# Mixed Presence in Mixed Reality: Charting the Challenges and Opportunities

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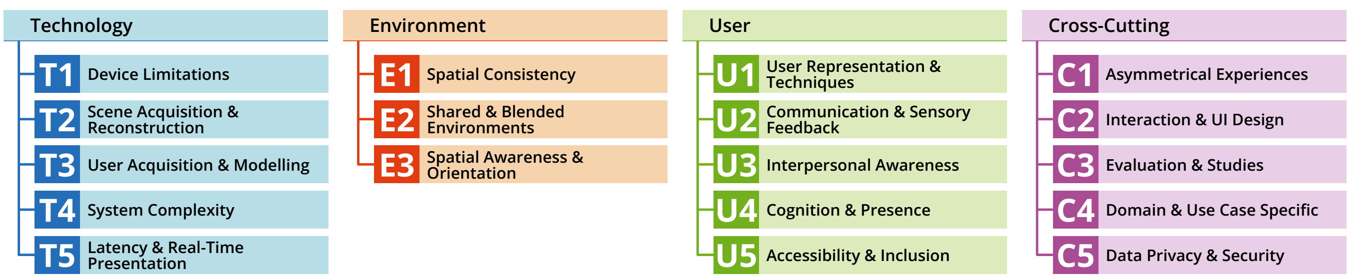


**Figure 1: An overview of the four challenge categories and their themes we identified through our survey, consisting of the three main components of Mixed Presence systems as well as cross-cutting challenges. The additional sub-themes of each challenge category can be found in the appendix (see Fig. A1).**

## Abstract

This paper investigates the challenges of designing mixed-presence environments for Mixed Reality and suggests future research directions derived from an expert workshop. Developing mixed-presence systems is a complex undertaking that combines the intricacies of both co-located and distributed mixed-reality spaces. Current literature in this field describes various promising design and development approaches but lacks a systematic overview, resulting in fragmented solutions to re-occurring challenges. Therefore, we conducted a comprehensive review of mixed-presence and multi-user remote mixed-reality systems, categorizing the prevalent challenges faced during the development of such systems, but also current trends, common use cases, study tasks and methodologies. Supported by these results, we then conducted an expert ideation workshop to collect and structure promising future research directions. As a result, we provide a detailed resource to orient and prepare developers for probable challenges and support researchers in making informed design decisions for future mixed-presence studies in Mixed Reality.

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## CCS Concepts

• **Human-centered computing → Mixed / augmented reality**;
• **General and reference → Surveys and overviews**.

## Keywords

Mixed Presence, Mixed Reality, Collaboration

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## 1 Introduction

With continuous technological developments, multi-user mixed-reality (MR) systems, ranging from purely *co-located* to fully *remote* endeavors, have seen increased interest. Recently, the concept of

*Mixed Presence* (MP) [130], which can cover the middle ground of shared MR spaces, has gained more attention. MP systems may advance mixed-reality collaboration by allowing both remote and local participation [130]. While many use cases still rely on co-located groups, they can be potentially enhanced by remote participants, e.g. during surgery, where medical personnel can be advised by a remote expert [100]; hybrid meetings, where far away members can still contribute while reducing travel time and expenses [37]; or hybrid classrooms that allow individual students to stay on top of their studies despite physical absence [3]. Thus, MP platforms in MR fuse co-located and remote MR interaction spaces, resulting in complex systems that aim to address the requirements and challenges of both seamlessly. The technical intricacies of remote collaboration, such as data transmission and remote user representation, are combined with the complexities brought by local participants, including ensuring synchronicity between co-located and remote users, differing physical environments, and challenges of spatial interactions. The exploration of MP systems in MR touches aspects of collaboration that warrant further investigation, such as user roles [88], social & spatial awareness [55], and how to blend different environments [38]. Despite the importance of these questions, the current research landscape lacks a common understanding of the fundamental challenges in the design and development of MP systems in MR. As a result, many researchers find themselves repeatedly addressing similar issues and devising analogous solutions. We, therefore, recognize a need to streamline the design and development process and aim to support future researchers and developers by providing a resource for orientation and preparation for informed design decisions during the research on MR MP systems.

Over the years, the term "Mixed Presence" has been used to describe fundamentally different setups and has only recently been adapted for MR, complicating targeted search for relevant literature. Therefore, we first propose a modern, narrowed-down definition of Mixed Presence systems in Mixed Reality, taking into account the current state of technology, specifically MR-capable devices, the concept of presence, and the associated possibilities.

Next, we report on a comprehensive review of the current literature. We give an account of common use cases and study designs, highlighting typical study methods and tasks, to allow future researchers to draw inspiration and make informed decisions that may shape the methodology of their own study design. With this overview we also provide crucial context for the main contribution of our work: We meticulously extracted challenges and requirements mentioned in the context of MR MP system development and evaluation and categorized them into a set of common themes (see Fig. 1), which we present in detail, enabling developers to better anticipate the practical realities of developing MP systems for MR, such as likely arising challenges and persisting technological issues, and offer pointers to prior work addressing problems they might face. To reflect on our findings, we conducted an expert workshop to collaboratively compile future directions for mixed-presence research in MR, inspired by the identified trends and underrepresented research areas, and map these out subsequently.

Our main goal is to empower developers and researchers of MR MP systems by providing a curated list of anticipated challenges and important considerations. By outlining the potential obstacles, we help them make informed design decisions, mitigate potential pitfalls, and proactively address common issues in their MP projects. With the suggested research directions, we aim to inspire and guide future research efforts that can advance the development of innovative and robust mixed-presence systems for Mixed Reality, and shine light on areas that remain underexplored. In summary, the contributions of this work are:

- A comprehensive **collection** of recent research on MR MP systems and an overview of **current trends**.
- Insights into typical **use cases, study methodologies, and tasks** in current MR MP research.
- A collection and categorization of common **challenges and requirements** faced by researchers during the design and evaluation of MR MP systems.
- A curated set of **future research directions** to motivate and guide upcoming research and developments on MR MP systems, based on the identified challenges and the results of an expert workshop.

## 2 Background

In the following, we narrow down the definition of Mixed Presence in the context of Mixed Reality and address previous work surveying collaboration in MR.

### 2.1 Defining Mixed Presence Environments in Mixed Reality

*2.1.1 Mixed Presence Groupware.* Originally, *mixed-presence* environments are broadly described as *facilitating collaboration and communication among co-located and distributed actors* [130]. Thus, the term can be used to describe systems with diverse setups, as long as they share a unified interactive space. In earlier research, MP systems often either center around video conferences [126, 127] or distributed tabletop environments, due to their practicability for collaboration in a co-located multi-user scenario [8, 15, 59, 77, 104, 137]. Researchers such as Schremmer et al. [112] recognized the opportunities of providing remote user representations in tabletop-centric systems early on and employed additional screens. Later, systems incorporate immersive head-worn Virtual Reality (VR) displays into tabletop environments, facilitating 3D remote user representation [73, 105, 106]. However, with maturing MR technology, the term Mixed Presence has shifted, being increasingly used to describe a specific type of *distributed Mixed Reality*[1] *environment*, where co-located users share an MR space with remote users, who access it through an HMD [13] or other devices like desktop computers [86–88]. At the same time, however, similar setups use various different terminologies to describe the same situation (e.g., Remote and colocated telepresence [50], one-to-many MR collaboration [65], MR multi-user asymmetric collaboration [155], etc.) making it difficult to effectively search for the aforementioned conditions. Thus, to facilitate targeted literature review and a consistent use of terminology for future MR research, we propose a definition for the technological components that define MP environments in MR. This definition is based on interpretations of the definition of MP in MR in recent literature. Contrary to original broad MP definitions, we take the concept of *presence* into account. This psychological

[1]We would like to highlight that the term Mixed Reality also has diverse definitions, as examined by Speicher et al. [124]

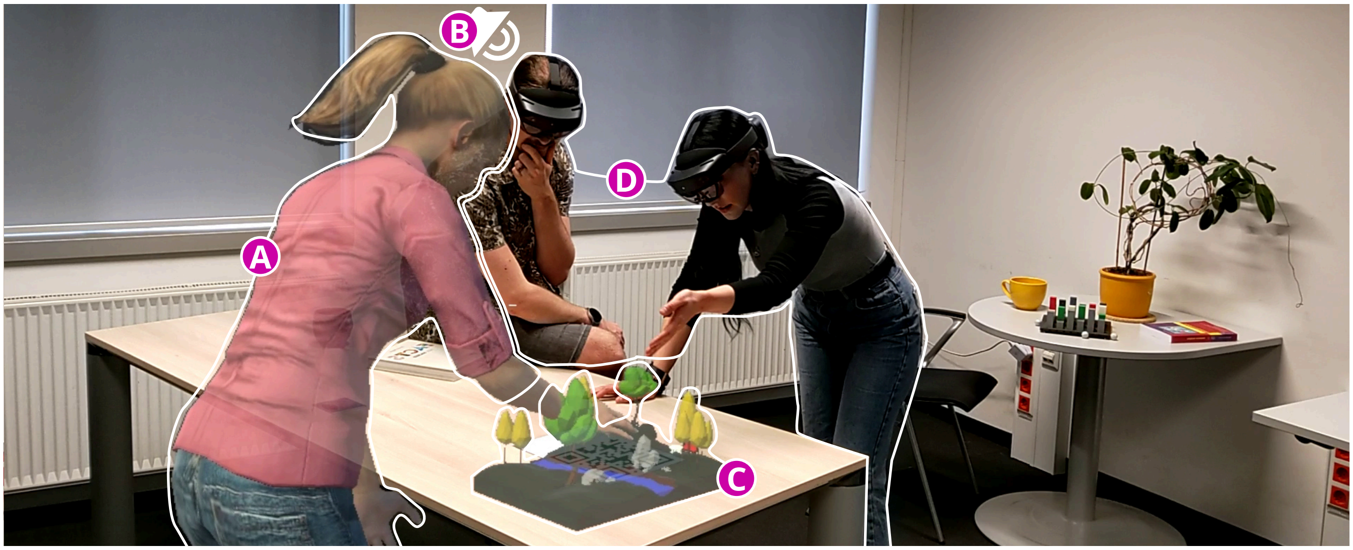


**Figure 2: Our proposed definition of mixed-presence environments for Mixed Reality. They are distributed Mixed Reality environments, in which (A) remote actors have (B) a visual and/or auditory representation and (C) share a three-dimensional interaction and communication space with (D) co-located actors.**

and media-technological construct is increasingly discussed in MR MP research and will be elaborated on in the following.

*2.1.2 Presence in Virtual Worlds.* The feeling of *presence* describes the sensation of "being there" [43], referring to physical (c.f. *telepresence* [80, 117]), imagined (e.g., through narrative media like books [36] or television [71]), or virtual spaces [9, 43]. At its core is the perceived transportation of the self, others, objects, or environments through "a medium that becomes invisible" [71]. Slater et al. [120, 122] define presence as a subjective response to the system's immersive properties (its enabling technological characteristics, such as display fidelity or tracking quality), enabled by a combination of place illusion (the perceptual illusion of being in a virtual space) and plausibility illusion (the credibility and coherence of events) [120, 122], aided by social contingencies [121] and embodiment [123]. Analogous to this, presence is often discussed in relation to the **environment**, the **self**, and to **others**. Feeling physically located in an **environment** [49] to the point where its artificial nature is no longer noticed [68] can be facilitated by providing a multitude of convincing sensory stimuli [9, 117] in an environment that has its own internal logic and autonomous behavior [157] and responds convincingly to user interactions [43, 110, 125, 157]. Presence can also emerge when ones sense of **self**, i.e., body-image, physiological and emotional states, and identity are integrated into the environment [9], often through embodiment of a convincing virtual body [43, 68]. The user's mental representation of and presence in the virtual environment can be shaped by the actions their body can perform in it, such as the ability to navigate or manipulate objects [113]. The feeling of presence can also be deeply social [32]. *Co-presence* refers to the basic feeling of being in a shared environment with **others** [10, 19, 49, 160]. *Social presence* arises when virtual actors are perceived as social actors [68] and interpersonal relationships become salient [119]. It requires possibilities for psychological involvement and behavioral engagement [10], and for intimate connections to be formed [89, 103], often facilitated through rich communication cues such as voice, facial expression, and touch [9, 103].

In Mixed Reality, feelings of presence can differ from those in purely virtual experiences [136]. As MR blends real and virtual elements [79], presence is not about being transported into a virtual world, but about perceiving the real and virtual as forming one coherent, integrated space [101, 145]. Here, presence can not be solely understood as perceptual illusions, but is fundamentally social and participatory, defined by how users interact with each other in hybrid physical-digital environments, making the concept of co- and social presence even more central than spatial illusions [140].

*2.1.3 Mixed Presence in Mixed Reality.* Combining the original collaboration-focused definition of Mixed Presence with the core dimensions of presence in MR, we describe MR MP environments as interactive spaces that support synchronized collaboration and natural communication, enabling social connection between co-located and remote users. This necessitates representing remote actors in a familiar manner through means such as human-like avatars with rich communication capabilities. Communication and interaction with remote actors in these spaces need to be seamless enough to not differ greatly from physically co-present collaborators. These requirements greatly exceed the original definition of *Mixed Presence*, which is why we specify the definition of mixed-presence environments in Mixed Reality as follows:

> *Mixed-presence environments in Mixed Reality are distributed environments in which* ***co-located actors who can perceive each other and their surroundings*** *share a* ***3D interaction and communication space*** *with remote actors, who are* ***represented audio-visually****.*

The current state of the art fulfilling this criterion mainly encompasses co-located HMD-driven AR systems with AR or VR remote participants embodied by humanoid avatars (see Fig. 2). However, this definition is not supposed to be restricted to specific technologies and can include alternative MP experiences, like the distributed CAVE system presented by Beck et al [6]. For the sake of simplicity, from here on we will use the term mixed-presence systems/environments to refer to mixed-presence systems in Mixed Reality.

## 2.2 Surveying Mixed Reality Collaboration

To our knowledge, no prior research has provided an in-depth investigation into challenges and future research directions for mixed-presence systems. However, with mixed-reality collaboration being a well-researched topic, we are not the first to zoom in on specific forms of collaborative systems. Pidel & Ackermann [94] wrote a survey on collaboration in Virtual and Augmented Reality (AR), focusing on the different types of collaboration but only briefly mentioning the resulting challenges. Similarly, Sereno et al. [116] surveyed collaborative work in AR, categorizing systems as a-/symmetric and a-/synchronous. However, we are interested in the intersection of those and the associated challenges, use cases, and study tasks. Schäfer et al. [108] surveyed synchronous remote collaboration systems in AR and VR, exploring their strengths and weaknesses. In contrast to their focus on remote systems, we want to explore MP systems specifically. Ens et al. [21] focused on documenting how technological innovations have shaped and influenced MR collaboration and which future directions are foreseeable. We are mainly interested in the challenges and requirements these technological innovations bring, and the evaluation types they enable. Wang et al. [144] also reviewed AR/MR collaboration but with a focus on physical tasks, while we want to regard a multitude of task types and also systems made for pure communication use cases. A survey specifically on remote assistance and training tasks in MR was presented by Fidalgo et al. [28]. While this is a narrower scope than in our work, we refer the reader to it for an in-depth look at an important use case.

Krauß et al. [63] explored current practices and challenges of collaborative AR/VR applications. However, their work is based on interviews instead of a literature survey. Furthermore, they approached this topic from an organizational and behavioral perspective, focusing on role distributions, tasks, and tools in developer teams. Also focusing on interviews, Ratcliffe et al. [99] specifically examined problems and opportunities of remote AR/VR experimentation without on-site researcher supervision, based on feedback by researchers and a thematic analysis on study types, participant recruitment, etc. Besides the different methodology and revolving around MP instead of just remote collaboration systems, we focus on the design, implementation, and application of such systems instead of the intricacies of study conduction. Marques et al.'s [76] taxonomy for collaborative AR is more broadly focused on categorizing and modeling the dimensions of collaboration in AR. While these dimensions are highly relevant and shape AR collaboration, we are focusing on the challenges that result from these aspects and the interplay of remote and co-located users.

By surveying MR MP systems specifically in regard to their challenges, use cases, and study methodology, and by synthesizing actionable research questions, we aim to provide a unique perspective on the research landscape and novel insights for developers and researchers.

# 3 Survey Methodology

We want to present an overview of Mixed-Presence (MP) systems and provide an entry point for future researchers and practitioners to investigate and develop such solutions. We built our investigation upon a corpus of current and relevant publications. We followed the PRISMA ("Preferred Reporting Items for Systematic Reviews") [93] guidelines to generate this corpus, similar to other recent research (e.g., [62, 78]). In the following, we will present the general search strategy (Sec. 3.1), selection process (Sec. 3.2), and data extraction (Sec. 3.3). The complete survey corpus, its coding, and the scripts used to prepare and analyze the data can be found in the supplementary material.

## 3.1 Search Strategy

Given that we primarily aim to analyze the challenges faced in MP system development and research, our survey aimed to focus on publications that present or at least mention MP systems. However, as discussed in Sec. 2.1, the term Mixed Presence is not uniformly used in the literature to describe MR-based systems matching our definition. Consequently, we had to build a broader query around a range of adjacent and relevant terms.

This query consists of several iteratively defined sets of keywords that aim to capture different aspects of MP systems. First, *Set A* focused on the spatially distributed nature of MP systems. Second, *Set B* prioritizes what MP systems can be used for, capturing the different forms of how people work together in an MP system. Lastly, with *Set C*, we further specify that such multi-user systems should be using mixed-reality technologies. The complete list of terms in each set is as follows[2]:

**Set A:** "Remote", "Distributed", "Telepresence", or "Co-Presence"
**Set B:** "Collaboration", "Communication", "Training", "Instruction", "Guidance", or "Teaching"
**Set C:** "Mixed Reality", "Augmented Reality", "Extended Reality", or "Cross-Reality"

Our final query is composed of these three sets (in addition to the term MP itself) and was constructed as follows:

```
("Mixed Presence" ||
(Set A && Set B && Set C))
```

We only considered archival and peer-reviewed publications. This includes journal articles, conference full and short papers, as well as book chapters, workshop submissions, posters, and work-in-progress papers. For that, we searched in common digital libraries for publications in Human-Computer Interaction and Visualization, namely IEEE Xplore and ACM Digital Library[3]. Using our search query[4] in these libraries resulted in a list of 962 publications (see Fig. 3). The search was last conducted on 26th June, 2025.

[2]All terms were used in singular and plural, as well as with or without hyphens (where appropriate).
[3]Links to the libraries: IEEE Xplore, ACM DL
[4]The specific query used for each library can be found in the supplemental material.

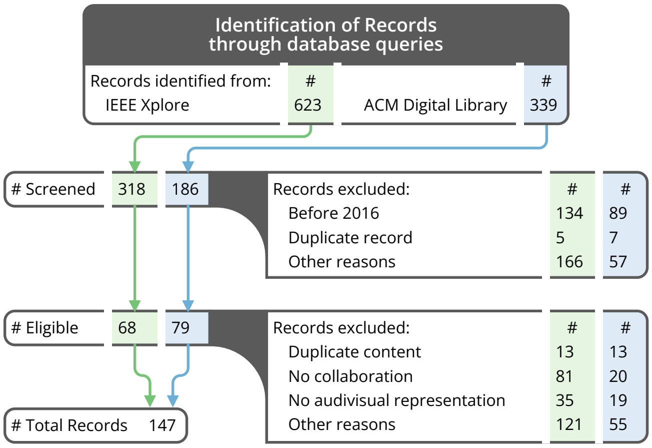


**Figure 3: Overview of our reviewing process including paper counts, following PRISMA.**

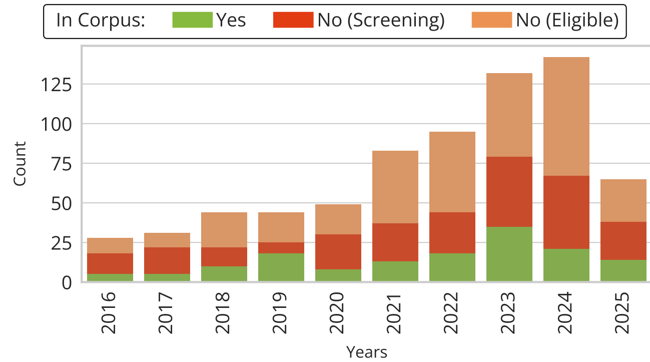


**Figure 4: Overview of how the survey process affected the final count of papers within our corpus beginning from 2016.**

### 3.2 Selection Process

After retrieving the full corpus of papers (n = 962), we preprocessed the different output formats and joined them into one table. As we are most interested in current challenges surrounding today's MP research, we narrowed our literature corpus to publications since 2016 for this investigation. We chose the cut-off year 2016 since the Microsoft HoloLens 1 and the first consumer version of the Oculus Rift were released that year, marking commercial availability of powerful mixed-reality hardware to consumers. This selection reduced the corpus by 223 publications, but it still spans nearly 10 years. For further discussion of the cut-off year, please also refer to Sec. 7.

Three authors then screened the corpus (n = 739). This step filtered out non-MR papers and duplicates (i.e., linked to the same publication). Further, we removed works without specific research results (e.g., workshop proposals or keynote abstracts) and publications that were merely a collection of other works (e.g., conference proceedings, complete books, dissertations), since we expect the relevant individual works to appear in our corpus anyway.

Lastly, the same three authors checked the eligibility of the remaining publications (n = 504). For that, we defined the following exclusion criteria, mostly based on our MR MP definition:

- The publication is a content-wise duplicate (e.g., a demo paper of a full paper).
- No prototype or system was presented.
- The presented system is not real-time capable (cf. asynchronous collaboration).
- The publication presents a pure VR system.
- The presented system only works co-located.
- Only a single-user system is presented.
- The users do not share a 3D interaction space.
- The users within the system have no 3D audio-visual representation.

With these criteria, we focused on distributed multi-user applications, where at least one user uses an MR-enabling device , and users can see their partners. Not all of those systems are explicitly described as MP-capable, but they naturally encounter challenges relevant for MP research.

The authors were in close contact throughout the screening and eligibility check process to discuss unclear publications. Fig. 4 shows an overview of the paper set by year. In total, this procedure resulted in a final corpus of 147 relevant publications (a full list can be found in the supplementary material).

### 3.3 Data Extraction and Code Book

The final paper set (n = 147) was read and examined by three authors. For each paper, we recorded notes for seven categories: The *Type of Encounter* was categorized as either remote AR or Mixed Presence, depending on whether simultaneous co-located collaboration is possible. We additionally took note of the described *Use Cases*, whether the systems were available as *Open-Source* software, and, if the papers contained a study, the employed *Study Tasks* and *Study Evaluation Methods*. Finally, and most importantly, we systematically extracted the *Challenges and Requirements* for developing and researching MP systems of each paper. Through this process, we could identify a total of 659 instances of challenges.

After the coding, the three authors thematically analyzed [84] the challenges. Once we defined an initial set of challenge codes, we randomly selected 10 papers from our survey corpus, whose challenges were coded by all three authors independently and then compared. This allowed us to (1) verify if the categorization works, (2) add missing codes, and (3) establish a common ground across all authors. With the finalized code, three authors coded the challenges of the remaining papers. Here, each paper was coded by two authors. Afterward, the three authors went over each challenge and combined their results, discussing any disagreements in the codes. In this phase, final adjustments to some of the categories were made by splitting or merging them and recoding the affected challenges when necessary. We used a similar procedure for coding the *Use Cases*, *Study Tasks*, and *Study Evaluation*, but did not discuss the individual results in detail among the authors, as we found them to be less subjective.

## 4 Application and Evaluation of Mixed Presence

Many of the papers in our corpus evaluate their presented MP system through user studies. The chosen parameters of those studies mirror the underlying research question and the intended application area of the system, both of which influence the implementation and the associated challenges, which is why we present them first. With this, we offer inspiration and support for researchers to decide on appropriate *Study Tasks* and *Methodologies* (i.e., qualitative or quantitative) for their established *Use Case* and/or *Type of Encounter* (Remote MR or MP). Additionally, we highlight the scarcity of available *Open-Source* frameworks for development and list the ones we found. For concrete pointers, we encourage researchers to look into the coded corpus provided in our supplemental material, as well as on our dedicated interactive website for easy filtering[5].

In our final set of 147 papers, we found 20 systems that match our definition of MP environments explicitly. On the other hand, the vast majority of the papers (127 of 147) do not specifically state support for mixed-presence (MP) scenarios, although some might implicitly do so. Remarkably, 13 of the MP system papers were published since 2023, supporting our belief that the definition and focus of MP systems have recently shifted and that those systems are increasingly gaining relevancy.

Overall, 18 of 147 papers in our corpus claim an open-source implementation, of which we could only locate 14. Typically, MP systems are built around a specific use case or study setup, and re-employing them for different application areas presumably requires significant re-implementation. Overall, the research field predominantly provides individual solutions to specific problems and use cases instead of overarching approaches, even though they share similar underlying problems.

In the following, we will look into the use cases commonly illustrated in our corpus (Sec. 4.1), the specific study tasks used in the corresponding studies (Sec. 4.2), and how those were evaluated (Sec. 4.3).[6] This can facilitate decision-making in the context of MP system development based on what has been proven to work for others or which gaps remain underexplored.

## 4.1 Use Cases: Task Types and Application Domains

Looking at the *types of tasks* addressed by the papers in our corpus, we identified two large groups, *Communication & Collaboration* (72 of 147 papers) and *Instruction & Guidance* (65 of 147). Only 9 papers cover both categories. This is partially due to our chosen search terms, but also highlights a split in the MP research between addressing general, often symmetric collaborative work (e.g., [55, 82]) and scenarios where (remote) experts are brought in to support on-site workers (e.g., [75, 115]).

In addition, we found that 27 papers cover *Assembly & Arrangement* tasks. 13 of these we also categorized as *Instruction & Guidance*, indicating the importance of assembly and picking guidance in the literature (e.g., [75, 131, 143]). 20 papers address *Problem Solving & Playing Games*, most of which (12 of 20) we also classified in *Communication & Collaboration.*

We also looked into the different application domains addressed in our corpus: Based on their occurrence, we categorized *Maintenance & Industry* (24 of 147), *Education & Knowledge Work* (16 of 147), *Medicine* (15 of 147), *Social & Play* (16 of 147), and *Design & Creativity* (12 of 147). Together, 74 papers are in one or more of these categories. The remaining papers (73 of 147) either didn't specify an application domain – mostly focusing on general techniques or studies – or only covered various other use cases.

Perhaps unsurprisingly, most papers that address maintenance tasks also cover instruction & guidance (21 of 24). This clear correlation between task type and application domain is also apparent in the medical context, where 14 out of 15 papers focus on instruction or guidance. Naturally, the category of *Education & Knowledge Work* strongly overlaps with the task type of *Instruction & Guidance* (11 of 16). However, it also includes four papers in the domain of collaborative data analysis [26, 34, 72, 129]. In *Social & Play*, we see diverse use cases such as board games (e.g., [41]), remote jam sessions (e.g., [109]), and remote Christmas celebrations (e.g., [158]). *Design & Creativity* includes instances of interior design and furniture placement (e.g., [22, 88]) but also design critique [70] and virtual maker spaces [98].

## 4.2 Study Tasks

Most of the corpus presented the result of studies (118 of 147 papers) evaluating their MP or remote AR systems. We charted the tasks performed in these studies and categorized them below. Two large categories are *assembly & puzzle* tasks (32 of 118) and the *arrangement of virtual or real-world objects* (17 of 118), with two papers [22, 60] covering both. Consistent with the use cases, pure *communication* (29 of 118) was another one of the major study task categories. Tasks include finding a hotel to share [29], introducing oneself [56], or describing some childhood memories [51]. While all of the studies supported some form of communication, the goal here was the conversation itself. Further noteworthy categories revolve around *giving and following instructions and advice*, such as following orders, training advice, or replicating the movements of others (21 of 118) (e.g., [100]) and *locating objects or other users in the shared environment* (21 of 118) [4]. Less common were tasks that required participants to extract or generate information (9 of 118), games (10 of 118), general walkthroughs (3 of 118), and avatar-centric tasks (6 of 118).

## 4.3 Study Methodology

Most studies focus on qualitative methods and user-reported feedback: In the 118 papers in our final set that report on a user study, user behavior was analyzed via *audio and video recordings* in 37 papers and with *interviews* in 43 papers. Different *questionnaires* were used to make the subjective opinions quantifiable.

An extensive set of established questionnaires, like the System Usability Scale (31 of 118), are used. Some of these questionnaires can also be grouped, focusing on *Social Presence* (39 of 118), like the Networked Minds Social Presence Inventory (NMSPI), *Spatial Presence* (14 of 118), like the MEC Spatial Presence Questionnaire (MEC-SPQ), or *Task Load Indices* (26 of 118), like the NASA-TLX. However, 79 papers used custom questionnaires, 5 of them exclusively.

Researchers also regularly collected quantitative measurements (49 of 118), like task completion times (e.g., [5]) or other performance-related values. Lastly, 12 papers also focus on *system-related measurements*, like latency (e.g., [20]) and frames per second (e.g., [114]),

[5]Interactive survey website: https://imldresden.github.io/mp-survey/
[6]We want to highlight that none of the categories are exclusive. For example, a paper may well cover multiple use cases or employ diverse study methods.

| Year | Device Limitations | General | Tracking | Display | Ergonomics | Scene Acquisition & Reconstruction | General | Point Cloud Level of Detail | Point Cloud Completeness | Point Cloud Stability | 3D Reconstruction | General Obj. Recognition & Alignment | Scale of Env. & Tracking Area | User Acqusition & Modelling | General | Hand Tracking | Face & Gaze Tracking | Body Tracking |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2016 | 1 | 0 | 0 | 1 | 0 | 2 | 0 | 1 | 1 | 1 | 2 | 0 | 1 | 2 | 1 | 1 | 0 | 0 |
| 2017 | 2 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| 2018 | 4 | 0 | 1 | 4 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 1 | 0 | 1 |
| 2019 | 8 | 1 | 2 | 7 | 4 | 4 | 1 | 0 | 1 | 0 | 3 | 1 | 0 | 3 | 1 | 1 | 2 | 1 |
| 2020 | 5 | 2 | 5 | 1 | 1 | 5 | 1 | 2 | 1 | 0 | 1 | 0 | 0 | 3 | 0 | 1 | 2 | 0 |
| 2021 | 5 | 2 | 3 | 0 | 0 | 7 | 1 | 1 | 0 | 2 | 1 | 2 | 2 | 3 | 1 | 3 | 3 | 1 |
| 2022 | 8 | 2 | 6 | 3 | 0 | 7 | 0 | 3 | 1 | 0 | 2 | 1 | 1 | 3 | 2 | 1 | 1 | 1 |
| 2023 | 14 | 3 | 8 | 5 | 2 | 10 | 3 | 4 | 2 | 3 | 1 | 3 | 1 | 11 | 5 | 4 | 2 | 3 |
| 2024 | 9 | 5 | 5 | 5 | 0 | 5 | 3 | 1 | 1 | 0 | 1 | 1 | 2 | 4 | 1 | 1 | 2 | 0 |
| 2025 | 6 | 1 | 1 | 3 | 1 | 3 | 0 | 2 | 2 | 1 | 1 | 0 | 2 | 6 | 0 | 3 | 1 | 3 |
| | 62 | 16 | 32 | 30 | 9 | 46 | 11 | 14 | 10 | 7 | 13 | 10 | 9 | 38 | 12 | 16 | 14 | 10 |

| Year | System Complexity | General | Heterogeneity & Interoperability | Devices & Sensors | Scalability | Computational Challenges | Latency & Real-Time Presentation | General | General Latency | Network Challenges | Bandwidth Issue | Performance | Synchronicity | Paper Count |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2016 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 5 |
| 2017 | 2 | 1 | 2 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 5 |
| 2018 | 1 | 0 | 1 | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 10 |
| 2019 | 3 | 0 | 1 | 2 | 1 | 0 | 4 | 0 | 2 | 0 | 0 | 1 | 2 | 18 |
| 2020 | 1 | 1 | 0 | 0 | 0 | 0 | 4 | 0 | 4 | 1 | 1 | 0 | 0 | 8 |
| 2021 | 5 | 0 | 0 | 2 | 2 | 2 | 4 | 1 | 1 | 3 | 2 | 1 | 1 | 13 |
| 2022 | 11 | 2 | 5 | 2 | 2 | 4 | 7 | 2 | 5 | 3 | 2 | 1 | 2 | 18 |
| 2023 | 18 | 4 | 7 | 6 | 6 | 3 | 14 | 2 | 8 | 4 | 5 | 4 | 3 | 35 |
| 2024 | 12 | 0 | 2 | 8 | 3 | 1 | 7 | 2 | 5 | 2 | 4 | 1 | 2 | 21 |
| 2025 | 3 | 0 | 0 | 1 | 2 | 0 | 6 | 0 | 4 | 3 | 3 | 0 | 0 | 14 |
| | 57 | 8 | 18 | 23 | 17 | 11 | 50 | 8 | 31 | 17 | 17 | 10 | 10 | |

**Figure 5: Overview of Technology challenges we discovered across 116 papers. Each cell within a row (i.e., year) is shaded based on how many papers focused on that challenge in the respective year, visualizing the relative development of that challenge over time (i.e., in a column). On the right, the overall number of papers for that year is shown.**

and 4 of those papers even solely report on such measurements [14, 33, 47, 159].

## 5 Challenges of Mixed Presence Systems

Having established the study background and research objectives of the systems in our corpus, we now discuss the extracted challenges. With this, we aim to provide an comprehensive overview over the diverse landscape of possible hurdles that might affect researchers during design, development and evaluation of their MP systems, preparing them for all contingencies. These challenges range from those related to the *Technology* (Sec. 5.1) to the two main components involved in such systems, the *Environment* (Sec. 5.2) and the *User* (Sec. 5.3). Additionally, we identified further *Cross-Cutting* challenges (Sec. 5.4). While many of these challenges are not unique to MP collaboration, addressing them is essential to achieving highly immersive MP systems. Each category contains a number of major themes (see Fig. 1) that are further divided into sub-themes. In the following, we will provide an overview of the identified themes, related sub-themes, and the associated number of papers that faced challenges in these areas.

Each category is accompanied by a figure, visualizing the distribution of papers that identified challenges within the themes and sub-themes across the years. Each cell contains the number of papers that mention a challenge in that theme in that year. The column sums are the total number of papers in our corpus that mention a respective challenge.[7] The background of the figures presents a *row-wise heatmap*, so a stronger shade means a higher percentage of papers in a year pointed out this sub-theme.

Fig. A1 shows a full list of themes and sub-themes. Further information including a complete overview of the corpus can be found in the supplemental material, as well as on our dedicated interactive website, presenting the entire corpus and its coding.

[7]A paper can hint at several challenges simultaneously, so the sum of the sub-themes does not necessarily add up to the theme's sum.

### 5.1 Technology

Different technologies must be combined to develop MP applications. This section will focus on challenges arising from these technologies and their combination (see Fig. 5).

T1 – *Device Limitations.* 62 out of 147 papers mention challenges regarding device limitations, making this category one of the largest in our corpus, proving this to be a foundational factor influencing design and development of such systems. The biggest share report *Tracking Limitations* (32 of 62), such as missing tracking capabilities (e.g., [51]), the loss of hand tracking mid-gesture (e.g., [65]), or eye tracking inaccuracies (e.g., [53]). (30 of 62) mention *Display Limitations*, with most of these specifically referring to issues caused by the limited field of view (FoV) of mostly optical-see-through-HMDs (e.g., [95]). Though, others also refer to the low resolution of video-see-through-HMDs (e.g., [96]) or display sensitivities, like needing specific lighting conditions for the displays (e.g., [143]). 9 papers further address *Ergonomic Issues*, such as head fatigue due to heavy headsets (e.g., [131]) or VR sickness (e.g., [96]).

T2 – *Scene Acquisition & Reconstruction.* To bring remote and co-located users into a shared space, many MP systems transmit data of the environment to remote collaborators, often as point clouds. Accordingly, 46 out of 147 papers report challenges in scene acquisition and reconstruction. Here, challenges related to the *Point Cloud Level of Detail* are the most prevalent (14 of 46), with papers generally describing issues with the resolution and density (e.g., [35]). Fewer papers mention the challenges regarding *Point Cloud Completeness* (10 of 46), describing dark spots (e.g., [131]) and depth shadows (e.g., [4]) or needing multiple depth cameras for a complete user reconstruction (e.g., [23]). Some papers also emphasize the *Point Cloud Stability* (7 of 46), naming examples such as distortion (e.g., [35]) and jitter (e.g., [135]). There is no standardized approach to capturing and processing environment point clouds in multi-user MR, making it a challenge for most researchers who do not specialize in it. The fact that MP spaces also combine shared physical and virtual artifacts and environments adds to the complexity. For instance, a large share of the papers (13 of 46) are concerned with issues regarding *3D Reconstruction*, talking about how it is a latency-inducing process (e.g., [56]), or produces visual artifacts (e.g., [92]). We also found challenges focused on *Object Recognition & Alignment* (10 of 46), describing difficulties when aligning real with virtual objects (e.g., [138]) or segmenting objects from busy backgrounds (e.g., [23]). 9 papers note issues related to the *Scale of the Environment & Tracking Area*, describing how avatars at the edge of the tracking volume were flickering (e.g., [92]), or how a limited tracking area affected user interaction (e.g., [55]).

T3 – *User Acquisition & Modeling.* Representing remote users in physical, real-world environments requires reliable tracking of their bodies and movements. 38 out of 147 papers mention facing challenges regarding user acquisition and modeling. Out of these, the biggest share (16 of 38) is concerned with challenges regarding *Hand Tracking*, describing inaccuracies such as occlusion and jitter (e.g., [150]) or those caused by gloves (e.g., [33]), and issues to differentiate hand ownership in co-located setups (e.g., [5]). The second largest mentioned theme (14 of 38) are issues with *Face & Gaze Tracking*. These include the necessity of additional sensors (e.g., [153]) and facial occlusion through HMDs (e.g., [109]). 10 papers further describe issues with *Body Tracking*, such as stiff movements (e.g., [141]), uncanny poses due to imperfect inverse kinematics (e.g., [95]), or needing additional hardware (e.g., [153]). 12 papers further describe *General Challenges* with user acquisition & modeling, pointing out issues such as difficulties determining head or hand poses in handheld AR (e.g., [70]), partial avatar reconstructions from incomplete point clouds (e.g., [23]), and the costs of realistically reconstructing users (e.g., [56]).

T4 – *System Complexity.* MP systems often necessitate a complex combination of various devices and sensors in multiple locations. With 57 out of 147 papers mentioning challenges in relation to system complexity, this and T1 are the largest categories in our corpus. The biggest concern regarding system complexity is *Quantity and Particularity of Devices & Sensors* (23 of 57), with the focus being on the need for high-end (e.g., [92]) and specialized (e.g., [20]) hardware, which leads to a complex setup (e.g., [16]). The *Heterogeneity & Interoperability* of devices is mentioned slightly less frequently (18 of 57), where the research describes difficulties with asymmetric device capabilities (e.g., [91]) resulting in experience gaps between devices (e.g., [151]), and enabling dynamic spaces that can be accessed from various displays (e.g., [23]). Another similarly frequently reported challenge is *Scalability* (17 of 57), in terms of flexibly allowing more users to participate (e.g., [47]) and incorporating a growing number of input and output channels (e.g., [133]). A slightly smaller amount of papers (11 of 57) hint at issues with *Computational Limitations*, which is mainly in regards to real-time rendering, such as needing multiple GPUs for real-time point cloud processing (e.g., [92]), limited capacities for decoding multiple video streams (e.g., [133]), and using remote rendering solutions to decrease the workload for the HMDs (e.g., [100]).

T5 – *Latency & Real-Time Presentation.* Ensuring lag-free real-time interaction and representation is essential for MP systems, since local users can directly compare interactions with remote users to co-located participants. 50 out of 147 papers mention encountering challenges in this pursuit. The biggest share of the papers (31 of 50) broadly report on aiming to reduce the *General Latency* to prevent delays during audio (e.g., [109]), video (e.g., [102]) transmission or during tracking (e.g., [152]). 17 out of 50 papers describe specific *Network Challenges* such as dealing with network outages (e.g., [1]) and building custom network architectures to meet the demands (e.g., [153]). The same amount of papers (17 out of 50) also mention specific issues and requirements regarding the *Bandwidth*, transmitting large amounts of data, such as point clouds (e.g., [69]), and mentioning how to prioritize data in the case of limited capacity (e.g., [1]). Another set of papers (10 of 50) is concerned with the topic of *Performance*, such as reducing point cloud refresh rates to guarantee 90 fps (e.g., [61]) or pre-processing highly detailed models to display them smoothly and natively on the headset (e.g., [138]). Lastly, 10 papers report on challenges with *Synchronicity*, among other things, describing efforts to synchronize shared objects (e.g., [16]), and real objects with their digital twins (e.g., [138]).

*Insights.* As the devices involved in MP applications evolve, one would expect to see fewer challenges regarding *device limitations*. However, as seen in the development of *Technology* challenges over time (see Fig. 5), such challenges persist, suggesting that technology is either not yet sufficient or that the expectations raised by the level of technological maturity are not being met. As technology advances, system complexity may decrease, as state-of-the-art HMDs already incorporate many previously separate components. However, novel use cases can, in turn, lead to larger and more heterogeneous device ensembles. This is supported by the data, which clearly shows that challenges related to *system complexity* have become more prominent since 2022. Similarly, we have seen a greater focus on challenges of *latency and real-time presentation* since 2022. It is apparent that developers of MP systems must often either invest significant effort in developing a suitable network architecture or carefully consider whether the components of their system align with the given network capabilities.

## 5.2 Environment

MP systems rely on a shared 3D interaction and communication space. This section will focus on the challenges of creating and maintaining such a space (see Fig. 6).

E1 – *Spatial Consistency.* For seamless interaction in MP, remote and co-located collaborators must have a common understanding of the layout of their shared space. 31 out of 147 papers mention challenges with spatial consistency in their work. (23 of 31) specifically address challenges regarding *Calibration and Alignment*. Here, most works talk about combining different coordinate

| | Spatial Consistency | General | Calibration & Alignment | Shared & Blended Environment | General | Dissimilar Spaces | Shared Objects | Virtual Content Positioning | Physical & Spatial Limits | Controlling Real-World Properties | Spatial Awareness & Orientation | General | Locating Objects & Users | Dynamic Changes | Comm. about the Environment | Paper Count |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2016 | 1 | 1 | 0 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 5 |
| 2017 | 0 | 0 | 0 | 3 | 1 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 2 | 5 |
| 2018 | 2 | 1 | 2 | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 3 | 0 | 2 | 1 | 2 | 10 |
| 2019 | 3 | 0 | 3 | 5 | 1 | 3 | 1 | 0 | 0 | 0 | 5 | 1 | 1 | 3 | 2 | 18 |
| 2020 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 8 |
| 2021 | 3 | 1 | 2 | 6 | 0 | 3 | 1 | 2 | 0 | 3 | 2 | 0 | 2 | 1 | 0 | 13 |
| 2022 | 6 | 2 | 4 | 5 | 1 | 2 | 3 | 3 | 3 | 1 | 10 | 4 | 5 | 3 | 3 | 18 |
| 2023 | 8 | 0 | 8 | 13 | 7 | 3 | 2 | 1 | 1 | 0 | 10 | 3 | 3 | 4 | 1 | 35 |
| 2024 | 6 | 5 | 2 | 12 | 2 | 5 | 7 | 3 | 2 | 1 | 5 | 3 | 1 | 2 | 1 | 21 |
| 2025 | 0 | 0 | 0 | 11 | 2 | 6 | 2 | 5 | 3 | 1 | 4 | 1 | 3 | 0 | 4 | 14 |
| | 31 | 10 | 23 | 59 | 15 | 24 | 17 | 15 | 10 | 6 | 43 | 13 | 28 | 14 | 16 | |

**Figure 6: Overview of Environment challenges we discovered across 81 papers. Each cell within a row (i.e., year) is shaded based on how many papers focused on that challenge in the respective year, visualizing the relative development of that challenge over time (i.e., in a column). On the right, the overall number of papers for that year is shown.**

systems (e.g., [111]), calibrating cameras and tracking hardware accordingly (e.g., [154]) and issues with misaligned objects (e.g., [30]). *General Challenges* are mentioned by 10 papers, including needing to register physical props in an AR scene (e.g., [139]).

E2 – *Shared & Blended Environment.* In an MP space, the physical environments of the users can differ greatly. For seamless interaction, a shared space must be created. 59 out of 147 papers report challenges in this area. Out of those, the biggest share of papers (24 of 59) is concerned with the challenges caused by *Dissimilar Spaces*, such as uniting differing physical spaces into one virtual space (e.g., [146]), avoiding fractured ecologies (e.g., [51]), and sharing physical artifacts (e.g., [51]). Many papers (17 of 59) mention challenges and requirements when it comes to *Shared Objects*, 15 out of 59 papers note *Virtual Content Positioning* to be important, identifying occlusion as a problem when overlaying real objects with virtual ones (e.g., [135]), and taking the limited FoV of some devices into account by providing virtual content primarily at these user's eye level (e.g., [118]). Some papers (10 out of 59) also point out *Physical and Spatial Limits* as difficult factors, mentioning the limited space to move in VR (e.g., [58]) and how some objects might be unreachable due to physical limitations in differing environments (e.g., [29]). A comparatively small number of papers (6 of 59) talk about *Controlling Real-World Properties*, where remote users are supposed to influence the local space (e.g., [158]) and virtually control physical objects (e.g., [98]). 15 papers mention further *General challenges* in regard to shared and blended environments, such as overlapping avatars of users from different spaces (e.g., [155]).

E3 – *Spatial Orientation & Awareness.* As shared and blended MP environments combine different virtual and real-world objects, they become hard to navigate. 43 out of 147 papers report challenges in the realm of spatial orientation and awareness. A large share (28 of 43) mention that *Locating Objects and Users* is difficult in these environments, talking about how a limited FoV contributes to objects and users being out of sight (e.g., [85]), which is why awareness cues should indicate the relative positions of other users (e.g., [95]). 16 out of 43 papers identify *Communication about the Environment* as particularly challenging, specifically communicating about the physical space (e.g., [22]), enabling spatial referencing (e.g., [82]) as well as referential pointing (e.g., [27]). Another factor (14 of 43) are *Dynamic Changes* in these environments, for example, when objects or users are added to or removed from the environment [29], when users lose track of each other when teleporting (e.g., [30]), or when they are approaching each other from out of view (e.g., [95]). 13 papers mention *General Challenges* regarding spatial orientation and awareness, such as reorientation when changing environments (e.g., [132]) and communicating system states, such as calibration status (e.g., [29]).

*Insights.* The *Environment* challenges (see Fig. 6) reveal that while tracking support through spatial anchors and QR codes is commonly available, ensuring spatial consistency remains challenging, partly due to the complexity of integrating diverse devices. Although no clear trend over time can be observed, matters of spatial awareness and orientation continue to pose problems, which highlights the need for improved awareness cues, intuitive communication tools, and strategies to support users in navigating dynamic and complex MP spaces. This becomes more important in *shared and blended environments*, a strong, recent trend as indicated by the number of related challenges mentioned in our corpus. Currently, there is no one-size-fits-all solution to blending different environments, as the ideal approach depends on diverse factors and use cases. This makes it a promising area for exploration to advance the adaptability of MP systems across various applications.

## 5.3 User

MP systems are used as collaborative or communication tools for different groups of users. This section will focus on challenges related to the users of such a system (see Fig. 7).

U1 – *User Representation & Techniques.* Representing remote users in MP systems is essential for seamless communication, independent of user's location. In MP systems, avatars have to co-exist with real people without looking out of place. 39 of 147 papers cover resulting challenges in user representations. Achieving high *Levels of Detail & Accuracy* (26 of 39) is difficult, especially for facial expressions, and is often hindered by technology limitations [153]. This includes general accuracy problems, but also the effects of facial levels of detail on presence (e.g., [56]), or how to virtually remove headsets from camera-captured user representations (e.g., [92]), and even the use of robots to embody users (e.g., [48]). Another main concern is the choice of a fitting *Avatar Design* (17 of 39) for the use case, setting, and research goal. Interestingly, 8 of those papers also point towards concerns about the level of detail & accuracy, showing how closely related these aspects are. The user should identify

| | User representation & techniques | General | Level of Detail & Accuracy | Avatar Designs & Uncanny Valley | Communication & Sensory Feedback | General | Gestures | Facial Expressions & Eyes | Non-Verbal | Verbal | Physical Props & Haptic Feedback | Interpersonal Awareness | General | Gaze & View Sharing | Content & Intention Sharing | Cognition & Presence | General | Co- & Social-Presence | Presence | Cognitive & Mental Load | Accessibility & Inclusion | Paper Count |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2016 | 1 | 0 | 1 | 1 | 4 | 0 | 3 | 2 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 |
| 2017 | 1 | 1 | 1 | 1 | 2 | 0 | 1 | 1 | 1 | 0 | 0 | 3 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 5 |
| 2018 | 2 | 1 | 1 | 1 | 4 | 0 | 2 | 1 | 1 | 1 | 1 | 3 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 10 |
| 2019 | 4 | 1 | 3 | 2 | 8 | 0 | 2 | 1 | 3 | 3 | 0 | 8 | 3 | 4 | 4 | 4 | 0 | 3 | 1 | 2 | 1 | 18 |
| 2020 | 2 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 4 | 1 | 4 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 8 |
| 2021 | 4 | 3 | 2 | 3 | 4 | 1 | 1 | 3 | 1 | 1 | 0 | 2 | 1 | 1 | 0 | 2 | 1 | 2 | 0 | 0 | 2 | 13 |
| 2022 | 4 | 2 | 3 | 0 | 7 | 1 | 3 | 1 | 2 | 3 | 2 | 8 | 0 | 6 | 4 | 4 | 0 | 3 | 0 | 1 | 0 | 18 |
| 2023 | 7 | 2 | 4 | 2 | 12 | 1 | 3 | 2 | 3 | 5 | 2 | 8 | 4 | 1 | 3 | 7 | 0 | 3 | 2 | 2 | 2 | 35 |
| 2024 | 8 | 2 | 5 | 4 | 8 | 0 | 3 | 2 | 2 | 4 | 1 | 3 | 0 | 3 | 2 | 6 | 0 | 2 | 1 | 3 | 3 | 21 |
| 2025 | 5 | 2 | 5 | 2 | 6 | 1 | 2 | 3 | 5 | 1 | 2 | 1 | 0 | 0 | 1 | 6 | 3 | 3 | 0 | 3 | 1 | 14 |
| | 38 | 14 | 26 | 17 | 56 | 4 | 20 | 16 | 18 | 20 | 8 | 41 | 10 | 23 | 19 | 30 | 5 | 16 | 4 | 11 | 10 | |

**Figure 7: Overview of User challenges we discovered across 95 papers. Each cell within a row (i.e., year) is shaded based on how many papers focused on that challenge in the respective year, visualizing the relative development of that challenge over time (i.e., in a column). On the right, the overall number of papers for that year is shown.**

with their avatar and feel embodied by it [55]. Avoiding the *Uncanny Valley* effect [81] while mapping user features to the avatar is a challenge mentioned by most (e.g., [25, 51, 92, 141]). Some papers ask how realistic avatars should be (e.g., [149]) or how to get users to identify with their representations (e.g., [55]). Other *General Challenges* regarding user representations (14 of 39) include considerations of scale (e.g., [2, 57]), occlusion (e.g., [39, 70]), and how to represent users when only devices are tracked (e.g., [34, 111]).

U2 – *Communication & Sensory Feedback.* Effective communication is a core aspect of collaborative MP systems. Thus, it is not surprising that we found 56 out of 147 papers dealing with challenges in this area. Interestingly, the largest sub-theme (20 of 56) describes challenges regarding (hand) *Gestures*, such as insufficient gesture recognition (e.g., [128]) and ambiguous pointing (e.g., [82]). A slightly smaller set (18 of 56) discusses *Non-Verbal Cues* in a general manner (e.g., [70, 141]) or mentions other challenges in this area, such as sketches & annotations (e.g., [60]). Further, (16 of 56) papers discuss more specific challenges regarding *Facial Expressions & Eye Gaze.* In addition to a general lack of facial expressions being pointed out (e.g., [31, 95]), we also saw discussions about the expressiveness of emotions (e.g., [56]) and problems with occlusion through HMDs (e.g., [23, 92, 109]). On the other hand, challenges with *Verbal* communication (20 of 56) include evaluating and implementing the correct audio source placement (i.e., to support spatial audio [29]). Here, we noticed that several publications circumvented the implementation of directed spatial audio and instead substituted it with stationary microphones and/or speakers (e.g., [50, 109]) or a quasi-remote approach, with co-located actors separated by a divider (e.g., [7, 12]). Lastly, a small set of papers (8 of 56) talk about challenges with *Physical Props & Haptic Feedback*, noting a lack of haptic feedback, hindering users from physically engaging with each other during a conversation ([25]). Several papers address this by providing haptic feedback through tangibles (e.g., [41, 139]), even including actuated tangibles in the form of small robots (e.g., [48, 142]).

U3 – *Interpersonal Awareness.* Shortcomings of MP systems, e.g., inaccurate tracking or a limited FoV, can impair users' awareness of their collaborators, actions, and goals. Therefore, it is especially important to support users in equally perceiving their physical and virtual co-actors' presence and intentions, for a fair and balanced experience. Accordingly, many sources in the literature recognize awareness support as a necessity, leading to 41 of 147 papers in our set discussing this issue. Many papers (23 of 41) deal with *Gaze & View Sharing*, i.e., visualizing where others look (e.g., [22, 156]). While common approaches allow visualizing the viewing direction and sharing the view or the content directly [156], cluttering an environment with awareness support features can also become distracting (e.g., [54, 143]). Another important group of challenges in this section revolves around view independence, the ability to choose one's view independently of that of another user. This mainly affects systems where a target environment or object is only captured by an on-site user and then viewed by a remote collaborator (e.g., [27, 96]). A slightly smaller set (19 of 41) relates to *Content & Intention Sharing*, i.e., conveying planned future actions or objects of reference (e.g., [60, 82]). It most often deals with the need for spatial referencing, usually by pointing at objects (e.g., [52, 82, 97]). However, it also covers challenges such as knowing whether point clouds of the environment have been successfully shared (e.g., [85]), how sketches can help to solve ambiguities in a user's intention (e.g., [60]), and even just knowing where other users are when they are not in view (e.g., [95]).

U4 – *Cognition & Presence.* Overall, 30 of the 147 papers discuss issues in the area of general cognition and mental load, as well as spatial and social presence, with an increasing interest over time (see Fig. 7). A large share of these (16 of 30) specifically mention challenges in *Co- & Social Presence*. For example, they mention a need to create the illusion that all users are in the same environment (e.g., [51]) and investigate how to better include remote users (e.g., [55, 156]). Achieving high co- and social presence is one of the core goals of MP systems, which is highlighted by the amount of papers evaluating it (see Sec. 4.3). The comparatively low number of related challenges is not surprising, as a decrease in co- or social presence is rarely described as a challenge itself, but rather as the result of another issue. 4 of 30 papers mention general threats to *Presence*: heterogeneous devices lacking immersion [88], collision issues with avatars being placed inside each other [50], and distraction from audio not directed at them [97]. Another group of challenges (11 of 30) describes that such issues not only impact presence but also potentially increase the *Cognitive & Mental Load* of users. This usually includes the impact of additional visualizations or visual cues (e.g., [54, 60]) or concerning spatial disassociation (e.g., [83, 156]).

U5 – *Accessibility & Inclusion.* Supporting a wide variety of users is essential to MP systems. However, only 10 of 147 papers in our corpus discuss *Accessibility & Inclusion* [40, 55, 66, 67, 141, 151]. This includes factoring in basic bodily properties like height and length of limbs but also supporting people with different types of disabilities, such as visual and auditory impairments [40] and those who are deaf or hard-of-hearing [67], as well as addressing problems with motion sickness [66] or general UI problems like small text sizes [141]. Another paper also mentions the challenge of matching the gender and ethnicity of users in the avatar design [151], a topic that has seen recent advances in the XR community (e.g., [18]).

*Insights.* Examining the *User* challenges (see Fig. 7), no clear trend is visible for the *user representation*, which remains a challenge. Developers should evaluate whether full-body realism is necessary for their use case or if simpler representations are sufficient, while also considering the impact of abstraction on embodiment and social presence. Furthermore, the large number of challenges reported suggests that, generally, delivering comprehensive *multi-sensory feedback* in MP communication is highly complex. So, research should not only focus on transmitting realistic experiences but also sufficiently substituting them if necessary. Since 2019, questions of *cognition and (co-)presence* have become an important focus. The data suggest a slight trend from questions of *interpersonal awareness* towards these more complex aspects, indicating their importance to the notion of mixed presence. Finally, the limited attention to *accessibility and inclusion* evident in our corpus does not indicate a general lack of interest in these issues, but rather suggests that much of the existing research in this area is conducted outside the context of MP environments. We believe these aspects need to be specifically evaluated in the context of MP.

## 5.4 Cross-Cutting

In addition to the three previously described categories of challenges, we also identified cross-cutting challenges (see Fig. 8).

C1 – *Asymmetric Experiences.* MP systems combine several environments and their information. Handling the resulting asymmetric experience poses significant challenges, and 39 out of 147 papers

| | Asymmetric Experiences | General | Content & Environment Sharing | Interaction & General Capabilities | User Representation | Awareness on Shared Personal Inf. | Interaction & UI Design | General | Workflow | Annotations | Adaptive & Customizable UI | Evaluation & Studies | Domain & Use Case Specific | Data Privacy & Security | Paper Count |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2016 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 5 |
| 2017 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 5 |
| 2018 | 3 | 0 | 2 | 0 | 1 | 0 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 10 |
| 2019 | 6 | 0 | 6 | 4 | 0 | 1 | 7 | 5 | 1 | 2 | 1 | 0 | 2 | 1 | 18 |
| 2020 | 4 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 3 | 1 | 0 | 8 |
| 2021 | 5 | 3 | 2 | 2 | 0 | 1 | 8 | 3 | 3 | 1 | 1 | 2 | 3 | 0 | 13 |
| 2022 | 5 | 1 | 3 | 2 | 1 | 1 | 6 | 4 | 2 | 1 | 0 | 3 | 1 | 0 | 18 |
| 2023 | 5 | 0 | 2 | 2 | 1 | 1 | 10 | 6 | 5 | 3 | 2 | 3 | 6 | 3 | 35 |
| 2024 | 5 | 0 | 3 | 2 | 1 | 0 | 7 | 5 | 1 | 0 | 2 | 1 | 3 | 0 | 21 |
| 2025 | 4 | 1 | 1 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 3 | 2 | 14 |
| | 39 | 6 | 20 | 16 | 6 | 5 | 44 | 29 | 12 | 7 | 6 | 13 | 20 | 6 | |

**Figure 8: Overview of Cross-Cutting challenges we discovered across 81 papers. Each cell within a row (i.e., year) is shaded based on how many papers focused on that challenge in the respective year, visualizing the relative development of that challenge over time (i.e., in a column). On the right, the overall number of papers for that year is shown.**

mention them. The majority (20 of 39) are concerned with *Content and Environment Sharing* in asymmetric spaces, such as fixed camera placement for non-mobile non-HMD users in a shared 3D environment (e.g., [88]), distance distortion and incorrect depth perceptions when a 3D environment is accessed on a 2D display (e.g., [22]), and how depth cues are needed for the 2D side (e.g., [12]). The second largest share (16 of 39) is *Interaction & General Capabilities*, talking about inconsistent abilities across different device classes (e.g., [158]), and enabling joint spatial referencing through pointing and gaze sharing in an asymmetric setups (e.g., [46]). Some works (6 of 39) mention differing *User Representations* in asymmetric environments, including the effect on co-presence (e.g., [118]). Another aspect to consider is the *Awareness of Shared Personal Information*, which is mentioned by 5 papers. This includes the need to communicate other users' abilities (e.g., [55]) and what users share with others (e.g., [135]).

C2 – *Interaction & UI Design.* In our corpus, 44 out of 147 papers mention challenges of interaction and UI design. A big share of those (12 of 44) is specifically concerned with the *Usage Workflow*, such as manual calibration steps (e.g., [11]), and pre-constructing physical objects (e.g., [69]) or avatars from photogrammetry setups (e.g., [153]). Another notable theme, which is mentioned by 7 out of 44 papers, revolves around *Annotations*. They are mostly used to aid communication regarding positions in 3D space (e.g., [30]) but are susceptible to misalignment (e.g., [30]) or referencing the wrong objects in dynamic environments (e.g., [115]). Some papers (6 of 44) mention topics regarding *Adaptive & Customizable UIs*, specifically about supporting users to configure their collaborative environment (e.g., [37]), also by providing virtual tool boxes for a specific usage context (e.g., [51]). In this category, the *General Challenges* is the largest sub-theme (29 of 44), probably because each system has very specific requirements for interaction and design, which can hardly be grouped into more overarching topics.

C3 – *Evaluation and Studies.* MP applications are highly complex systems combining different technologies, environments, and users. While crucial, evaluating these systems is also exceedingly challenging, including the development, implementation, and analysis of user studies. 13 out of 147 papers describe challenges regarding evaluation and studies. Since many of these systems revolve around guidance by remote experts, the limited availability of experts is an influential difficulty (e.g., [74]). Others mention difficulties optimizing the combination of subjective and objective measures (e.g., [91]), and the need for longitudinal studies across different labs (e.g., [139]).

C4 – *Domain and Use Case Specific.* Some of the papers in our corpus (20 of 147) also list challenges that are mainly relevant to their specific domains and use cases.[8] The challenges in this category include those for outdoor scenarios, such as tracking large-scale environments under changing lighting conditions (e.g., [90]), and challenges for medical systems, such as rigorous clinical evaluation and tests (e.g., [33]) and interaction with non-sterile devices (e.g., [74]).

C5 – *Data Privacy and Security.* In MP systems, a lot of information about users, their environments, and their actions is collected and transferred over the network. Few papers in our corpus (6 of 147) address the cross-cutting issue of providing privacy and security in distributed systems. They acknowledge the need for data encryption (e.g., [11]) and access management (e.g., [138]) or are concerned about data privacy in a health context (e.g., [33]) or in regard to eye tracking data (e.g., [134]).

*Insights.* In the area of *Cross-Cutting* challenges (see Fig. 8), we see several underrepresented aspects. Regarding *evaluation & studies*, the required number of participants, ideally in different locations, just to test an MP system under realistic conditions, is especially challenging for the often small teams in academic research. However, this topic is typically not discussed within the scope of scientific papers. Similarly, the lack of research on matters of *domain & use case* specific challenges, as well as on *privacy and security*, may be explained by the primarily academic setting, often focused on study purposes and technological feasibility rather than real-world deployment. Missing privacy and security mechanisms also do not immediately affect a system's usability, which is why they may be frequently overlooked and often not considered a necessity to address in controlled environments.

Evidently, there are also many challenges regarding *asymmetric experiences* and general *interaction and UI design*. When MP systems become device-inclusive and broadly accessible, experiences will become even more asymmetric, necessitating strategies to compensate for this. We believe that MP-specific modular frameworks and tools are elementary to not only support the efficient design of tailored UIs, but to facilitate productive MP research in general, as the initial implementation overhead slows down processes and can discourage researchers.

[8]See Sec. 4.1 for an overview of the use cases.

# 6 Future Directions and Research Opportunities

Through our intensive survey on the topic of Mixed Presence, we identified and categorized a wide range of challenges, as a base to identify key areas for future research. To better explore these potential research directions for future MP systems, we conducted an expert workshop, a method successfully used in prior work such as [147]. Building on the identified categories and based on the initial corpus of papers[9], we encouraged workshop participants to derive further topics and outline the most important research objectives for the suggested topics.

Below, we first describe the details of this workshop before presenting the resulting collection of future research directions consisting of eight main categories (see Sec. 6.1 to 6.8).

**Workshop on Mixed-Presence Challenges** Five authors of this paper conducted the workshop with ten invited researchers. As apparent from our extracted challenges, the topic of MP branches out into many adjacent research directions, which is why we deliberately opted for diverse expertise to get perspectives beyond our own preconceptions. The experts cover several relevant fields of research, such as Mixed Reality (eight participants, four with expertise in MR collaboration), general HCI (5), Visualization (4), Computer Graphics (4), and Machine Learning & Computer Vision (4). On average, the external participants had eight years of academic experience in their fields. Overall, the 15 participants comprised two professors, four PostDocs, and nine PhD students.

The half-day workshop was conducted on-site, one participant joined remotely. Participants received a reduced version of this paper (i.e., Sections 4 and 5 and the MP definition) a few days in advance to ensure that they were familiar with our definition of Mixed Presence and the survey-derived challenges. Participants were asked to reflect on the survey results, open questions, and potential research directions from the perspective of their own fields. Starting the workshop, we first introduced the topic, collected participants' initial thoughts and presented an initial list of seven breakout topics[10] as a discussion basis. Participants could refine and adjust these, which resulted in a set of nine topics, mixing author-prepared and participant-proposed directions. We then decided on the group constellations for the following breakout sessions, lasting 30 minutes each. At least one author joined each group, contributing to the discussion and taking notes. After the sessions, we collected the final thoughts and debriefed participants. Using affinity diagramming [42], the authors then clustered their session notes across groups, and, informed by the survey challenges, synthesized major topics and novel research questions raised during the workshop. This yielded eight topics that form the research agenda presented in the following, which are also summarized in Fig. 9. The complete workshop material, including the initial and proposed topics set, is provided as supplemental material.

[9]The workshop took place after we ran our query on July 3rd, 2024 (yielding 805 publications). Our corpus was later updated on June 26th, 2025 (adding 157 papers.)
[10]Based on the author's reflections on the challenges and future research directions from our survey.

## 6.1 Handling System Complexity

MP environments involve multiple people, their representations, and shared physical and virtual objects, while potentially incorporating heterogeneous devices. From our data, it is immediately clear that system complexity is a significant development challenge (see Sec. 5.1, T4). In light of this complexity, it is important to ask: *Just because we can capture, transmit, and reconstruct all this data, does it mean we need to?* Together with our workshop participants, we collected research questions surrounding this core trade-off.

**Investigate the necessary level of immersion and how it contributes to successful MP systems** A central question that came up in our discussions is how much immersion on a technical level is necessary for mixed-presence systems. This results in research opportunities to examine which qualities of MP systems actually affect collaboration, a feeling of presence, or even just the general user experience. For example, full-body tracking or visually realistic avatars might not always be necessary to support MP group work.

**Define a core set of standard collaborative features and tools for MP systems** A guiding question for future work that came up during the workshop was what the equivalents of the default artifacts and techniques used in traditional, co-located scenarios are. That is, what are the whiteboards, pens, and paper of mixed-presence systems? We believe that future research into this question will help to define a core set of necessary features of MP systems.

**Investigate how MP systems can support mobile and dynamic settings** Current MP systems mostly connect a set number of people in fixed places. However, we believe future MP systems will support dynamic setups and workflows. Here, system complexity comes from, e.g., dynamically switching contexts or scaling systems up or down. Collecting best practices to support, e.g., mixed mobile and stationary use will be another future research objective.

**Examine affordances to aid discoverability of MP system capabilities** Due to the system complexity and the dynamics of novel use cases in MP system design, future applications may offer varying services and capabilities. A future research objective is how to communicate these services to the users through clear and thoughtful [107] applied affordances: How can users discover the capabilities of a given MP system, e.g., with respect to interacting with the environment?

## 6.2 Blended Realities

MP systems aim to achieve a feeling of belonging and immersion, allowing each participant to contribute and experience equally. Blending the different realities of the participants is therefore of utmost importance, as also discussed by the publications in our corpus (see Sec. 5.2, E2).

**Investigate how to merge different physical spaces based on object relevance** Although approaches to fuse dissimilar environments into a single coherent scene have already been presented (e.g., [44, 146, 148]), merging widely different or highly dynamic environments remains challenging. Since most merges are only partial, the *relevance of environmental features or objects* is important. To this end, future research should investigate how to determine, in real time and depending on the context, which objects are relevant and should therefore be shared across environments.

**Develop effective representations of shared environmental features in MP systems** Representing virtual environments encompasses general considerations of rendering techniques, styles, and performance concerns. However, the representation of partially shared environments raises even further questions. This includes how to highlight dynamic or interactive parts of the remote environment. Sharing one's environment naturally also brings up privacy issues (see Sec. 6.6), and research is needed on how to make local users aware of how much of their own environment is shared with remote users and in which way.

**Investigate the use of physical artifacts in MP environments** In addition to larger geometric features, specific objects can also be of interest for any given communication. Such objects may be directly related to the session, e.g., a building model in an architectural planning meeting; they could be used as a stand-in, e.g., to visualize a concept; or they may even be used as tangible input devices. Future research should investigate how semantically meaningful objects can be captured and shared with remote users and how meaning (and functionality) can be assigned to objects and communicated at runtime.

## 6.3 Developing, Testing, and Evaluating Mixed Presence

Developing and studying MP systems is complicated, resulting in many issues surrounding technical complexity (see Sec. 5.1, T4). MP systems combine the logistical challenges of distributed multi-user systems with the uncertainties of developing for evolving cutting-edge HMD hardware, affecting the development and testing process.

**Identify suitable baselines and references for comparing MP systems** We should question the gold standard status of classic in-person meetings. As Holan & Stornetta pointed out, *"the efficacy of imitating face-to-face communication is an unquestioned presupposition"* [45], for electronic communication that may not always hold. Therefore, future research should focus on working out common tasks, datasets, and benchmarks necessary to compare different systems.

**Support the development and evaluation of MP systems by simulating users, sensors, or the environment** One of the practical problems when working on MP systems is the setup, including all sensors, clients, etc. We believe that mock-ups using recorded data streams and clever simulations of sensor or even user data can address this issue. Still, research is necessary on how to effectively record and playback the complex multi-input-stream events of MP systems and how to guarantee consistency between simulated and real data sources. Furthermore, investigating whether AI agents could reliably simulate real users and their behaviors is an interesting research objective.

## 6.4 Representation, Cognition, and Presence

A key promise of mixed-presence systems is to allow everyone to feel present, implying that communication, representation, and interaction feel natural (see Sec. 5.3, U1 and U4). During the workshop, we agreed that for something to feel natural, it does not need to look photorealistic. Also, for a satisfying experience, users should feel included.

**Investigate how side-by-side comparison with physically present humans shapes avatar design requirements** It is unclear if previous research on the effects of avatar realism and completeness in MR can be directly applied to mixed-presence environments since these spaces allow users to compare remote avatars to physically present individuals directly. While a simple head and hands avatar might suffice for some tasks, seeing it next to a physical human being might emphasize the incompleteness in an irritating way.

**Examine how perception gaps between co-located and remote users impact collaboration and whether multi-sensory compensation cues can close them** Due to technical aspects, e.g., the limited FoV of some headsets, it is harder to perceive and be aware of remote users compared to co-located users, which potentially introduces bias and results in unequal treatment. Additional awareness support, such as custom multi-sensory cues (e.g., vibrotactile or thermal), might help keeping track of virtual co-actors and equalize interpersonal perception.

**Investigate how device capabilities influence task and role distribution in groups** It is still unclear to what extent feelings of (co-) presence in MP depend on technological and contextual factors, and how different device capabilities (e.g., when using a tablet instead of an HMD) determine which tasks and roles users are assigned. Here, researchers would benefit from a taxonomy encompassing common tasks, roles, and capability distribution in mixed-presence environments. Based on this, experiments can be designed to determine in which situations equal capabilities and opportunities are preferable, and when roles tailored to specific capabilities lead to better outcomes.

**Examine the effects of MP on social dynamics and whether local or remote participants experiences disadvantages** Since virtual co-actors might differ greatly from co-located ones, research should also consider whether they are being treated differently. Social factors such as interpersonal attention, empathy, trust, and our tolerance for social norm violations need to be evaluated, investigating whether one or the other group is negatively affected during group activities. Research should also look into how virtually versus physically present co-actors affect proxemics.

## 6.5 Somatosensory Feedback and Multi-Sensory Experiences

The absence of a physical body in the scene is the main notable difference between local and remote actors, removing touch as a communication channel. Our survey showed that haptic feedback in the MP context is comparatively underexplored (see Sec. 5.3, U2). However, this is not the only sensory channel traditionally unavailable to remote participants. In the workshop, we discussed the following research directions:

**Examine the social and safety implications of haptic and simulated touch experiences in MP** Interpersonal affective touch has been recognized as an important communication channel [17, 24], so haptic technologies could be an impactful contribution to distributed MR. Given the scarcity of this technology research should consider whether simulated interpersonal touch sensations (e.g., visually emphasizing when touch occurs among remote actors) can also enhance the feelings of co-presence, trust, or empathy with virtual actors in an MP setting. Considering the safety risks in multi-user multisensory environments [64], it is imperative to explore how users can be supported in upholding personal boundaries regarding transmitted touch sensations, and how these boundaries differ when comparing physically and virtually present co-actors.

**Study the impact of asymmetry in touch capabilities between local and remote users** Future research should investigate whether haptic technologies are able to bridge the gap between physically and virtually present participants, and further examine the implications of asymmetric touch experiences in MP environments. For example, if I can feel the high-five of one colleague but not the other, it might affect our relationship dynamic.

**Investigate the role of non-audiovisual sensory cues in MP and their impact on mood and co-presence for remote participants** Most people predominantly perceive information audio-visually. However, other sensory experiences, such as smell or temperature perception, can be crucial in establishing a common understanding of the current scene. Co-located users have a unique shared multi-sensory experience that remains largely hidden from the remote co-actors. Here, the importance of additional sensory experiences should be explored, creating a hierarchy of senses, and informing the design of sensory substitutions, which would also benefit physically impaired individuals (see Sec. 6.7).

## 6.6 Privacy and Safety

MP environments also unite the dangers of co-located and distributed multi-user scenarios. However, we find that privacy and safety aspects remain unjustifiably underexplored (see Sec. 5.4, C5), which is why we discussed the following topics in our workshop:

**Analyze security and privacy vulnerabilities in MP and design safeguards to prevent unauthorized access and user profiling** MP spaces potentially create new abuse scenarios and security threats by transferring rich data streams across the network, like video, audio, biometrics, and environmental scans. These streams can inadvertently disclose sensitive personal information, which must be protected from accidental sharing and malicious unauthorized access. Therefore, threat models should be developed specifically for MP systems. Moreover, the data collected in MP systems provides deep insights into a user's habits, preferences, and even relationships with others. To prevent misuse, it is crucial to establish technical and ethical safeguards that limit user profiling and surveillance.

**Develop mechanisms to prevent involuntary bystander sensing and design user-controlled protection tools** Sensors in MP systems rarely differentiate between active participants and bystanders who have not consented to being tracked or monitored. This necessitates robust protection mechanisms and the design of tools to empower users to protect themselves from being involuntarily captured. E.g., consider requiring users to actively opt into being captured with physical tokens that can be carried on the person.

**Develop strategies and design cues to minimize physical safety risks in MP environments** Virtual objects and remote user avatars can distract co-located users or can hide physical objects and people. This can lead to accidents and injuries. Here, multisensory cues could be designed that enable MP systems to enhance spatial awareness and provide alert assistance to navigate shared physical spaces safely.

## 6.7 Accessibility and Inclusion

Accessibility is not a novel focus; however, it is underrepresented in the context of MP systems (see Sec. 5.3, U5). Future MP systems bring both novel accessibility problems and opportunities. On one hand, the technical complexity and usage of multi-modal input and output channels might easily exclude people, be it for accessibility or monetary reasons. On the other hand, virtual spaces and multisensory systems offer the chance to uniquely cater to people with special needs and capabilities (see also Sec. 6.5).

**Investigate adaptive support, sensory substitution, and inclusive representation for diverse human factors and user needs in MP** To make MP spaces more accessible, we must consider the large spectrum of user needs. Most importantly, MP system should be able do dynamically support (i.e., adapt to) users with different degrees of physical or cognitive impairments. One way to achieve this is the substitute of one (impaired) sense with another. We see potential in employing AI to provide automatically generated tailored aids, such as closed captions or audible scene descriptions, or to take over distracting tasks during collaboration, e.g., being the dedicated keeper of the meeting minutes, making discussions more inclusive for all roles. However, since active participation is not only about perception but also about being perceived, the representation of users with special needs requires additional attention and adaptation.

**Develop and evaluate MP systems that dynamically adapt to environmental or contextual factors** Users in MP environments can join from vastly different contexts, each presenting unique challenges. One person might join from a loud or brightly lit environment, another from a small or crowded space where speaking aloud is impossible. This potential environment disparity makes it imperative that future MP system have to accommodate and adjust to various contextual conditions. Especially the substitution of capabilities, like replacing voice communication with text chat if the former isn't feasibly, should be considered. However, if this dynamic capability substitution enhances participant equity is yet unknown and needs to be studied.

**Investigate strategies for equitable participation despite individual technological differences among users** In distributed systems, users often rely on heterogeneous technologies with varying capabilities, such as bandwidth or device performance differences. To ensure equitable participation despite technological disparities, different approaches can be considered. First, a subtractive approach can be used, that lowers the overall experience to match the least-capable system. However, what the minimum threshold of technological functionality required for effective collaboration is, needs to be studied. Secondly, an additive approach is possible, which specifically focuses on enhancing and accommodating weaker systems. Lastly, it is also conceivable to embrace the differences in capabilities by assigning matching roles to individual users.

## 6.8 Mixed-Presence Authoring Tools

For some use cases, bringing people together in a shared space is enough. However, more complex use cases may benefit from – or even require – authoring tools to set up and customize the system. While this aspect is under-represented in our surveyed challenges, the following possibilities and challenges were discussed in the workshop:

**Design tools for in-situ authoring in MP** Authoring in mixed-reality environments is already challenging and becomes even more complex for MP environments due to the joint work of co-located and remote users. Future systems need to create and maintain contextual awareness between the different participants while they author MP environments, and handle transitions between private and shared objects.

**Explore AI tools for assisting users to customize avatars, spaces, and interactions effectively** We believe that supporting ad-hoc content creation and customization in MP systems is a promising research direction which can be enabled and supported by AI tools that allow for the quick creation of user generated content on the fly. As MP systems consist of many different components, like the users, the real-world environments, or virtual artifacts, it is yet unclear if every type of customization is equally suited. Furthermore, research should be conducted in how to achieve visual consistency between the aforementioned components. Lastly, the use of AI tools for content creation and customization is also connected to potential ethical and privacy concerns as such tools could use and alter depictions of real users or their private rooms.

**Investigate how equity and true participation by local and remote authors can be ensured** Authoring in Mixed Presence is itself an MP use case. As such, we find that how remote users should be empowered to equally contribute to the authoring process in the local environment is of importance. This means that the roles or capabilities between both user types need to be considered. More specifically, this can mean that feedback from both local and remote users should to be integrated into the iterative authoring processes while balancing access to environmental manipulations between both.

# 7 Limitations

We presented a thorough investigation of challenges, use cases, and studies in the context of mixed-presence systems in Mixed Reality, which we sourced from a large literature corpus. However, there are some limitations of our work that we discuss in the following.

## 7.1 Paper Selection

MP systems are often broadly categorized as "distributed", "remote", or generally "collaborative", making it hard to distinguish them from the plethora of collaborative MR research. We tried to narrow the search with our query (as described in Sec. 3.1), which bears

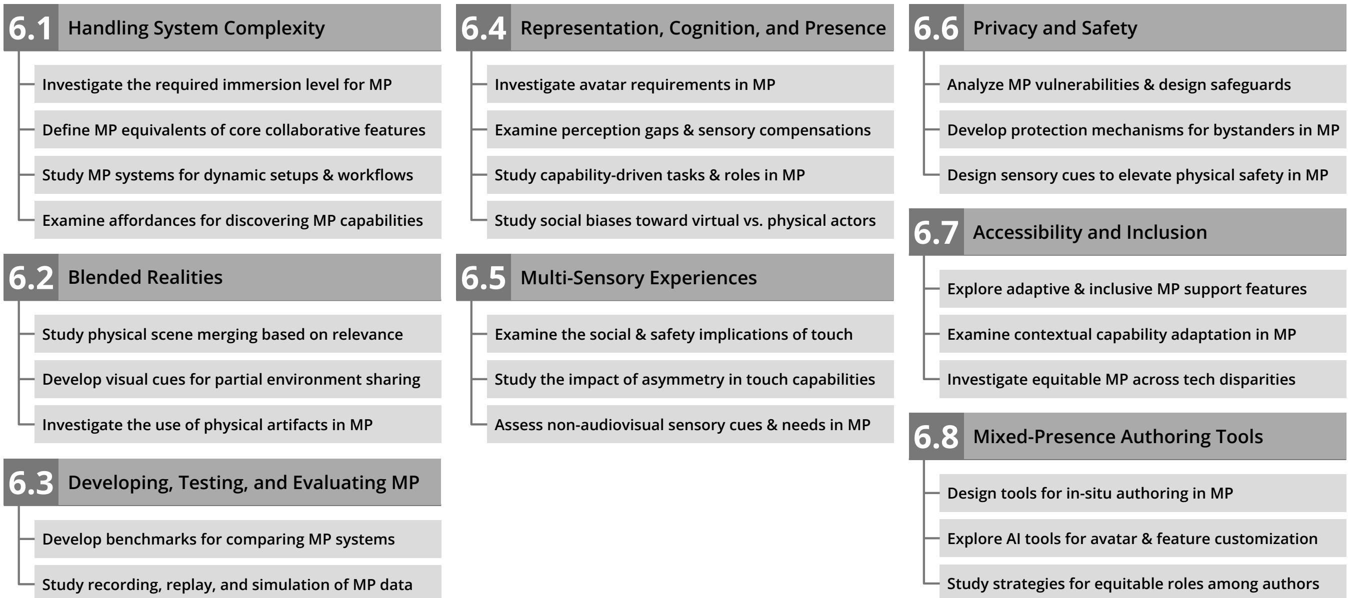


**Figure 9: An overview of the future directions and actionable items extracted from our expert workshop and related to the development and design of MP systems for MR.**

the risk of excluding relevant resources that do not contain the defined keywords. Similarly, there are numerous terms describing mixed-reality concepts, and papers may not use any of the ones that we included in our query. We also only searched within the IEEE and ACM digital libraries because we deemed them the most important and extensive sources for this field of research.

Furthermore, while our corpus spans almost 10 years and the cut-off year of 2016 was carefully chosen based on the first commercial availability of powerful mixed-reality devices (see Sec. 3.2), it still removed 223 records, roughly 23% of the initial paper set. We value this older and often ground-breaking research and do not claim that these papers are irrelevant. However, focusing on challenges specifically, we argue that many of those described in these early works have already been successfully compensated by recent hardware- and software advancements, especially in the area of technological challenges. More importantly, we expect that most challenges that remain relevant will be mentioned in the more recent literature in our corpus as well.

Finally, the exclusion criteria (see Sec. 3.2) were rather strict. In our goal to extract as many challenges and requirements as possible for the design, development, and evaluation of MR MP systems, we excluded work that does not present a system. We acknowledge that papers which solely present theoretical frameworks might have yielded additional insights but were not regarded in this work. We also excluded pure VR remote systems. Besides investigating interpersonal behaviors, we were also interested in the influence of the interplay between the real and virtual environment, leading to a focus on AR. This is mostly in line with our definition of Mixed Presence but might have excluded edge cases such as group telepresence using virtual environments.

## 7.2 Extracted Challenges and Scope

Besides the survey procedure limitations laid out above, in our reporting, we are limited by what challenges are mentioned in our set of papers. While we have considered a final set of 147 papers and have coded 659 challenges, it is plausible that many authors might not comprehensively document all the challenges encountered during the development of their respective MP systems. Reasons for that could include constraints on their research scope, paper length restrictions, or the desire to present a more polished image of a system. In addition, we also do not differentiate between challenges for which solutions are presented in the papers and those that are merely mentioned. Finally, even for challenges underrepresented in our corpus, adjacent research areas may offer solutions or valuable insights. With this survey, we give an overview of the field and provide pointers for specific categories of challenges, raising awareness of many pitfalls when designing for mixed-presence mixed-reality environments. We encourage the reader to also look beyond this survey and our proposed research directions and consider the literature in related areas.

## 7.3 Research Directions

Our research directions (as discussed in Sec. 6) provide important entry points into areas where we see strong potential for future MP research. However, we do not claim that no prior research has been conducted in these directions, instead, many build on insights from prior work established in diverse surrounding fields and communities. A comprehensive review of that work lies beyond the scope of this survey, which is why we encourage readers to also consider the relevant existing literature outside of MR research. Since existing work might not yet have been explored in the specific context of Mixed Presence, addresses narrowly defined use cases, or relies on very specific technological setups, we see our contribution in the explicit formulation of these research opportunities in the context of Mixed Presence, where impact and applicability of existing approaches remain underexplored.

## 8 Conclusion

We hypothesize that in the future, mixed-presence experiences in mixed-reality environments will become a major driving application in a hybrid real-digital world. To pave the way for conducting more research towards this vision, in this paper, we systematically explored challenges and illustrated opportunities for mixed-presence research in Mixed Reality. We contributed insights from an extensive survey into the existing literature on immersive MP and collaborative remote AR systems, systematically extracting challenges, common use cases, study tasks, and methodologies. Based on our observations from previous work, our own experiences, and the results of an expert workshop, we provided pointers to gaps and possible future directions specific to mixed-presence MR research. With the structured set of identified challenges and our discussion of major related aspects and research questions, we hope to provide the groundwork and cornerstones for a future MR MP research agenda, supporting researchers and developers in further shaping the exciting and up-and-coming field of Mixed Presence in Mixed Reality.

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**Figure A1: An overview of the four challenge categories, their themes, and sub-themes we identified through our survey, consisting of the three main components of Mixed-Presence systems as well as cross-cutting challenges.**