

Advancing Co-located and Distributed Multi-user Mixed Reality

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Figure 1: Multi-user Mixed Reality allows for (A) co-located, distributed, and (B) hybrid scenarios.

Abstract

Mixed Reality (MR) enables new forms of social interaction by blending physical and virtual spaces across co-located, distributed, and hybrid settings. In these environments, interpersonal encounters are shaped not only by technical constraints but also by interaction design, perception, and social dynamics. In my research, I investigate key questions across these dimensions and contribute to a deeper understanding of multi-user MR system development and of how people perceive, interact, and engage with one another in shared MR spaces. To this end, we conducted a structured review of design and research challenges in multi-user MR systems, explored interaction strategies that support collaborative activity while preserving social and contextual awareness, and examined how avatar self-views influence communication and attention in multi-user scenarios. My next steps include exploring how MR visualizations can support and mediate social dynamics and collaborative flow in group meeting contexts.

CCS Concepts

• **Human-centered computing** → **Mixed / augmented reality**;
Collaborative interaction.

Keywords

Mixed Reality, Multi-User, Collaboration, Social Interaction, Co-Located, Distributed, Mixed Presence



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1 Introduction and Background

Multi-user Mixed Reality (MR) spaces offer a variety of possibilities for social interaction along the reality-virtuality continuum [37]. In these environments, gatherings can transcend exclusively physical or virtual settings through a range of configurations, including co-located users sharing both virtual and physical objects (see fig. 1, A), and remote participants joining local groups through avatar representations (see fig. 1, B). However, social interaction in MR is not trivial, as perception and communication are constrained and mediated by technology. As a result, coming together in MR fundamentally differs from both traditional face-to-face and screen-based remote interaction. In my dissertation, I aim to deepen the understanding of social multi-user MR spaces and their potential by approaching them from three defining perspectives: as a *technological* challenge, as a medium for collaborative *interaction*, and as a facilitator for *social and perceptual awareness*.

Technology. The perks of many multi-user MR spaces, such as intuitive interaction [42], multimodal in- and output [44], and the opportunity for asymmetrical technology usage [42], are also what makes them technologically complex. Research is often hindered by device limitations, complex setups [39] and diverse development challenges [26]. Additional application-specific issues, such as limited non-verbal communication channels or insufficient support for content creation [42], can further impede collaboration. To design and develop these platforms effectively, the current research

landscape would benefit from a differentiated consideration of anticipated challenges during design, implementation, and deployment of co-located, remote, and hybrid multi-user MR systems.

Interaction. Intuitive and natural interaction is a key advantage of immersive technologies. However, the complexity of certain collaborative tasks, e.g., collaborative Immersive Analytics [2, 8], can exceed what traditional mid-air gestures adequately support. Unintuitive or tedious interactions may interrupt workflows, shifting attention away from the collaborative goal and decreasing performance [15, 36]. Consequently, many MR applications introduce additional devices, such as tablets or smartphones [3, 6, 17, 35]. While these devices enable convenient in- and output, they may also disrupt the social flow of collaboration by diverting attention or obscuring faces in co-located settings, thereby hindering communication. This highlights the need for a deeper investigation into how awareness can be maintained and supported when interaction becomes complex.

Social and Perceptual Awareness. A key consideration of multi-user MR is how people perceive and communicate with one another. In remote scenarios, avatar design plays an important role in shaping social interactions through levels of realism and detail [23, 24, 41], facial expressions [25, 34, 45, 48], auditory representations [13], and characteristics such as attractiveness [49] or transparency [50]. Beyond the perception of others, one's own virtual appearance can also shape social interaction. While prior research highlights the emotional impact of avatar customization [4, 41, 47] and embodiment [9, 10], as well as the Proteus effect [49], comparatively little is known about how actively perceiving one's own avatar in live multi-user settings impacts communication and self-perception. Notably, in video conferencing, continuously seeing one's own image has been associated with Zoom fatigue [1] and mirror anxiety [12], motivating the question of whether similar effects emerge in immersive avatar-mediated environments.

Perceiving and maintaining awareness of others remains critical regardless of avatar design or fidelity. Here, prior work has explored spatial awareness enhancements for localization of others, such as proximity indicators [40], off-screen direction cues [46], path and map visualizations [43], and auditory notifications when users join or leave shared spaces [14]. However, more sensitive social signals, such as declining attention or changes in emotional states, can also be lost in multi-user MR. This holds true not only in remote avatar-mediated scenarios, but also in co-located settings due to occlusion caused by head-mounted displays (HMD) and handheld devices. As a result, prior research has explored additional supporting visualizations, such as explicit gaze sharing [20–22] and manually triggered symbolic representations of emotional states [18, 19]. Together, these observations underline the need for further research into how perception and awareness of the self and others can be supported in multi-user MR, and how such mechanisms shape communication, social interaction, and interpersonal dynamics.

2 Overview of the Research Questions

In this dissertation, I approach multi-user Mixed Reality from two complementary perspectives: the technological foundations that enable these systems, and the ways in which people perceive, interact,

and engage with within them. By grounding these aspects in concrete system designs and empirical investigations across co-located, distributed, and hybrid configurations, I aim to deepen the understanding of multi-user MR systems and suggest advancements. The following research questions guide this investigation:

RQ1: What design and research challenges emerge when multi-user Mixed Reality systems support co-located, distributed, and hybrid participation? To understand the challenges across configurations, we conducted a systematic literature review covering technical and environmental constraints, user-related aspects such as representation, communication, and awareness, as well as cross-cutting system design and evaluation issues. Based on this analysis, we outline open challenges and future research directions. This establishes the theoretical foundation for the following research questions.

RQ2: How can social and perceptual awareness be maintained in demanding, collaborative interaction scenarios? Task complexity during professional collaboration can quickly exceed the capabilities of mid-air gestures. Although additional input devices may improve efficiency, they can disrupt awareness by diverting attention, causing occlusion, or encouraging parallelized work. To address this, we designed and implemented an occlusion-avoiding input device for collaborative work in multi-user MR.

RQ3: How can perceptual awareness of the self and others be supported to facilitate communication in multi-user Mixed Reality? Technical constraints, such as low-fidelity user representations or face occlusion, can limit the perception of social cues in MR. At the same time, users may feel uncertain about how they are perceived by others and whether their non-verbal communication is conveyed correctly. Therefore, for this RQ, we investigate mechanisms that support self- and other-awareness, through avatar self-views, social signal visualizations, and by mitigating facial occlusion.

RQ4: How can multi-user Mixed Reality systems influence and advance social interaction and interpersonal dynamics? Coming together in MR fundamentally differs from both face-to-face and video-mediated communication. Virtual content and user representations can impact social interaction and interpersonal dynamics by affecting self-confidence, causing distractions, and influencing communication and group processes. Here, we investigate how MR both challenges and supports social interaction by evaluating the effects of virtual self-views and by exploring social expression in group meetings through virtual augmentations.

3 Research To Date

So far, we have conducted several projects in which I have addressed parts of the aforementioned research questions. Our results have been published in the proceedings of IEEE ISMAR '22 and '24, PACMHCI '25, and CHI '23 and '26. Our methodologies include a systematic literature review, lab-controlled user studies, expert feedback and expert workshops, soft- and hardware prototype development, and interaction and visualization design. In the following, I will elaborate on this research and its relation to the aforementioned research questions.



Figure 2: CleAR Sight [30] enables a variety of collaborative activities, by (A) facilitating the creation of virtual annotations on physical documents, as a (B) shared frame of reference for collaborative data analysis, as a (C) tangible artifact to physically manipulate data, or to (D) create large, projected presentation-style annotations on shared surfaces.

Charting the Challenges (RQ1, RQ2, RQ3). Mixed presence (MP) in Mixed Reality describes configurations where physically present collaborators share a space with remote participants represented by virtual avatars (see fig. 1, B), combining the intricacies of both co-located and distributed settings. Since current literature lacks a systematic overview over the challenges and requirements of MP solutions, a lot of research addresses re-occurring challenges with fragmented and individualized solutions. To address this, we conducted a comprehensive review of MR MP environments [29]. Because the term “mixed presence” has been used inconsistently in prior literature, we first proposed a clear definition of the technological components of MP environments in MR. We then conducted a systematic literature review following PRISMA [38] guidelines, which resulted in a corpus of 147 relevant publications. We coded the mentioned challenges and requirements into four main categories: *technology*, *environment*, *user*, and *cross-cutting*, each comprising of multiple subcategories. Based on these results, we then conducted an expert ideation workshop to compile and structure promising future directions for MP research in MR. With this, we provide a resource for developers to anticipate practical challenges in MP system development and to aid informed design decisions. We further developed an extensible research platform and toolkit for studying co-located, MP and remote MR scenarios [7] (see fig. 1, B), allowing us to directly engage with and address many of the identified challenges. With these works, we gained deep insights into the development of co-located, remote and mixed-presence MR systems, addressing RQ1 and establishing the epistemic foundation of the other research endeavors in this dissertation, especially underlying questions for RQ2 and RQ3.

Advancing Collaborative Interaction Devices (RQ2, RQ3). A key advantage of Mixed and Augmented Reality (AR) over Virtual Reality is the continued visibility of the physical environment, enabling integration of documents, whiteboards, and other artifacts into collaborative workflows. In practice, collaborative work often involves complex or intricate tasks that exceed the capabilities of intuitive mid-air gestures, e.g., precise sketching or elaborate transformations. Additional mobile input devices can improve precision but may occlude collaborators and environmental context, obscuring facial expressions and social cues. To address this, we developed CleAR Sight [30], a transparent interaction panel for co-located multi-user MR (see fig. 1, A). The panel provides a tangible interaction surface for spatially tracked capacitive pen and touch

input and acts as a see-through frame for selection and manipulation. CleAR Sight supports a range of collaborative interaction techniques, including by attaching virtual content to its surface for tangible hand-overs, annotating shared paper documents, and creating large shared spatial sketches on distant surfaces (see Figure 2). We evaluated three representative use cases in a hands-on session with five MR experts, who highlighted the practicability of the panel’s transparency for collaborative scenarios and to maintain contextual awareness. Finally, we also demonstrated our prototype as an interactivity at CHI’23 [5]. With this, we proposed a strategy of supporting perceptual and social awareness in collaborative scenarios, addressing RQ2 from the perspective of co-located MR. The transparency of the panel avoids the occlusion of collaborators and their faces, thereby also informing aspects of RQ3.

Investigating Self-Perception as Avatars (RQ3, RQ4). Recently, public and academic discourse has emphasized the Metaverse as the future of coming together digitally [16], a virtual world in which social interaction is mediated by 3D avatars. While prior work has shown that other users’ avatar appearance influences communication, research also indicates that users care deeply about their own avatar representation. In conventional video conferencing contexts, continuously seeing oneself has shown to affect attention and self-confidence and cause fatigue. To investigate whether similar effects occur in immersive settings, we conducted the Mirror Me project [31], investigating how avatar self-views influence self-perception, mental load, and attention allocation in multi-user VR communication. In a within-subjects user study (N=32) dyads played a word-guessing game involving a verbal and a gesture-based communication task. Here, three self-view variants (*Remote Perspective View*, *Personal Mirror*, *Miniature Avatar*) were compared against a baseline with no additional self-view (see fig. 3). Afterwards we assessed user preferences and perceived helpfulness of the self-views. Our results show the benefits of self-views in dual-user communication scenarios that require expressive body language. Based on our findings, we derive design recommendations for future avatar self-view implementations. With this, we contribute to RQ3 by addressing self-perception in multi-user communication, while informing RQ4 through the analysis of attention and perceived social distraction.

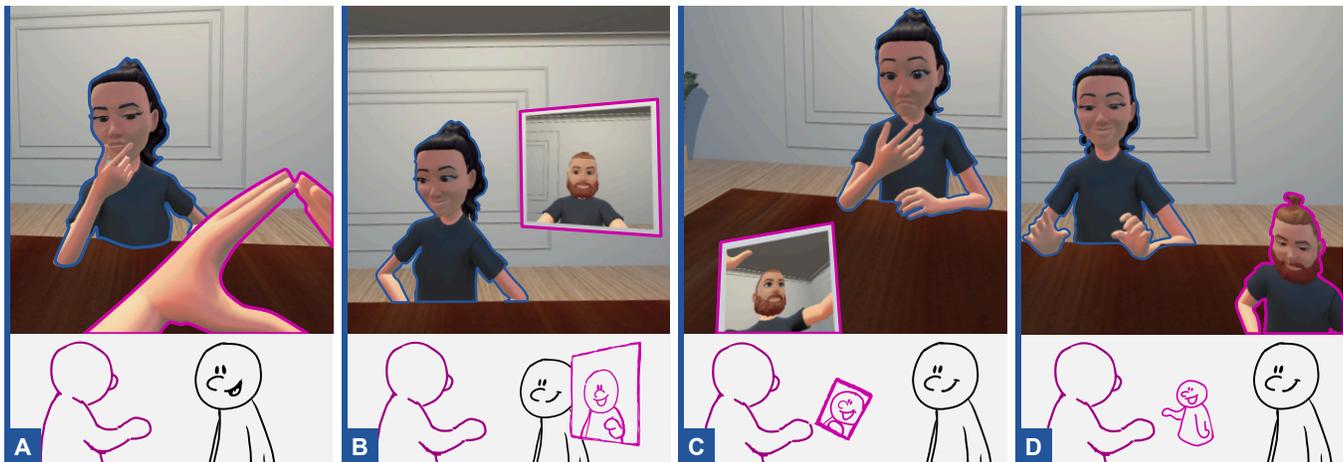


Figure 3: In the Mirror Me project [31] (Images © Krug et al., CC by 4.0, combined and adapted), we compared three different avatar self-view variants against (A) a baseline with no additional self-view: (B) Remote perspective view, (C) personal mirror, and (D) miniature avatar.

4 Next Steps and Ideas

As a next step, I plan to integrate my people-centered research foci (RQ3, and RQ4) into a unified application scenario, focusing on visual MR enhancements for face-to-face group meetings. While imperative to creative and knowledge-intensive collaboration, in-person meetings are shaped by complex factors, including physical and digital artifacts, structural or procedural constraints, interpersonal strains and communication difficulties, environmental restrictions, or time and flow management. I want to investigate the potential of visual MR-enhancements to address these challenges. I am specifically interested in finding out how MR visualizations could communicate procedurally relevant information, such as remaining time, speaker order, agenda progression, or task priority, to support collaborative processes and smooth meeting flow. I want to explore visual metaphors for intuitive information communication, ranging from ambient, subtle cues to more explicit signals of urgency or priority. Beyond procedural support, I want to assess how such visualizations can foster interpersonal awareness and positively shape social dynamics. Depending on the social context of the meeting, participants may hesitate to verbalize personal issues, such as fatigue, irritation, or feelings of mistreatment. Collective emotional shifts are often sensed but rarely addressed, resulting in a lack of action to get the group back on track. I believe that MR offers the potential to make such underlying states perceptible in a respectful and individualized manner, supporting social regulation without requiring disruptive verbalization. Through these investigations, I seek to understand how virtual enhancements can help mediating interpersonal understanding and facilitate reflective group meetings.

5 Dissertation Status and Long-Term Goals

I am a fourth-year Ph.D. student at the Interactive Media Lab Dresden, Faculty of Computer Science, TUD Dresden University of Technology, supervised by Prof. Raimund Dachsel. I have not previously attended a doctoral consortium. For this research topic, I

have published five papers, including three full papers [29–31], one interactivity [5] and one archival workshop paper [7], and I aim to complete the proposed research projects and my dissertation by early 2027. I view multi-user Mixed Reality not only as a means of bridging distance, but as an opportunity to reimagine how we meet, communicate, and express ourselves. Therefore, in addition to the core projects described here, I have explored multiple further aspects of multi-user MR in smaller works [11, 27, 28, 32, 33], touching on aspects such as inclusivity, consent, and emotional expression, which I am open to expand upon in the future. Through this mentoring program, I hope to receive feedback on the framing and positioning of my dissertation, refine my next steps, and gain broader viewpoints on the current research landscape and future perspectives in academia.

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