote MR collaboration, we came up with the requirements for designing our adaptive avatar as shown in Table 1. We created an adaptive avatar, Mini-Me, to improve the local AR user's awareness of non-verbal communication cues from the remote VR user. The Mini-Me is an extension to the VR user's life-size avatar and both avatars can co-exist in the MR environment. The Mini-Me is only visible to the local AR user and its actions are automated so it does not add any concerns to the VR user. We designed and implemented the Mini-Me to meet the design requirements with seven features listed in Table 1.

In this section, we describe the technical details of solutions and design alternatives we investigated for implementing the Mini-Me. We developed our MR system and the Mini-Me using Unity game engine version 2017.1.0p4. For the AR side, we implemented the Mini-Me on the Microsoft HoloLens which provided spatial mapping capability and an optical see-through display. For the VR user, we use the HTC Vive for their room scale tracking capability. The two spaces are aligned based on the Vuforia Image Target technology [49]. Once the HoloLens detects the image target, it sends the transformation data to the VR side, which applies the transformation to the tracking space of the VR user.

Problem Statements	Design Requirements	Design Solution (Avatar's Features)
P1) Past research [4, 39] indicates that limited FOV of the OST-HMD is one of the fundamental limitations of the current MR experience. This may affects the sense of co-presence in a remote collaboration between AR and VR users.	*R1)* The local AR user should be able to locate and see the adaptive avatar easily, with the visibility of the avatar's face and upper-body at least. The avatar must not make a sudden movement that might startle or interfere with the AR user's focus.	*F1)* Adaptive Transformation: The Mini-Me is automatically translated, rotated, and scaled with respect to the AR user's position and gaze. The transformation considers the AR display's field of view (FOV) and the distance between the gaze target and the user.
P2) Environment awareness or spatial understanding is a crucial feature in MR that seamlessly merges the virtual content into the real-world [30]. MR interfaces should support this feature for better naturalness and intuitiveness.	*R2)* The adaptive avatar should be oriented appropriately on the projected surface in the environment.	*F2)* Adaptive Surface Projection: The Mini-Me adapts itself on different surfaces e.g., the user can see the full-body of the Mini-Me when it is standing on the floor or a table, or its upper-body when it is next to a wall or a shelf.
P3) Non-verbal cues, such as facial expressions and body gestures, are crucial for achieving effective communication [40]. It is important to provide these cues to the collaborators.	*R3)* By looking at the adaptive avatar, the AR user should be able to tell when and where the remote VR user is looking and pointing. The avatar's pose should be natural and not uncanny.	*F3)* Redirected Gaze and Gestures: The Mini-Me looks or points at the same place that the remote VR user (and his life-size avatar) is looking or pointing.
		F4) Pointing Ray: A ray is cast from the Mini-Me's index finger to indicate the pointed target.
P4) The transitions during an approach or a departure are essential social conventions and the avatar should also behave accordingly [10].	*R4)* The adaptive avatar should inform the user as it approaches/enters/exits the AR user's vision.	*F5)* Proximity Aura: The Mini-Me has a soft blue glow around the body, allowing the user to see the glow before the Mini-Me enters the AR user's FOV.
P5) The user should be able to identify the relative location of their collaborator in the shared MR space [39].	*R5)* The adaptive avatar should indicate where the remote VR user is located.	*F6)* Ring Indicator: A blue ring at the feet of the Mini-Me points towards the direction where the VR user (or their life-size avatar) is located.
P6) It should be easy to distinguish the adaptive avatar from the life-size avatar. Our system allows the VR user to scale up/down, therefore, it can be difficult to distinguish between them when the VR user is in the miniature mode [39].	*R6)* The AR user should be able to easily distinguish between the adaptive avatar and the life-size avatar.	*F7)* Toon Shaded: To help the AR user distinguish the Mini-Me from the life-size avatar and to improve the saliency of the Mini-Me through an OST-HMD, we apply a toon shader to the Mini-Me.

Table 1: The problem statements, design requirements, and design solution for our Mini-Me adaptive avatar.

Adaptive Transformation (F1)

To address *R1* (see Table 1), we experimented with several solutions of where the Mini-Me could be located in the AR user's vision and space. We implemented a version where the Mini-Me was always positioned in front of the AR user at the gaze location in the environment, but found that it could be distracting to the user to always see the avatar directly in front of them. Next, we had a version that the Mini-Me was positioned to one side of the display at a fixed distance from the user's view, and found this better than the first version. However, it did not take advantage of the user's environment and occupied a portion of the display space like a heads-up display (HUD).

In our final implementation, we took the surface properties of the area where the user is gazing into consideration. The Mini-Me scaling factor is calculated by finding the distance between the AR user's head position and the gaze point projected onto the surface plane, divided by the maximum distance that the Mini-Me could adapt its scale (three meters in our case). This ratio was clamped with a scaling threshold (between 5-50% of the original life-size avatar). Finally, the Mini-Me's position and orientation are determined by an adaptive surface projection algorithm explained in F2.

Adaptive Surface Projection (F2)

For *R2*, the Mini-Me adapts its transformation based on the surface gazed at. We considered the surface geometry [13] by examining the normal vector of the surface at the gaze point and its neighbor points within a pre-defined radius to predict the type of surface. For example, when the AR user gazes at the whiteboard (a vertical plane), the Mini-Me will position itself in front of the whiteboard. If the surface is a large flat horizontal plane, such as a floor or a tabletop, the Mini-Me will stand on top of this plane and behind the AR user's gaze point. However, if the surface is irregular, the Mini-Me uses its default pose, standing behind the gaze location. Regarding its body orientation, the Mini-Me is oriented toward the mid-point between the AR user's location and the VR user's gaze point. This allows the Mini-Me to turn its head naturally to look back and forth at the AR user's face and the VR user's gaze location.

Redirected Gaze and Gestures + Pointing Ray (F3, F4)

To achieve *R3*, we apply inverse kinematics to the Mini-Me's humanoid rigged character. The Mini-Me's avatar head is redirected to always look toward the VR user's gaze location. The Mini-Me's orientation, calculated in *F2*, accounts for this, and orients the Mini-Me's body to look natural by interpolating between the AR user's position and the VR user's gaze location (see Figure 2a and 2b). The poses of the Mini-Me's arms are calculated from the VR

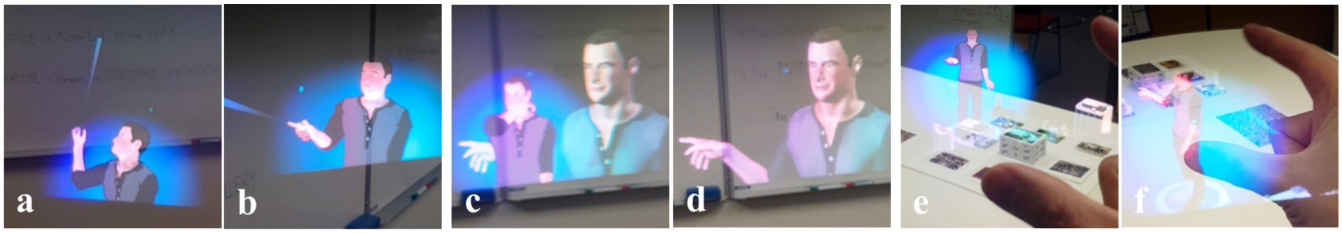

Figure 2: The AR user views the Mini-Me from two different perspectives showing Mini-Me consistently gazing and pointing at the same location: a) in front of the whiteboard, b) side view of the whiteboard, c) As the AR user gazes at the remote VR user's life-size avatar, the Mini-Me moves toward this avatar and d) fuses with it and disappears, e) AR user can gaze at the Mini-Me and perform an air-tap to pin it in place or f) Tap again to unpin it from that location.

user's tracking information, where inverse kinematics is applied to the avatar's shoulders, elbow, and wrist joints depending on the relative transformation between the hand-held VR controllers and the VR HMD. Pointing is a common feature supported in a collaborative/social VR application [2, 31]. When the VR user is pointing (by holding down a trigger button on the controller), the redirected pointing mechanism takes control of Mini-Me and enables the pointing animation with its own inverse kinematics to make the Mini-Me's arm point at the position where the VR user is pointing at. In addition to animating the arm, a ray is cast from the index finger of the Mini-Me's pointing hand towards the pointing target. The VR user sees their own ray cast from their life-size avatar's hand. We applied this feature to the Mini-Me to improve the precision and eliminate the ambiguity in pointing.

Proximity Aura (F5)

Buxton [10] suggests that social conventions of transitions such as approach and departure, are important in collaborative systems. The collaborator should not abruptly enter or depart, violating normal social conventions of approach. To address this, the Mini-Me enters and departs the AR user's FOV gracefully with a cue to indicate its approach. We normally rely on our peripheral vision and spatial sound to sense the direction of approach. Our focus is to enhance the visual cue and to achieve this, we propose a proximity aura, a soft blue glow that emanates from the Mini-Me. In contrast to previous research such as Halo [4], which indicated the proximity and direction of an off-screen point of interest, our proximity aura provided an indicator as the Mini-Me enters/exits the user's FOV. This gives the AR user an extra cue as the Mini-Me approaches. The proximity aura works well even for a display with limited FOV such as the HoloLens. The glow effect is always enabled as we found during pilot tests that turning the effect on and off frequently becomes distracting with the small FOV of the HoloLens, hence we decided to provide a constant glow for consistency.

Ring Indicator (F6)

To improve the AR user's awareness of the remote VR user's location as they teleport from one place to another, we designed a ring-shaped indicator that points to the direction of the VR user. This has a non-obtrusive minimal design addressing *R5*. Through pilot tests, we found that the ring indicator helped in identifying the VR user's position after teleportation.

Toon Shaded (F7)

A see-through display such as the HoloLens, is susceptible to environmental lighting. To overcome this problem, we applied a toon shader to the Mini-Me avatar with an unlit material and a dark outline around the model, improving its saliency and for the user to be able to distinguish it from the remote VR user's avatar. We chose a toon shader as it provides good contrast making it more visible on an OST-HMD display, and also distinguishable from the life-size avatar of VR users who can intentionally scale themselves down into miniature size, as well. This multi-scale collaboration is another feature of our AR/VR collaborative system, which is discussed in the section called "Snow Dome: An Application of VR User Transformation".

INTERACTING WITH THE MINI-ME

Enabling/Disabling the Mini-Me

The Mini-Me can be enabled or disabled by the AR user performing an "air-tap", a selection method on the HoloLens, while looking at the VR user's life-size avatar. When the Mini-Me is enabled, as the user gazes away from the VR user's avatar, the Mini-Me avatar emerges from the life-size avatar and starts following the AR user's gaze. As soon as the AR user gazes at the VR user's life-size avatar, the Mini-Me returns to the life-size avatar and disappear as if they fuse together (see Figure 2c and 2d).

Pinning the Mini-Me

The AR user can pin the Mini-Me in space by performing an air-tap gesture while looking at the Mini-Me's body. When the Mini-Me is pinned, it stays fixed in place and does not follow the user's gaze anymore. The user can tap again to unpin it (see Figure 2e and 2f). This feature is useful when the user has a fixed task space that best utilizes the Mini-Me avatar by positioning it in one place.

Embodying the Mini-Me

If needed, the VR user can scale himself into different sizes, either into a miniature or a giant. This could work as if embodying the Mini-Me avatar in certain cases where the Mini-Me avatar would be replaced by a scaled-down version of a life-size avatar as the VR user miniaturizes and teleports to where the Mini-Me avatar is. Yet as the AR user looks away from this avatar, Mini-Me will re-appear as

Figure 3: a) Scaled down VR user's perspective seeing the AR user as a giant, b) VR user shrunk down interacting inside the miniature dome, c) VR user is a giant looking down at the AR reconstructed space, d) The real experimental space for the AR user, and e) its virtual reconstruction for the VR user

the miniaturized VR user's avatar moves out of the AR user's FOV. Figure 3 shows an example of this with an application named "Snow Dome," a remote MR collaboration application that demonstrates how AR and VR collaboration can be enhanced with multi-scale interaction. The VR user can change their perspective by scaling up into a giant or down to a miniature. When they scale down, the VR user's virtual viewpoint initially snaps to the current Mini-Me's location. The Mini-Me is still independent of the VR user and only its transformation is used by the VR user's avatar. We support this feature because it can be useful to instantly be in front of the AR user's task space as shown in Figure 3a. In Snow Dome, the VR user is placed in a reconstructed space of the AR user. A virtual miniature dome is situated on top of a table in the room. Any virtual objects entering the dome shrink into a miniature size, and as they exit the dome, they enlarge again. The VR user can shrink down and teleport into the dome to interact with the miniature objects as shown in Figure 3b. Alternatively, the VR user can enlarge into a giant and interact with the reconstructed space as if the AR user is miniaturized (Figure 3c).

USER STUDY

We conducted a two-part user study to evaluate the Mini-Me against the *baseline* condition in terms of Social Presence and usability. In the *baseline* condition, a life-size full-body avatar is presented at the actual location where the remote user is at in the shared space. The condition also provides an additional cue when the remote user is pointing; a ray is cast from the avatar's hand to the pointing target. In the Mini-Me condition, in addition to a life-size full-body avatar, as the local user looks away from the remote VR user's life-size avatar, the Mini-Me avatar emerges from this avatar as an additional cue. As the remote user points at a target, a ray is cast from the Mini-Me avatar's hand instead of the life-size avatar. Both conditions included verbal communication. All the participants participated in the AR user role using a Microsoft HoloLens, while an actor played the role of remote VR user. The user study took approximately one hour to complete for each participant.

Study Design

The experiment was a within-subject design where we investigated the effects of providing the Mini-Me avatar to the local AR user. The independent variable was the presence of the Mini-Me avatar forming two conditions: present (*Mini-Me*) or absent (*Baseline*). As dependent variables, we measured Social Presence and usability. After each condition, participants answered a questionnaire based on Networked Mind Measure of Social Presence [17], and in terms of usability, Single Ease Question (SEQ) [41] and the Subjective Mental Effort Question (SMEQ) [51]. The experiment consisted of two parts with different task scenarios. At the end of each part of the study, we also collected a post-task questionnaire for user preferences and subjective feedback. In the first part of the study, we also recorded the task completion time to compare the performance difference between the two conditions.

Setup

We divided our experimental space into two separate rooms using a physical divider. The local AR user side was furnished to replicate a workspace, while the remote VR user side was empty. For reconstructing the physical environment on AR user side, we used the HoloLens Image-based Texturing software to create the spatial map and captured texture images. Figure 3d and 3e show the original AR space and the result of the reconstruction showed to the VR user. The hardware equipment used in this study was: VR Side - an HTC Vive driven by a Windows 10 laptop computer (Intel Core i7-6700HQ at 2.6 GHz, 16 GB RAM, and NVIDIA GeForce GTX 1070); AR Side - Microsoft HoloLens. The two sides were networked using a 1GB WLAN. Videos were recorded in each trial using a DSLR camera on the AR user side, and the VR user's view was screen recorded.

Participants

We recruited 16 participants from the local campus community (5 female and 11 male) with an average age of 28.44 (SD=5.766). Their familiarity with AR or VR interfaces was high (M=5.63, SD=0.78, measured on a 7-point Likert scale from 1 to 7). We recruited participants with some experience with AR or VR to reduce the impact of novelty effect on the subjective ratings. Most participants used AR or VR interfaces a few times a week (n=7) or a few times a month (n=6). The participants participated as a local AR user, while the actor was in VR.

Tasks and Procedures

The study was divided into two different use case scenarios to evaluate the Mini-Me with both asymmetric and symmetric tasks. In the first scenario, called "Tea Party," we mimicked a scenario for displaying products in a retail store with the AR user being a local worker and the VR user being

Figure 4. *Baseline* condition illustrating how the remote VR user's avatar look through a HoloLens. (a-d) Tea Party task (a) VR user asks the AR user to pick up a tea box (b) the AR user follows the pointing ray from the avatar's hand to a correct tea box with a virtual replica overlaid on the physical box (c) VR user points at the shelf to place the box (d) AR user adjusts the orientation of the box as the VR user instructs (e-h) Urban Planner task (e) VR view showing VR and AR users sitting side by side (f) AR user looks at the VR user's avatar (g) VR user is pointing at the building at the top while AR user is pointing at the one at the bottom (h) AR user looks at a physical model that the VR user is pointing. The gaze cursors of both users can be seen here.

a remote helper. This scenario exhibited asymmetric collaboration, as the users had different roles. Past research had demonstrated a similar task in their evaluation of a MR collaboration [19]. In the second part, we created and used a logic puzzle game called "Urban Planner," inspired by past research in MR collaboration [6]. This simulated an urban planning task where both users worked as equal collaborators, and depicted a symmetric collaboration task, in which both users had more equal roles to play than the Tea Party task. In both tasks, an actor played the VR user. The same actor was employed for all tasks and participants to ensure the presentation of the Mini-Me adaptive avatar was as consistent as possible across all participants. The tasks in both scenarios were randomized and never repeated so that our actor could not anticipate the task.

The order of the two conditions, the *Mini-Me* and the *Baseline*, were counter-balanced for each task. At the beginning of each condition, the experimenter explained the difference of each condition in the presence or absence of the Mini-Me avatar. After each condition, the participants were asked to rate the task difficulty using SEQ on a 7-point Likert scale (1: Very Difficult ~ 7: Very Easy), SMEQ (0 ~ 150: 0=Not at all hard to do) and Social Presence questionnaire with a 7-point Likert scale (1: Strongly Disagree ~ 7: Strongly Agree). For the post-task questionnaire, they were asked for their preferred condition and the reason for the preference.

Study Part 1: Tea Party (Asymmetric Collaboration)

In the Tea Party task, participants had a role of the local AR user following the VR user's instruction for where to place tea boxes on one of the two display shelves. At the beginning of each trial, there were six different tea boxes placed on a table at the center of the experimental space. The remote VR helper instructed the local AR worker to pick up one of the tea boxes and asked them to place it onto one of the shelves. There were two shelves, one on the left side of the room and another on the right. Since the VR user was immersed in a static reconstructed space, we used the front face of each tea box as a tracking target to update the position and orientation of the box in the virtual environment. We used the Vuforia Image Target technology [49] for tracking. A virtual replica of the tea boxes was shown to both users, so that the AR user was aware of what the VR user could see (see Figure 4).

For each trial, the VR user (an actor) saw a random target placement appearing for each tea box. This was to avoid a learning effect of the instructor, so one could not anticipate the order and placement location. The VR user was given enough space to walk around the virtual shared space from one shelf to another. However, we disabled the teleporting feature so that the AR user could keep track of their current location without discontinuity. Although, these factors would not have a direct impact on our dependent variables, we were vigilant and tried to limit any confounding factors. The participants were given one practice trial for each condition. We recorded the task completion time for each trial. Each participant had three trials for each condition, a total of six trials for both conditions.

Study Part 2: Urban Planner (Symmetric Collaboration)

To simulate a collaboration around a meeting table, we looked to past research in MR collaboration [9, 29]. Two application domains stood out, urban planning and board games. We recreated a collaborative logic puzzle [6] where the two scenarios were combined. This task involved placing nine buildings on a 3x3 street grid. We created a board with nine cut out squares. We attached a unique image on each square corresponding to the building it represented. The images were used for Vuforia Image Target for 6 DOF tracking. All nine buildings had virtual representations that both users shared. One of the buildings had an actual paper model attached on the square with the image target on top. This was to give an example to participants of how a Tangible User Interface could be used in MR collaboration, mixing real and virtual objects together (see Figure 4).

To solve the puzzle, the buildings must be placed to satisfy given rules. For each condition, there was a set of ten rules, and each user was given five rules, so they needed to collaborate. The rules were not contradictory and included statements such as "The MALL is east of the WAREHOUSE", "The HOTEL is between the GALLERY and the PARK". For every condition, a new set of rules were created with similar level of difficulty so that the actor did not know the solution to the puzzle. For this task, we had participants seated in front of the table facing the whiteboard where the rules were written. For the AR user, the rules were physically written on the whiteboard, and for the VR user, the rules were virtual text overlaid on the whiteboard. They could freely use speech and gestures to collaborate. The actor was also seated, and his life-size avatar positioned at the right side of the AR user. The two users were positioned side by side sharing the same perspective of their task space, as if they were sitting next to each other at a meeting table. During the pilot tests, we found that time taken was primarily influenced by the participants' level of experience in solving logic puzzle rather than the interface provided in each condition. We anticipated this, hence did not enforce any time constraint for this task. On average, the task took approximately five to ten minutes to complete.

Results

We present the analysis of the results from both objective and subjective data. Subjective data included a Social Presence questionnaire, usability (i.e. SEQ, and SMEQ), and qualitative feedback for each condition. For the objective data, task completion time was collected in the first part of the study to check for any performance difference with a total of 2 (conditions) x 3 (trials per condition) x 16 participants = 96 data points. For the subjective data, we collected 2 (conditions) x 2 (tasks) x 16 participants = 64 data points. We also collected a post-task preference and overall feedback, which contributed another 2 (tasks) x 16 participants = 32 data points.

Objective Data

Task Completion Time: *Part 1* - We calculated the time taken by participants to place all the six tea boxes correctly on the shelf following actor's instruction (see Figure 4). A Shapiro-Wilk test found our data not following normal distribution (*Baseline*: W=0.929, p=0.006, *Mini-Me*: W=0.908, p=0.001). Hence, we used a Wilcoxon Signed Rank (WSR) test (α=0.05) with continuity correction and found the Mini-Me took significantly less time to complete the task compared to *Baseline* (V = 859, p=0.005). The plot is shown in Figure 5. *Part 2* - We did not enforce a time constraint for this puzzle solving task.

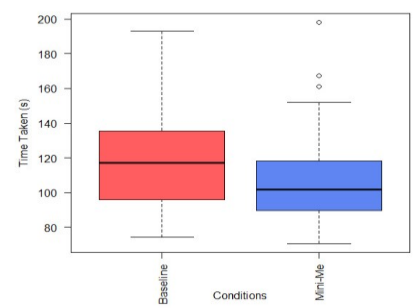

Figure 5. Task completion time.

Subjective Data

We used a Wilcoxon Signed Rank test (α=0.05) to analyze the questionnaire results.

Task Difficulty (SEQ): *Part 1* - We found that tasks performed with the Mini-Me were rated significantly easier than *Baseline* in the asymmetric collaboration (V=73.5, p=0.006), see Table 2. *Part 2* - We did not find significant difference between the two conditions for the symmetric collaboration.

Subjective Mental Effort Questionnaire (SMEQ): *Part 1* - It was found that the Mini-Me condition required significantly lower mental effort than the *Baseline* (V=10, p=0.025), see Table 2. *Part 2* - We did not find significant differences for SMEQ in the part two of the study.

Enjoyment and Level of Focus on the Task: *Part 1* - We did not find any significant differences in terms of enjoyment and level of focus, while the overall ratings were positive for both conditions. *Part 2* - We found significantly higher levels of focus with the Mini-Me present (V=41.5, p=0.024) but no significant difference was found for enjoyment.

Social Presence: The Social Presence questionnaires included three sub-scales: Co-Presence (*CP*), Attentional Allocation (*AA*), and Perceived Message Understanding (*PU*). We also combined the three categories into a single score, Aggregated Social Presence Score (*AS*). We checked the internal consistency with Cronbach's alpha for *Part 1: Mini-Me* – α_{AS} = 0.77 (α_{CP} = 0.81, α_{AA} = 0.71, α_{PU} = 0.86), *Baseline* – α_{AS} = 0.89 (α_{CP} = 0.86, α_{AA} = 0.78, α_{PU} = 0.93), and *Part 2: Mini-Me* – α_{AS} = 0.95 (α_{CP} = 0.96, α_{AA} = 0.89, α_{PU} = 0.91), *Baseline* – α_{AS} = 0.89 (α_{CP} = 0.88, α_{AA} = 0.64, α_{PU} = 0.78). We found significant differences in favor of the Mini-Me for the overall *AS* in both *Part 1* (V=114.5, p=0.017) and *Part 2* (V=124, p=0.002). We also analyzed each sub-scale: *Part 1* - a significant difference found for *CP* (V=108.5, p=0.006) but no significant difference for *AA* and *PU*; *Part 2*

#	Statements	Cond	PART 1: Tea Party (Asymmetric Collaboration) Frequencies	Mean	SD	p	PART 2: Urban Planner (Symmetric Collaboration) Frequencies	Mean	SD	p
	Usability - Task Difficulty (SEQ)									
Q1	Overall, the task was… (Very Difficult … Very Easy)	*MM*		6.31	0.87	*0.006		5.06	1.44	0.301
		BL		5.44	0.96			4.44	1.55	
	Usability - Subjective Mental Effort Questionnaire (SMEQ)									
Q2	Based on the scale provided on Mental Effort (0 … 150)	*MM*		13.44	9.98	*0.025		31.25	17.18	0.134
		BL		21.19	16.65			39.31	20.30	
	Usability - Enjoyment and Level of Focus on the Task									
Q3	I enjoyed the experience.	*MM*		6.31	0.87	0.081		6.06	1.00	0.077
		BL		5.81	0.98			5.38	1.41	
Q4	I was able to focus on the task activities. (Strongly Disagree … Strongly Agree)	*MM*		6.38	0.81	0.135		6.19	0.66	*0.024
		BL		5.88	0.89			5.38	1.26	
	Social Presence									
	Aggregated Social Presence Scores from Q5 to Q14	*MM*	Cronbach's α = 0.77	6.03	0.57	*0.017	Cronbach's α = 0.95	4.57	1.32	*0.002
		BL	Cronbach's α = 0.89	5.33	0.99		Cronbach's α = 0.89	3.62	1.2	
	Co-Presence (Aggregated Scores from Q5 to Q7)		MM: Mean = 6.31 SD = 0.71, BL: Mean = 5.19 SD = 1.20				MM: Mean = 4.54 SD = 1.48, BL: Mean = 3.08 SD = 1.37			
Q5	I noticed my partner.	*MM*		6.38	0.81	*0.006		4.56	1.50	*0.003
		BL		5.19	1.47			2.94	1.65	
Q6	My partner's presence was obvious to me.	*MM*		6.19	0.98			4.44	1.71	
		BL		4.94	1.44			2.94	1.57	
Q7	My partner caught my attention. (Strongly Disagree … Strongly Agree)	*MM*		6.38	0.72			4.63	1.36	
		BL		5.44	1.15			3.38	1.36	
	Attentional Allocation (Aggregated Scores from Q8 to Q10)		MM: Mean = 5.71 SD = 1.16, BL: Mean = 5.17 SD = 1.33				MM: Mean = 4.42 SD = 1.47, BL: Mean = 3.75 SD = 1.42			
Q8	I was easily distracted from my partner when other things were going on.	*MM*		2.38	1.67	0.148		3.31	1.62	*0.035
		BL		2.69	1.74			3.31	1.96	
Q9	I remained focused on my partner throughout our interaction.	*MM*		5.88	0.89			4.19	1.60	
		BL		4.81	1.47			2.88	1.89	
Q10	My partner did not receive my full attention. (Strongly Disagree … Strongly Agree)	*MM*		2.38	1.67			3.63	1.67	
		BL		2.63	1.59			4.31	1.74	
	Perceived Message Understanding (Aggregated Scores from Q11 to Q14)		MM: Mean = 6.08 SD = 0.89, BL: Mean = 5.64 SD = 1.14				MM: Mean = 4.77 SD = 1.38, BL: Mean = 4.03 SD = 1.22			
Q11	I understood where my partner's focus was on.	*MM*		5.94	1.18	0.377		4.38	1.67	*0.030
		BL		5.44	1.41			2.94	1.69	
Q12	My partner's thoughts were clear to me.	*MM*		5.81	1.17			4.75	1.44	
		BL		5.50	1.21			4.13	1.71	
Q13	It was easy to understand my partner.	*MM*		6.19	1.05			5.25	1.34	
		BL		5.69	1.25			4.50	1.37	
Q14	Understanding my partner was difficult. (Strongly Disagree … Strongly Agree)	*MM*		1.63	0.81			3.31	1.74	
		BL		2.06	1.12			3.44	1.55	
	Preference									
Q15	Which condition do you prefer? (*Mini-Me (MM)* / *Baseline (BL)* / *No Preference*)		75% (12) / 25% (4)			*0.004	63% (10) / 31% (5) / 6% (1)			*0.035

Table 2: Questionnaire results for each condition (*MM = Mini-Me*, *BL = Baseline*) from part 1 and 2 of the user study.

- significant differences found for *CP* (V=112, p=0.003), *AA* (V=76, p=0.035), and *PU* (V=87.5, p=0.030).

Preference: We asked participants to choose their preferred condition. In case they answered no preference between the two condition, we allocated them equally to each condition [23]. We analyzed the results with a binomial test and found significant differences in favor of the Mini-Me for both *Part 1* (p = 0.004) and *Part 2* (p = 0.035).

Observation and Feedback

We collected subjective feedback for each condition and task. After each condition, we asked participants to explain their reasoning for task difficulty and what they liked and disliked about the condition. For the post-task feedback, we asked them to explain why they preferred the condition and how the Mini-Me avatar could be improved.

General Feedback: We summarize common feedback for both tasks. Participants found the pointing ray very helpful. In *Baseline*, this ray was cast from the life-size avatar's hand and in the Mini-Me, from the Mini-Me avatar's hand. Most participants found the Mini-Me very useful as *P6* stated – *"…useful for interpreting communicative intent and required less looking back and forth between my partner and the task space"*, *P2* stated - *"…I found the adaptive avatar to be quite useful and felt much closer to the person"*, and *P3* commented – *"The logical placement of the avatar, it made sense scaling the avatar and placing it near where you were looking. You did not lose the avatar. Then you could see where the avatar was looking"*. They also liked the look and feel of the Mini-Me for example *P12* – *"I liked the appearance and movement of the avatar. It was very fluid and guided me nicely"*. They also liked the life-size avatar as *P6* mentioned - *"I liked seeing the avatar as though it was standing next to me -- avatar appearance was very realistic and convincing"* and *P9* – *"It was well animated and always looked like it pointed where it should"*. *P5* pointed out benefits of each avatar – *"Each avatar has its own advantage. Fixed avatar allows me to feel like I am having a real person standing on a fixed spot, as well as give instruction. However, the Adaptive avatar gives me different type of perception information while interpreting the instruction"*.

Several participants mentioned that they disliked the small FOV of the HoloLens display. They also disliked having to position their head in-front of the target object so that HoloLens' front camera could scan and update the transformation of the virtual replica. Participants also contributed ideas for improving the avatars and tasks for example *P5* – *"Adaptive avatar might be good to have other type of character representative e.g. a robot …This is because if an avatar is represented as small as a palm, it would relate to a fairy or some other object other than a human..."* and *P4* – *"The adaptive avatar could have variety of poses such as sitting down, including facial expression."*

Part 1 (Asymmetric Collaboration): Overall, participants found this task easy to perform. They thought that the instructions were clear and straight forward. The presence of the Mini-Me also improved their understanding of their partner. *P5* said that *"The ability to see the small avatar … enhance the speed of solving the task"* and *P7* – *"easy and quick to interact with the partner"*. *P6* stated - *"…I liked seeing the avatar gesture for tip the box over…"*. This same gesture was used repeatedly in both conditions, but participant did not take notice in *Baseline*.

Part 2 (Symmetric Collaboration): Participants' responses to this task difficulty varied. Some found the task challenging but most participants could solve it. They liked the puzzle game and found the collaboration enjoyable. Participants mentioned that they relied a lot more on verbal communication in this task and less on the non-verbal cues from the avatar. Some participants still preferred seeing the Mini-Me avatar as they communicated with their partner, *P1* said *"I feel like I am talking to my partner"* and *P2 – "it is easy to see the gestures from the adaptive avatar"*.

DISCUSSION

Mini-Me: Presence vs Absence

The presence of the Mini-Me adaptive avatar yielded a significantly higher Aggregated Social Presence Score for both asymmetric and symmetric collaboration, than the absence of such avatar. We also found significantly lower ratings for task difficulty and mental effort for the asymmetric collaboration when the Mini-Me avatar was used, which might help explaining the observation of a significant reduction in task completion time for this task.

These findings were likely influenced by the nature of the collaboration and the role of the non-verbal cues in the asymmetric collaboration task, Tea Party, and the symmetric collaboration task, Urban Planner. In the Tea Party, the local AR user was on the receiving end of the communication most of the time and relied heavily on the spatial information from the remote VR user. The Mini-Me's features provided salient non-verbal cues, especially pointing cues at the target locations. In the Urban Planner, the participants needed to exchange clues, which required a constant two-way communication. The Mini-Me helped improved the user focus on task activities and helped them understand where their partner was focusing on. The users enjoyed the tasks with or without the Mini-Me and they did not find the Mini-Me distracting. They paid similar level of attention to their partner regardless of the Mini-Me was in use. Participants also felt that their partner's thoughts were clear to them in both conditions, and they could understand their partner equally well in both conditions.

Implications for MR Collaborative Interface Design

In this paper, we proposed and used the Mini-Me avatar to address one of the important aspects of collaborative MR systems – namely how to share non-verbal communication and awareness cues. The use of the Mini-Me reduced the need for users to be constantly looking at the life-sized avatars of their partners. The study results imply that people developing a MR collaborative interface for asymmetric remote collaboration on a spatial layout task should consider adding the Mini-Me or similar interface element capable of transmitting remote pointing and awareness cues. The constant availability of these cues will likely reduce the task difficulty and mental effort, leading to improved performance time. Similarly, in a symmetric task that involves shared problem solving and negotiation, the Mini-Me could be useful for improving Social Presence and awareness of the collaboration partner.

Limitations

Although our research has shown the value of using the Mini-Me avatar, there are a number of limitations that could be addressed to improve it even further. Firstly, although we took precautions and recruited participants with some experience with AR or VR to minimize the influence of the novelty effect on the study, it is still difficult to draw any conclusive results and further study is necessary to make more focused investigation on social factors while controlling for the novelty effect. Secondly, the Mini-Me's inverse kinematics could be further improved where certain poses were still uncanny. Thirdly, our system supports spatial audio, however, we did not use this feature in our study. Spatial audio would offer an extra cue in guiding a user to the audio source indicating the speaker's position in space. Fourthly, our task activities were simplified and did not require much training or prior knowledge. A follow up study with more difficult tasks would potentially help improving our system and the Mini-Me to better support a complex collaboration for professional use. Lastly, the VR user was played by an actor who was an expert. Therefore, it is necessary to conduct a user study with participants in both AR and VR roles to help identify the issues on the VR side.

CONCLUSION AND FUTURE WORK

In this paper, we presented our concept, design, and implementation of the Mini-Me, a novel adaptive avatar with redirected gaze and gestures for enhancing remote MR collaboration. We evaluated the impact of the Mini-Me on Social Presence, task difficulty, and mental effort for two collaborative scenarios. And we discussed the implications of the Mini-Me for MR collaborative interface design. Overall, we found that the Mini-Me avatar was able to convey the non-verbal communication cues necessary to improve the performance on an asymmetric object placement task. It was also useful for improving Social Presence in both asymmetric and symmetric tasks. In both cases users overwhelmingly preferred having the Mini-Me avatar. This supports our belief that adding the adaptive Mini-Me avatar could improve the user's awareness of their partner in a collaborative MR interface between AR and VR.

For our future work, we would like to improve the Mini-Me's adaptive surface projection technique. We are considering applying an automatic alignment technique, such as *SnapToReality* [30] that automatically aligns virtual objects to physical constraints calculated from the real world in real-time. A similar feature is also available as part of the Microsoft MR platform called "Spatial Understanding" [28], which we plan to use in our next iteration. We also would like to improve the empathy of the remote collaboration by recognizing and mapping facial expression of the VR/AR user onto the avatar [26]. We plan to conduct a follow up study for more complex tasks.

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