Revisiting Collaboration through Mixed Reality: The Evolution of Groupware

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Abstract

Collaborative Mixed Reality (MR) systems are at a critical point in time as they are soon to become more commonplace. However, MR technology has only recently matured to the point where researchers can focus deeply on the nuances of supporting collaboration, rather than needing to focus on creating the enabling technology. In parallel, but largely independently, the field of Computer Supported Cooperative Work (CSCW) has focused on the fundamental concerns that underlie human communication and collaboration over the past 30-plus years. Since MR research is now on the brink of moving into the real world, we reflect on three decades of collaborative MR research and try to reconcile it with existing theory from CSCW, to help position MR researchers to pursue fruitful directions for their work. To do this, we review the history of collaborative MR systems, investigating how the common taxonomies and frameworks in CSCW and MR research can be applied to existing work on collaborative MR systems, exploring where they have fallen behind, and look for new ways to describe current trends. Through identifying emergent trends, we suggest future directions for MR, and also find where CSCW researchers can explore new theory that more fully represents the future of working, playing and being with others.

Keywords: Collaborative Mixed Reality, Mixed Reality, Augmented Reality, Computer Supported Cooperative Work, Collaborative Technology

1. Introduction

While collaborative Mixed Reality (MR) research is well into its third decade, it is currently a topic of public attention due the recent advent of commodity technology that makes its application to real world problems possible. Leading technology companies including Microsoft and Apple are racing to launch new and better MR hardware in order to secure their share of a growing market. Among the possible applications in MR, it is widely viewed that collaborative systems are to be among its *killer applications*. Research that has studied technology to support more general forms of collaboration also has a long history, and has occurred mostly in parallel to work on MR.

Groupware is a term applied to early collaborative software that provided the first experiences of sharing digital workspaces, and formed a focal point of early Computer Supported Cooperative Work (CSCW) research. Some 30 years later, this body of work has culminated in rich theory about the nature of collaborations, the roles that collaborators take, and how collaboration can be more than the sum of its parts. Over roughly the same time, MR technology developed alongside CSCW to enable rich shared experiences with nearby companions and knowledge sharing with remote experts. However, early MR systems faced significant engineering hurdles, and have only recently started catching up to provide new theories and lessons for collaboration.

Mixed Reality presents a wide space of new design possibilities for collaboration, which in turn, affect how we need to model and understand collaboration. For instance, early CSCW literature established theories of collaborator embodiment, yet these frameworks were based on relatively crude proxies based on the technologies of the time; today's MR provide designers with entirely new ways of providing collaborators with a sense of presence, partly by being able to capture far richer models of human activity in collaborative spaces. The present work takes the first steps in reconciling our understanding of collaboration theories with the emerging trends and new capabilities presented by MR technologies.

This paper aims to document how technological innovations have influenced collaborative MR research, and to improve our analytical prowess by superimposing traditional CSCW concepts over this history. With this exercise, we hope to measure the success of current theories at describing the many new systems arising from emergent MR technologies, and to identify where our understanding can be improved. From a review of the history of collaborative MR systems, we first investigate how past CSCW frameworks map to developments in MR. Second, from a detailed look at each framework dimension across time, we begin to see where past frameworks have fallen behind, and where new theories are required to describe current trends. Finally, we close by offering insights inspired by our review on the path of future collaborative systems, highlighting what researchers and designers need to consider to support collaboration in future MR-based systems.

2. Key Concepts in MR Collaboration

We begin by reviewing important concepts and taxonomies needed to understand the design space of MR collaborative systems. We first provide a brief history of research that overlaps CSCW with early MR systems, primarily from early research in Augmented Reality (AR). Next, we give a more detailed introduction to several descriptive frameworks of groupware that characterize basic attributes of collaboration. We follow by discussing several well-know descriptive frameworks of MR interfaces, and explain how these contribute to the design space of MR collaboration.

2.1. A Brief History of Collaborative AR

CSCW has long been concerned with understanding and designing technologies to support collaboration. From this discipline, rich theories about how people work together have influenced the design of collaboration technologies.

Perhaps the most canonical example of collaboration technology is Engelbart's oN-Line System (NLS) [1], or "The Mother of All Demos", which in 1968 first illustrated video conferencing and screen sharing in a real-time collaborative text editor. This work has since inspired researchers to apply communication theories (e.g., [2, 3]) to entirely new collaboration designs and contexts [4].

Around the same time that Engelbart developed these innovative technologies, Ivan Sutherland was exploring the future of display technologies. In 1965 he wrote about the "Ultimate Display" [5] in which the real and digital spaces were seamlessly combined. By 1968 Sutherland had succeeded in developing a working prototype, a head mounted display (HMD) that combined two small cathode ray tubes with transparent optical elements to overlay virtual images on the real world [6]. Connected to a computer and head tracking system, this formed the first fully functional Augmented Reality (AR) system. Sutherland's system allowed the user to see simple interactive graphics floating in space but seemingly affixed to their location as the viewer walked around them. In this way Sutherland's system satisfied the three key defining properties of AR [7]:

1. the combination of real and virtual content,
2. allowing interaction with virtual content, and
3. representation of virtual content in three dimensions.

As AR matured, CSCW researchers explored how it can provide collaborators with shared understanding or common ground. For example, many early systems merged distant spaces using a "simplified" AR approach; by using cameras and half-silvered mirrors to provide a more realistic rendition of a virtual collaborator's eye gaze (e.g., VideoDraw [8], VideoWhiteboard [9], and ClearBoard [10]). One such system, ClearBoard, allowed coordinated "drawing on a pane of glass". This early work foreshadowed later systems that realized remote collaboration through the use of AR technologies with free-moving camera viewpoints. For example, AR teleconference applications where people used tracked AR displays to view live virtual video of remote collaborators superimposed over the real world [11] (Figure 1), or applications that allowed a local user to

Figure 1: Augmented Reality teleconferencing with live virtual video avatars[11]

share their camera view with a remote user, providing the experience of looking through a collaborator's eyes [12].

Other early work focused on the technological innovations needed to enhance face-to-face cooperative work. In Rekimoto's Transvision [13] collaborators sat across a table using handheld displays with cameras attached to view AR content on the table. Concurrently, Billinghurst [14, 15] and Schmalstieg [16] explored the use of see-through HMDs for face-to-face collaborative AR. These early work showed AR allows the task space to be seamlessly combined with the communication space, unlike other collaborative technologies where there can be a separation.

While such ideas of supporting collaboration through AR clearly motivated early researchers, AR research also has been limited by the contemporary capabilities of technology, and advancements in the field have often coincided with new technical advances. For example, early work focused on face-to-face scenarios, since the network bandwidth needed was still a major barrier to research studying remote scenarios. More generally, it is only very recently that AR research has been able to focus squarely on the human concerns that underlie communication and collaboration, rather than the technology that makes AR collaboration possible. For instance, seminal work by Feiner et al. [17] on the Touring Machine brought together wearable HMDs with mobile computing, where users could explore and digitally annotate a university campus using a see-through display. Similarly, Benko et al. [18] illustrated how a digital workbench can be integrated with a head-mounted AR experience to support AR collaborative exploration. These works showed monumental progress in integrating an array of developing technologies to create high-level systems that serve human concerns. However, these advances have enabled more contemporary collaborative AR researchers to focus on the human experience of collaboration, where the designs and experiments are grounded in theories (e.g.[19, 20, 21, 22, 23, 24]).

2.2. Early CSCW: Designing Groupware

"Groupware" was coined to describe systems that support group processes [25, 26]. Johansen [27] proposed the time-space matrix to describe groupware tools (Figure 2), which delineates tools into four quadrants depending on *when* people work together (at the same or different times—*synchronous vs. asynchronous* collaboration), and the physical arrangement of *where* people work (in the same place or different places). People can interact in either the same place (*colocated*) or in different places (*remote*). Although more contemporary accounts argue for more sophisticated models of collaborative activity (e.g., Lee & Paine [28]), the Time-Space matrix still forms a basis for how we understand software support for collaborative activity.

A major thread of early CSCW research focused on understanding the role of collaborative behaviours in physical spaces. As researchers designed and built distributed workspace tools to support colocated activities (e.g., [29]), it became clear that two theoretical elements demanded further exploration. First, understanding how to enable awareness for collaborators (e.g., [4, 30]) — knowledge of who is in the workspace, and what they are doing. Second, articulating an understanding of how visual information supports collaboration (e.g., [31, 32, 33]).

2.2.1. Mechanisms to Enable Awareness

Gutwin and Greenberg [4] provide a lucid explanation of the role workspace awareness plays in collaboration, describing how people build and maintain this

	Synchronous (same time)	Asynchronous (different time)
Colocated (same place)	Face to face interactions	Continuous task
Remote (different place)	Remote interactions	Communication & Coordination

Figure 2: CSCW Time-Space Matrix (adapted from [27])

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awareness in shared virtual spaces. For instance, as a team works on a shared document in real-time, a collaborator would be concerned with understanding ‘Who is around?’ ‘What are they looking at?’ ‘What are they writing?’ and so on. In colocated spaces, we gather this awareness information in real life through three things: peoples’ bodily interactions with the workspace, conversation and explicit gestures, and the workspace artefacts themselves. Each of these have analogues in virtual worlds, and considerable follow up research has explored the design of visual cues to provide this awareness information (e.g., [34, 35, 36, 37]).

Groupware researchers have explored embodiment to address the loss of physicality in remote work. In colocated collaborations, information produced by collaborators’ bodily interactions with the workspace provides collaborators with awareness about what we are doing, and helps them predict future actions [4]. For instance, Segal describe how pilots spend over 50% of their time watching their co-pilot’s activities in the cockpit [38]. This allows each pilot to coordinate their activities based on the other’s physical actions. Digital systems rely on embodiments to provide such information for workspace collaboration. These embodiments stand-in for the functions that a collaborator’s body or hands would play in a workspace — they represent one’s view or interest, provide a means to gesture and point, or simply represent a location that one occupies. For instance, in a shared document editor, a cursor represents where one’s focus is (i.e., where the “writing pen” would be). Collaborators make movements with these cursors to gesture, point or otherwise communicate explicitly through deictic references [39]. Other researchers have relied on video-based embodiments (video-captured arms or bodies) that are digitally reproduced in the remote site (e.g. [8, 40, 41, 42]), which provide higher degrees of expressive freedom. In exploring collaborative virtual environments, researchers explored the use of avatars to represent collaborators, which can represent the collaborator's location and view [43].

2.2.2. Gesture and Shared Visual Information

Many systems have explored ways of allowing collaborators to gesture fluidly, since gestures allow people to communicate about a shared visual context. This is particularly important when the speech and gestures are related to an object (or environment) of discussion. In an AR context, some have realized these through digital pointers or icons (e.g. [44, 45]), whereas others have realized these via video-captured and modeled hand/arm embodiments (e.g. [46, 47]). Yet another approach has explored simply annotating the environment with text labels anchored in space (e.g., [22]), while others have enabled structured annotations (e.g., [48, 49]), or free-hand annotations (e.g.,[21, 32]). Prior work has suggested strongly that these rich hand-based embodiments produce more effective means to communicate fluidly about objects or the relationships between them (e.g., [50, 51]). Even so, it seems that even simple actions like pointing at objects seem largely difficult to resolve in 3D environments [52].

Yet while we know that embodiments and gestures are important for collaborative work, we still do not have a framework that articulates the specific domain- or task- specific needs in relation to different needs in terms of embodiments and gesture support. Instead, most of our understanding arises from artificial tasks studied in laboratory studies uncovering general principles. Designers will need a more specific distillation of these principles to make appropriate application-specific design decisions.

2.2.3. Visual Information and Disjoint Views

Research by Kraut, Fussell, Gergle and colleagues have established that shared visual information provides an important converational resource in collaboration [31, 32, 33]; however, in contemporary collaboration scenarios (e.g. mobile video conferencing), we know that views into the environment are not fixed—consequently, researchers are still working to understand the challenges of communication given disjoint viewing perspectives. For instance, Jones et al. [53] and Liocoppe et al. [54] explore how collaborators share and collaborate using mobile video when communicating about remote environments, presenting two fundamental challenges that designers need to address: first, how do we allow remote collaborators to independently explore the environment, and second, how can collaborators easily and effectively understand one anothers' views of the environment.

Lanir et al. [19] address this first challenge through a remote-controlled pan-tilt camera, while others have explored the use of 360 cameras (e.g., Kasahara et al. [35], Lee et al. [55], and Tang et al. [56]). Yet, smoothly communicating each collaborator's view to one another has still not been adequately addressed [57]. For instance, point solutions are available for contexts where the perspective of the environment is fixed (e.g., D'Angelo et al. [58]), but we still do not have good ways of doing this in general (e.g., Kuzuoka et al. [59]). This is increasingly problematic as we continue to consider novel capture contexts for remote collaboration (e.g., drones as in Jones et al. [53], multiple cameras as in Kasahara et al. [60]), particularly where a collaborator can move a virtual camera through the environment without a physical embodiment (e.g., Poelman et al. [61]). Resolving this problem is a fundamental challenge in many AR collaboration contexts, hence considerable work has demonstrated that a shared understanding of the visual context is important to collaborate effectively [33].

2.3. Mixed Reality Taxonomies

Milgram's Reality-Virtuality Continuum [62, 63] is one of the most widely adopted concepts in explaining the design space of MR interfaces (Figure 3).

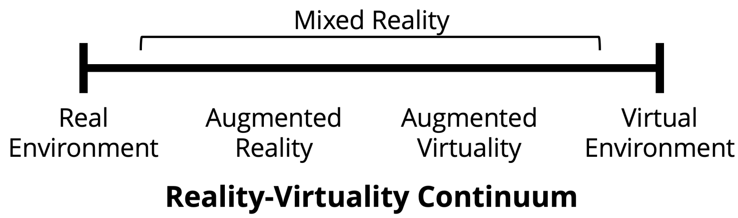

Figure 3: Milgram's Reality-Virtuality Continuum [62]

The continuum depicts a design space with two extremes, *Reality*, which describes a purely physical environment, and *Virtuality*, which is purely virtual, computer-generated environment. Virtual Reality (VR) interfaces sit on the Virtuality end of this continuum while physical interfaces such as Tangible User Interfaces [40] are towards the other end. In-between is a continuum where a class of systems that merge computer generated virtual environments with real physical environment, known as Mixed Reality (MR). One of the well known subsets of MR is Augmented Reality (AR), which sits closer to the Reality end of the continuum, combining virtual objects into real world scenes [7]. Towards the other end of the spectrum, is Augmented Virtuality (AV), which introduces physical objects into the virtual environment.

Benford et al. [64] proposed a taxonomy for collaborative MR systems, which is comprised of three dimensions: artificiality, transportation, and spatiality. The first of these dimensions, Artificiality, is comparable to Milgram's Reality-Virtuality continuum, which depicts the extent of how much portion of the scene is synthetic or physical. The second dimension, Transportation, explains the extent of participants or physical objects being transported to a remote environment from the local space. For example, one extreme is a face-to-face colocated AR collaboration, while the other extreme would be immersive telepresence or immersive shared VR systems. The two dimensions form the broad classification of collaborative MR as shown in Figure 4. Benford's third dimension, Spatiality, explains how much support is provided for promoting a shared spatial frame. One extreme is having no spatial reference frame but just

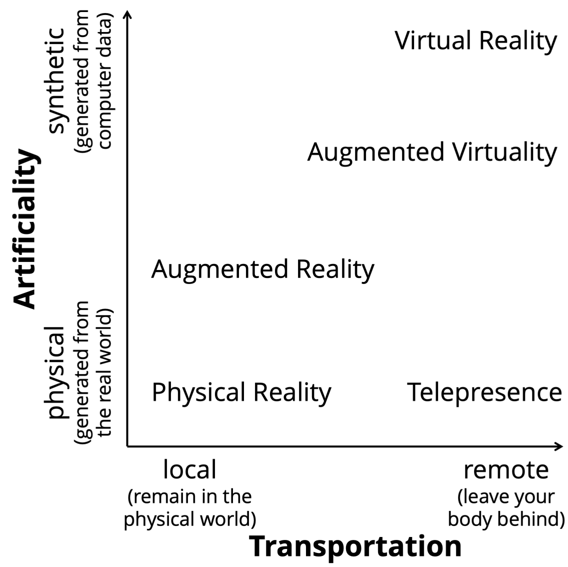

Figure 4: Artificiality and Transportation dimensions of Benford's taxonomy [64]

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a notion or identification of a conceptual space; for example, a text-based chatroom. The other extreme is having a fully shared spatial frame (i.e., Cartesian space), such as in shared virtual environments. In MR collaboration systems, at least some level of shared spatial frame is necessary using spatial tracking and registration [7].

We note that the Transportation dimension of Benford's taxonomy is closely related to the Space dimension in CSCW matrix. In colocated face-to-face collaboration, no transportation is involved as every participant being local, while in remote collaboration, it is expected that at least one of the participants would be transported into a remote space. In contrast to collaborative virtual environments, most cases in collaborative MR involve asymmetry in transportation that one user is transported to a remote environment where another user is local.

Symmetry is a concept commonly associated with collaboration in MR systems. Various reasons for asymmetry were formalised by Billinghurst et al. [65]. Asymmetry often arises from properties of different technologies when these are mixed by collaborators. For instance, a head-mounted AR display may contain an outward-facing camera, which captures a view of the wearer's surroundings, whereas a webcam on a desktop computer will capture the collaborator's face. These differences in the physical setup often lead to differences in the functionality available to each collaborator. Asymmetries can also result from differences in user roles, from differences in ability to access information, or from the nature of a specific collaborative task.

3. Review of Collaborative MR Systems

One of the aims of this work is to examine how the common taxonomies and frameworks discussed in the previous section can be applied to existing research on collaborative MR systems. To achieve this, we began with a review of related research, where we attempted to categorise this work according to existing frameworks. An additional goal of our analyses was to determine whether these collaborative MR systems can be clearly categorised by the existing frameworks. As we describe below, we identify potential reasons why this is not the case.

3.1. Method and Analysis

We conducted an extensive literature review covering collaborative MR research from the last three decades that spanned the areas of MR and CSCW. This was a focused review to provide a snapshot of work over this period, where we systematically searched for relevant papers from primary conference proceedings such as CHI, ISMAR and CSCW. We supplemented these with other papers we were aware of, and those cited in related literature surveys [7, 66, 67, 68, 69].

In particular, we sought papers that met the following criteria: 1) included a novel concept, hardware component, software system or user study that used MR technology; and 2) collaboration is a fundamental element of the study or system. To include a broad collection while also maintaining a desired focus, we additionally considered the following: 1) Whereas systems should include MR as a primary focus, they need not be about MR only—for instance, we included systems that involve collaboration between MR and VR or a desktop. 2) We did not limit our exploration to any specific MR technology, but rather aimed to include interesting concepts—however, MR systems must include a mixture of physical and digital representations of a person, object or environment with at least some minimal form of real-world tracking and registration. These criteria place our search within the central MR segment of Milgram's continuum (Figure 3, previous section). The resulting works are primarily focused on AR systems, however we also identified a few works on Augmented Virtuality.

We classified each paper along a set of six dimensions. The first set of four dimensions were strictly derived from the previous literature Section 2. We developed a second set of dimensions based on an iterative open coding (thematic clustering) process, where we further refined these dimensions through an axial coding exercise.

Time and **Space** — the classic CSCW matrix dimensions (Figure 2) including the values *synchronous/asynchronous* and *colocated/remote* respectively. We also included a *both* value for both dimensions to account for systems that could not be cleanly dichotomised.

Symmetry — we classified symmetry based on whether collaborators have the same basic roles and capabilities (*symmetric*) or whether they have different roles or capabilities (*asymmetric*).

Artificiality — "the extent to which a space is either synthetic or is based on the physical world" [64], spanning the extremes from entirely physical to entirely digital (based on [62], and further refined by [64]). We used the values *mostly physical*, *mostly digital*, or *hybrid*.

Focus — describes the primary target of collaborative activity. These are coarsely defined as *environment*, *workspace*, *person* and *object*;

Scenario — attempts to summarize the overall concept of a system according to the users and use case. We settled on the concise set of values *remote expert*, *shared workspace*, *shared experience*, *telepresence* and *co-annotation*.

3.2. Paper Summary

Overall, we examined a total of 110 papers (full list available in appendix) that employed MR technology and were motivated by, or addressed challenges in collaborative scenarios that involved two or more people. While this exploration spanned many publication venues spanning Human-Computer Interaction, Augmented Reality and Virtual Reality, the most common publication venues included CHI (23 papers), ISMAR (17 papers) and CSCW (11). Figure 5 shows the distribution of these papers according to their time of publication. As can be seen, there was a rise in the number of papers published from 2012 and onward. We believe that the reason for this rise is mostly due to an increased interest in AR by the general public and industry during this time, with a focus on the potential commercial applications (e.g., a magazine ad for BMW[1]). This interest may also have been brought on by increased computational power in processors and graphic cards to support AR displays, as well as progress and availability of cheap sensors such as motion, rotation and depth sensors that allow easy tracking, content creation and interaction. In addition, the increased availability of computationally powerful smartphones created a situation in which it was much easier, both in industry and in academia, to implement mobile AR applications.

3.3. Analysis of Trends

We report here on the coding of the different dimensions. Overall, while some of the dimensions were useful for differentiating different "categories" of systems, others were more evenly balanced across the papers and less helpful. Below we describe how the papers were distributed across dimensions and how this distribution changed over time.

[1] `https://www.youtube.com/watch?v=dBser6_gToA`

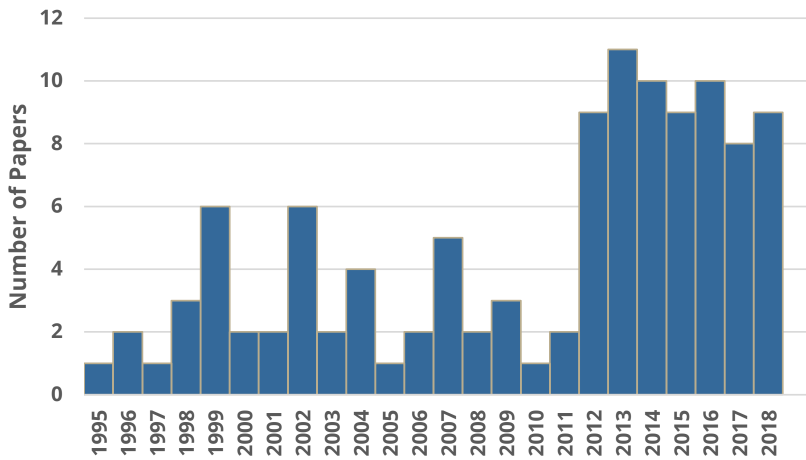


Figure 5: Distribution of the papers we examined according to year of publication

3.3.1. Traditional CSCW matrix dimensions

One of the most common ways to conceptualize collaborative systems is by using the traditional CSCW matrix (see Section 2.2). Looking at the *time* dimension (synchronous - asynchronous), we found that the vast majority of papers (106, or 95%) focus primarily on synchronous collaboration. A few exceptions are Kasahara et al. [70], which supports asynchronous annotations placed at certain locations and left for later users to interact with; Poleman [61], which supports tagging of a virtual police investigation scene; and Irlitti et al. [71], which outlined challenges and opportunities in asynchronous AR collaboration. The latter's earlier work [72] demonstrated a tagging marker used as a tangible container of virtual information used in spatial AR-based [73] asynchronous collaboration.

Within the *space* dimension (colocated / remote), we found much more variability within the papers with 30 papers (27%) working on a colocated setting, 75 papers (68%) on a remote setting, and 6 systems (5%) supporting both settings. Figure 6 presents the distribution of the papers according to the space dimension according to their year of publication. As we can see in the figure, much focus fell on colocated work in the earlier years (up to 2005). This has

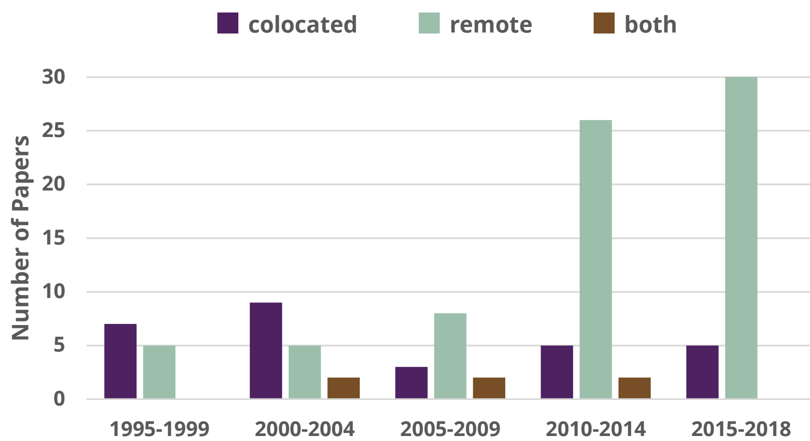


Figure 6: Distribution of papers by the space dimension according to their year of publication

changed, and from 2006 and onward most work has focused on remote collaboration, which falls in the "same time / different place" quadrant of the traditional CSCW matrix.

3.3.2. Symmetry

From the papers we examined, 45 (41%) were symmetric, 63 (57%) were asymmetric, and 2 papers (2%) supported both types of interaction. Their distribution according to year of publication is presented in Figure 7. Symmetric interaction took place both in colocated and remote situations. In colocated symmetric systems (24 papers), usually two or more users collaboratively explore a shared setting (e.g., [13, 18, 74]). Thus, they have the same capabilities for their exploration task. Colocated asymmetric systems are less common (only 6 papers) and refer to systems that include users with different devices working together — for example, one user using VR with the other using AR ([75]), or systems that enable instrumented users to interact with non-instrumented ones ([76, 77]). Looking at remote systems, most were asymmetric (57 of 76 papers). These were often remote collaboration scenarios in which the remote person guides or helps a local user, and thus, the two users use different types

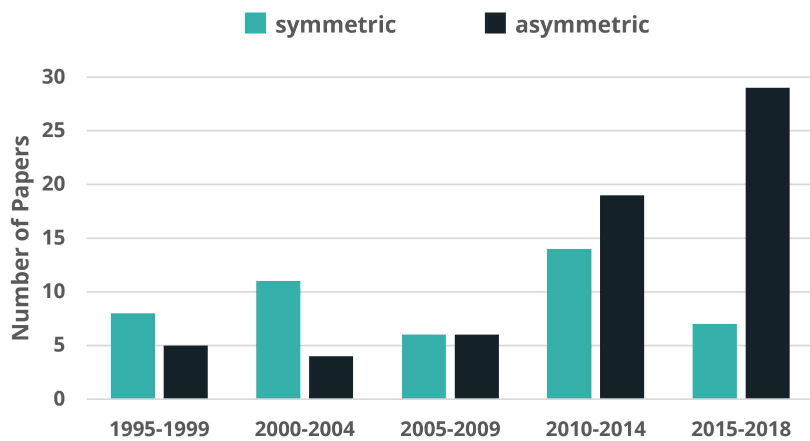


Figure 7: Distribution of papers by the symmetry dimension according to year of publication

of technologies (e.g., [45, 78, 79]). Remote symmetric systems (19 papers) were usually situations in which two remote users share a virtual workspace (e.g., [41, 80, 81]).

3.3.3. Artificiality

A system that is mostly physical has its information drawn mostly from the physical world with minor virtual augmentations added to it. For example, adding a pointer or annotations on top of the real-world view [45, 82, 32, 83] or adding virtual augmentations to a videoconferencing system to show gaze direction or other types of information [84, 85]. A system that is mostly digital has its information drawn mostly from the digital world. For example, when the focus is on collaborating around a digital artifact and the physical world is shown only for context or awareness (e.g., [18, 13, 86]). We also coded systems as being hybrid in which there is an emphasis both on the physical world and the digital artifacts. For example, in colocated AR games [87, 88, 89] both the digital artifacts and the surrounding world are in focus. Figure 8 shows the distribution of papers according to the their artificiality along the years.

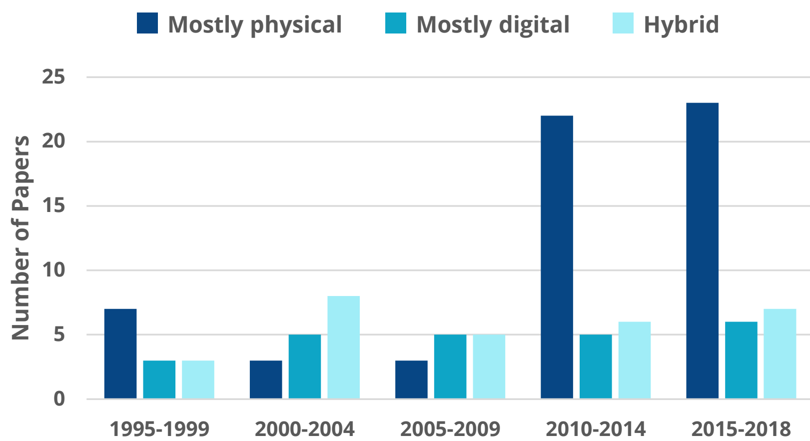


Figure 8: Distribution of papers by the artificiality dimension according to their year of publication

3.3.4. Focus

We found that the target of the collaborative activity varied from system to system, but that these variations could be limited to a fairly small set: environment, workspace, object and person. Each category of system implied that collaboration support needed to vary—for instance, beyond the scale of the interaction, the type of awareness cues that were important, and the kinds of collaborative actions that were supported through the system. The focus dimension describes the focus of the collaboration, which can be either physical or artificial. The Environment category means that users are interested in seeing the surroundings of their collaborator, either in full or a subset, often for the purpose of situational awareness (e.g., [90, 91, 55]). Workspace broadly encompasses any physical or artificial region of interest at the center of collaboration (e.g., [45] [75]), including a digital document, virtual model or game apparatus. The Object category denotes attention paid to a real physical artifact (or a virtual replica transmitted to a collaboration). For example, in the work of Oda et al. [92], spatial referencing in AR was investigated on a digital replica of the referenced object. The Person category implies that users are highly interested

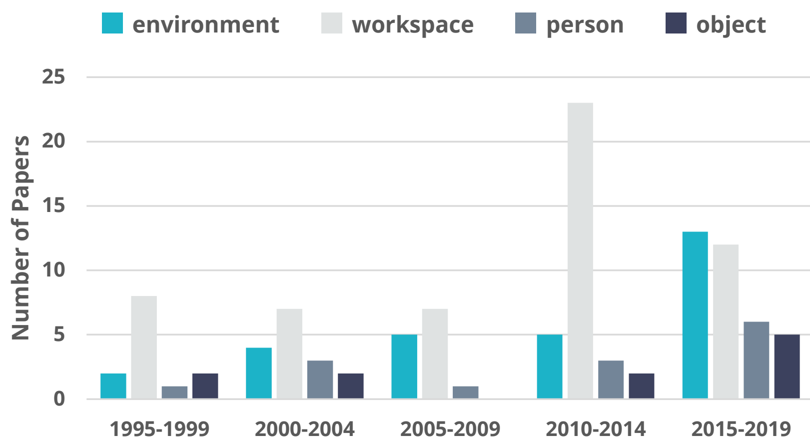


Figure 9: Distribution of papers by the focus dimension according to their year of publication

in seeing their collaborator, typically their face or entire body (e.g., [93]) but optionally any part of a person such as hands or feet or a digital embodiment thereof (e.g., [94]). Figure 9 shows the distribution of focus by 5-year period.

3.4. Scenarios

We also found that the vast majority of papers and systems could be categorized into a set of five basic collaborative scenarios: remote expert, shared workspace, shared experience, telepresence, and co-annotation. These stemmed from how the papers were motivated, but also manifest in the kinds of collaborative actions that were supported through the systems—specifically, for instance, the kinds of tasks that they could support, or the tasks that would be explored in a user study. *Remote expert* typically involves a remote knowledgeable person guiding a local person around a physical task. *Shared workspace* is a catch-all for systems or studies that include a strong focus on a combined physical and virtual workspace. *Shared experience* include works that focus on the personal experience of the collaborators rather than the task they are working on. *Telepresence* includes works that are highly focused on communication between two or more participants. And finally, *co-annotation*, involves systems that inscribe virtual annotations on an object or environment of interest to be read by others. Figure 10 shows the distribution of papers in each scenario according to the other dimensions discussed so far.

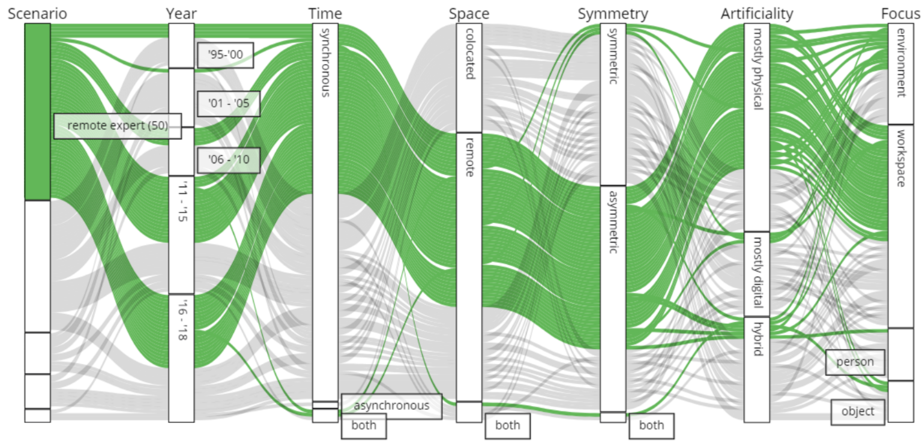
Figure 10 shows the distribution of papers for each scenario, across each 5-year period and all dimensions. As can be seen in this figure, remote expert is the most popular scenario. It typically involves remote, asymmetric, synchronous collaboration mostly including the physical artificiality and with a focus on workspace and environment. This scenario appears in some of the earliest works, but flourishes in the last decade, accounting for the bulk of works that comprise the explosion of papers in these years.

Shared workspace works include both colocated and remote systems, however, the main characteristic when considering this scenario according to the other dimensions is that most of the works in this category are symmetrical (although some asymmetrical works do exist). We can also see a stronger incline towards digital artificiality and on the workspace focus. A colocated example of this category is in the work of Benko et al. [18], which supported the collaborative exploration of an archeological excavation. A remote example is IllumiShare [81], a system that enables sharing of digital and physical objects while providing referential awareness by using two remote synchronized lamp-like devices, that consist of a camera and a pico-projector. This class of works was dominant in the early years of our survey, and seems to extend directly from the legacy of shared documents or GUIs in groupware systems. However, it continues to recent works with the introduction of more complex types of digital as well as physical workspaces.

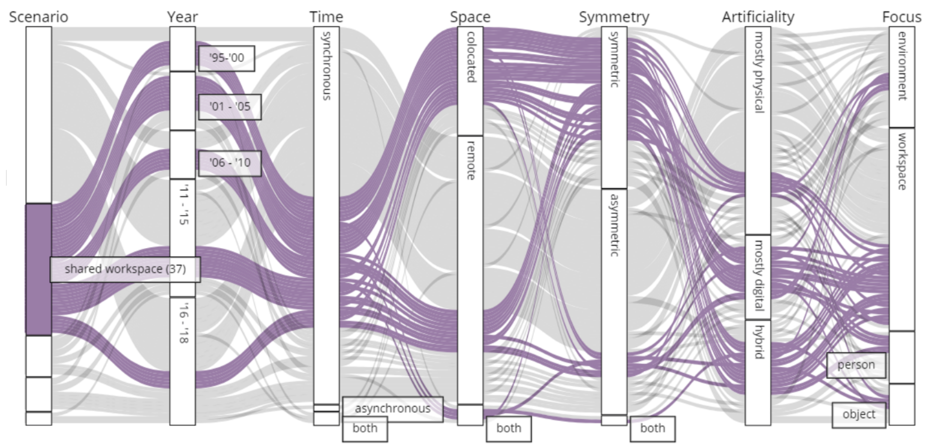
Shared experience works include a broader variety including both colocated and remote systems as well as both symmetric and asymmetric works. These works seem not to fall within other dimensional categories mostly spanning evenly across all other dimensions. There are distinct styles for colocated works and for remote shared experience works. The former (e.g., Gugenheimer et al. [77]) mainly focus on awareness of a colocated collaborator's unseen virtual surroundings, while the latter focus more on sharing remote interpersonal experiences (e.g., the Lighthouse project [95] enabling a shared museum visit for remote and local visitors).

The Telepresence scenario deals with remote communication between two participants and therefore the works include only remote use cases and have mostly a person focus. We can see in Figure 10 that most of the work in this category was done recently, with older works supporting symmetric telepresence and newer works exploring more asymmetric communication forms. This category is well-known in the CSCW, Presence and HRI literature but is underrepresented here due to our focus on MR, which excludes a great number of purely virtual systems and primarily-screen-based systems.

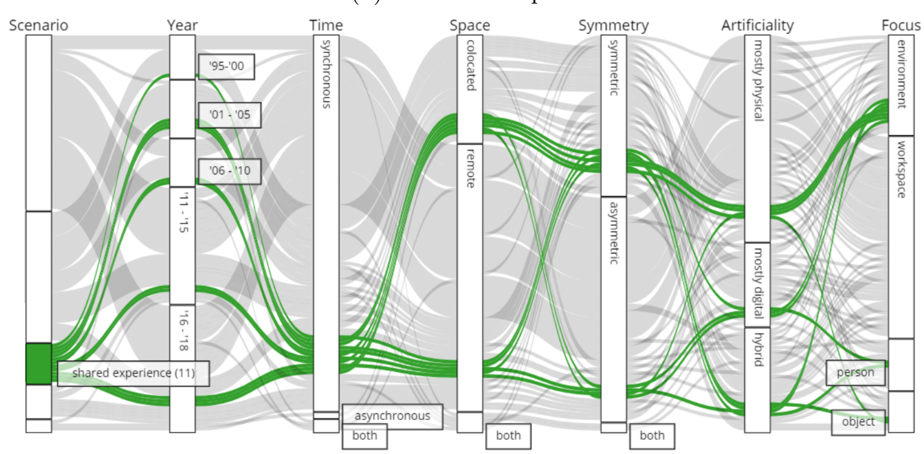
The final scenario category, co-annotation, includes only three papers. It involves asynchronous collaboration (usually co-located and symmetrical). These have only been explored in AR systems relatively recently, presenting a contrast with traditional CSCW systems, where asynchronous communication is quite common.



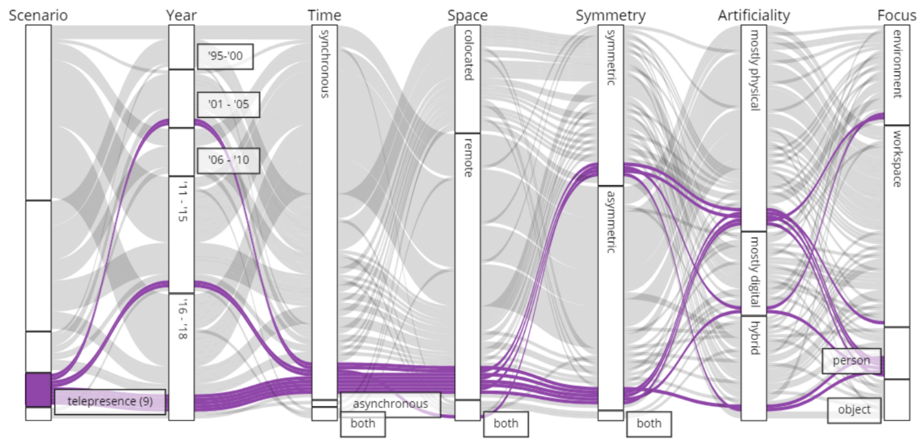
(a) remote expert



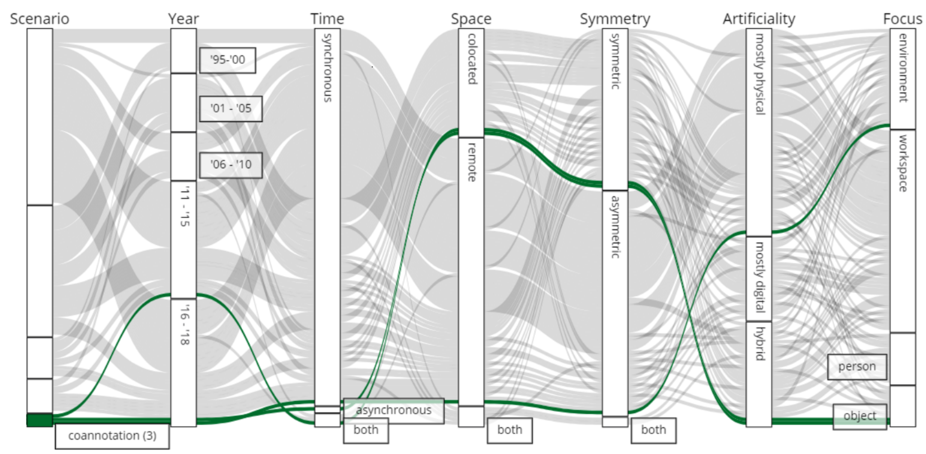
(b) shared workspace



(c) shared experience



(d) telepresence



(e) co-annotation

Figure 10: Distribution of papers in each scenario according to the different dimensions. An interactive version of this figure is available online at `http://hci.cs.unb.ca/collabMR/`

3.5. Discussion

Many of the earlier works focused on the design and implementation of large, novel technology-oriented systems, showing proof of concept for early ideas. As can be seen in Figure 6, most of the works between 1995-2004 focused on colocated work. Rekimoto [13], Billinghurst [14], and Schmalstieg [16] introduced the concept of collaborative colocated AR interaction around a digital artifact and provided an initial infrastructure for its support. A common early use case to examine the feasibility and user behavior in colocated AR collaboration was games [15, 87, 96, 97, 98]. Other earlier works looked at how to combine VR technology, which was more established at the time, with the newer AR technologies. MagicBook [99] explored the transition between AR and VR using a system that enabled users to collaboratively view a book, switching between an AR and VR view, while Kiyokawa, Takemura and Yokoya [75] seamlessly combined a shared virtual environment with a shared augmented environment.

As with colocated works, early remote collaborative MR works also focused on system architecture and solutions to various technical challenges (e.g, [100, 82, 101]). Kato and Billingurst [100] introduced a tracking and calibration solution to support AR in remote collaboration. Other works explored the novel design spaces that were introduced with the availability of the new technology. Examples are the Lighthouse project [95] which examined a MR space that enabled a shared museum visit experience between visitors at the museum and at home, and works by Regenbrecht et al. [102, 103] who looked at augmented virtuality, showing remote users' video in a collaborative virtual space indicating their viewpoint and viewing direction.

As the field matured, later works started to look more and more at the human factors and human aspects of the technical solutions, performing various user studies, and examining different aspects of the solutions and design spaces. Looking at the change over time of the different dimensions and scenarios, it seems that the upsurge in works dealing with collaboration in MR that started at 2012 (see Figure 5) consists mostly of works related to the remote expert scenario, of remote, asymmetric, workspace-focused studies and systems looking at these issues. This is evident, looking at Figures 6 & 10(a), which show a clear marked increase of remote works starting from 2005 and onward, with many of these focusing on the remote expert scenario. Fussell et al. [32] performed an early examination of the role and possible employment of gestures, looking at how people communicate and use annotations in a remote expert scenario around a physical task. Other studies in remote, asymmetric collaboration soon followed, examining issues such as gaze [104, 105, 106], annotations [107, 21, 108, 83], partial and full embodiment [41, 93, 109], point of view [19] and more.

We can see from Figure 10(b) that the shared workspace scenario was also heavily explored, second only to remote expert (but with a more even distribution over the years). Unlike the remote expert scenario, the shared workspace scenario is more varied and may include both colocated and remote use cases. One subcategory of shared workspace is collaborative design (e.g., [110, 111, 13]). These works look at collaborative interaction around a virtual object or workspace, with the purpose of designing or prototyping the object or the workspace. Another subcategory is games [88, 87, 96, 98, 97, 89], which was a commonly-explored use case, and can also fall within the shared experience scenario depending on the implementation of the game.

As we have seen, there were very few papers that were categorized as asynchronous. Because most of the works in our survey occupy the AR segment of the MR spectrum, which deals with augmenting real physical spaces with artificial information, they coincide with the "same place / different time" quadrant of the classic CSCW matrix. In classical CSCW, this quadrant is occupied by systems working in a stationary location supporting a continuous task, for example, large public displays or shift-work groupware applications (e.g., [112], [113],[114]). Similarly, AR applications can leave digital information at specific locations for later users. For example, digital graffiti and annotations can be placed at certain locations and viewed or interacted by users at a later time [70]. Another example is the tagging of environmental features for an ongoing task [61]. The challenge is to build tools that would enable the producer of the information to leave clear AR annotations and instructions, as well as enable the consumer to understand these messages. While existing research have considered the production of AR information, as well as the consumption of AR information as separate actions, the asynchronous combination of these actions has seldom been considered [71]. We further discuss the potential direction of research in asynchronous collaboration in Section 4.

Returning to our goal stated at the beginning of this section: Are we able to clearly describe distinct categories of collaborative MR research based on the existing dimensions? To some extent, yes, however the result is not wholly satisfying. The classic CSCW dimension of space, along with symmetry, artificiality and focus tell part of the story. For instance, the works in the remote expert scenario, as can be seen in Figure 10(a), can be mostly defined according to the remote-asymmetric-mostly physical-workspace line. However, these dimension do not suffice to describe all scenarios. For example, it is difficult to distinguish between the features of the shared workspace and the shared experience scenarios who mostly use the same dimensions and many Telepresence works are very similar to the remote scenario signature that was stated above. Thus, it seems there is something distinctly different about these scenarios that is not entirely captured by these existing frameworks.

While somewhat useful, the dimensions we used are fairly technical, and focus mainly on mechanical aspects of the system or properties of the underlying technologies. For instance, Benford et al. [64] show that their dimensions are highly useful for classifying different types of collaborative systems, but these do not focus squarely the qualities of the user experiences. Perhaps additional dimensions with a greater focus on user experience would better allow for capturing the essence of these scenarios. For example, by investigating the focus dimension we were able to identify common interests in each scenario (i.e., environment in shared experience, and person in telepresence). Still, this is not enough to uniquely define each scenario.

One clear trend we have noticed is that research has progressed from a focus on solving initial technical challenges in MR toward more meaningful investigations of collaboration. The same appears to be true of individual component technologies of MR. For instance, as capacity for replicating physical objects and environments improved, these became increasingly explored, expanding the settings for collaboration. Similarly, improvements in network connectivity led to a greater abundance of remote collaborative systems, and better sensing technologies allow a local user's environment to be more easily shared in remote expert systems. As new capabilities emerge, such as the ability to explore variations in scale, and handling collaboration in large groups, we expect to see this trend continue, with an initial focus on perfecting the systems, followed by deeper explorations of collaboration. In the following section, we discuss where some of these emerging technologies will likely lead in the near future.

4. Foreseeable Directions

In prior sections we reviewed past and current research trends. Based on these observations, we devote this final section to discussing potential directions that we envision research will follow in coming years. Rather than focusing on technical advances, we try to highlight features that would support human-centred interaction between users in MR collaboration systems. We identify these directions by extrapolating trends we observed in our review, by identifying unusual works that stand out from our classifications, and by looking at developments in collaborative systems outside of MR. In particular we identify the following research opportunities:

- Complex Collaboration Structures in Time, Space, and Symmetry
- Convergence and Transitional Interfaces
- Empathic Collaboration
- Collaboration Beyond the Physical Limits
- Social and Ethical Implications

In this section we describe each of these areas in more detail.

4.1. Complex Collaboration Structures in Time, Space, and Symmetry

The vast majority of the work we uncovered in our review focused on simple one-on-one collaborative structures—typically in either a “remote expert” scenario, or in scenarios where collaborators were essentially peers such as in a “shared workspace” scenario. However, future AR collaboration systems need to support participation structures that match the complexity of real world collaborative tasks (in addition to supporting new participation structures that are enabled by AR technologies). This encompasses issues including: (1) the size of the collaborating group, (2) supporting mixed presence in the group, (3) the synchronicity of the collaborating group, and (4) the roles of members in the groups (as well as the dynamic nature of these roles).

Most of the works we reviewed focused on simple, one-to-one collaboration as an initial use case to explore collaborative MR issues. However, large-sized groups are commonplace in physical and virtual environments, and it seems likely that collaborating groups making use of MR technology will also be large. For instance, teams that work on architectural designs for built environments or on automotive designs tend to be quite large, with project teams scaling into the hundreds depending on the size of the project. In a more ludic context, massive multiplayer online games support hundreds to thousands of people playing in a shared virtual environment. VR platforms such as Sansar (https://www.sansar.com), AltspaceVR (https://altvr.com), or VRChat (http://vrchat.net) enable casual interaction between tens to hundreds of people in virtual worlds. We are already beginning to see large group participation in MR technology–for instance, in the livestreaming space [115], where one livestreamer broadcasts and interacts with a large audience, we are now beginning to see the use of 360° capture technologies to broadcast to and interact with large audiences, sometimes as large as thousands. Yet, the challenges of how to support these groups and their interactions with one another remain unaddressed. For instance, how do audience members communicate about objects they see, or to direct the livestreamer in a timely way? Kasahara et al. [60] explored an interesting setup of many-to-many sharing of first person view video allowing each participants to see all others' view in parallel. While their study was in a relatively small group of four participants, it pointed to needs for future investigation on interaction and visualisation techniques for organising and assisting collaboration between a large group of people sharing their experiences.

In Space dimension, we see supporting mixed presence, where remote subgroups collaborate with one another, as being likely commonplace future use-cases. For instance, remote expert prototypes to this point have focused on the core communicative actions across the remote link between two collaborators (i.e., verbal communication combined with some sort of visual representation of gesture or annotation), yet in complex problem solving scenarios, we expect expertise to come from a team of experts. Similarly, we expect that collaborative systems supporting boardroom-style teleconferencing scenarios will also need to support mixed reality interaction and exploration of data. In both these cases, further research needs to explore how to support collaboration between team-members who are both colocated and remote, as the physical embodiment of collaborators affects how they can work with one another. A key challenge to address here is to afford all the benefits of collocation while similarly realizing the presence of remote collaborators in ways that all can participate effectively.

As discussed in Section 3, the majority of past works focus on synchronous collaboration scenarios in the Time dimension. However, in future we expect to see more opportunities for asynchronous systems to arise (Irlitti et al. [71] provide a broad discussion of such opportunites). Much as decision-making and creativity work occurs on documents over long periods of time, where collaborators will take on different parts of a document, making edits asynchronously, we expect that further work needs to explore how to enable asynchronous forms of collaboration around spaces and artefacts–be they digital or physical ones. In many ways, this sort of place-based annotation already happens with wide-scale use of map-based review systems (e.g., restaurants, stores, etc.), yet there are challenges yet to be solved before such vision-based tracking can robustly support place-identification in contemporary AR systems (e.g., inconsistent lighting, changes in a particular place over time, etc.). We also expect collaborative systems to transition between asynchronous and synchronous modes rather than strictly staying in one type; thus, we expect researchers need to consider how to design support to enable smooth transitions between asynchronous and synchronous styles of work.

Finally, the vast majority of MR collaboration prototype interfaces have so-far considered relatively simplistic roles, whereas real-world collaborative roles are considerably more complex. For instance, many early prototypes seem to be peer-based user interfaces, where users each have symmetric abilities to interact with the space (see Figure 7). Beyond this, remote expert systems have begun to explore the impact of roles on the interfaces, where an expert's interface (for instance, an annotation or gestural interface) differs from a novice's one (for instance, a see-through AR interface). We have seen collaborative systems with highly granular differentiation depending on the specific roles collaborators have in the project (e.g., document editing tools such a Wikipedia typically split apart owner, editor, writer, viewer roles), and researchers will need to consider what the roles should be and how they should manifest in collaborative MR systems of the future.

4.2. Convergence and Transitional Interfaces

Milgram [62, 63] viewed Mixed Reality (MR) as a continuum that spans between two extremes, pure physical reality and pure Virtual Reality, with any amount of mixture between considered MR. In our framework, we distinguished between papers according to their focus as seen on this continuum using the *artificiality* dimension (Section 3.3.3). While Milgram used particular terms to distinguish a particular ratio of mixture, such as Augmented Reality or Augmented Virtuality, the MR as a continuum suggests that there is no dividing line between these concepts — similarly, advances in technology will inevitably allow these platforms to converge and become indistinguishable. In fact, many of the common low level technologies are already shared in AR, AV, and VR systems.

Based on this notion, researchers have proposed and investigated a concept of transitional interface that allows users to move from pure physical space to AR and to pure VR environment. For example, Billinghurst et al. [99] proposed Magic Book which supports such transitional interface in story telling application where the user can start from reading a physical book, then use an AR interface to watch a relevant virtual scene pop out from the physical book, and further transfer into an immersive VR environment by flying into a virtual story book scene. Transitioning along the MR continuum is as simple as raising an AR display or pressing a button on the display to switch between AR and VR modes. Magic Book also supported colocated collaboration where two or more people partaking in the experience of reading the same story book and collaborating across the Mixed Reality continuum.

With convergence of AR and VR technology, it is envisioned that transitional interfaces would be also applied to MR remote collaboration. Many of the recent work in MR collaboration systems use both AR and VR interfaces together (e.g., Oda et al. [92], Piumsomboon et al. [116]), although in most cases a user is still dedicated to either an AR (usually local user) or VR (usually remote user) interface at any one time. These systems are usually designed for asymmetric collaboration where the user sharing the physical environment and their remotely-located collaborator use different interfaces and have different roles expected. However, as the technology matures, it is likely that people will use an integrated device interface that supports both capturing and joining the shared experience, as people now use the same smartphones for making a video call. And with the advent of such MR device interfaces, support for both capturing and displaying AR/VR experiences will allow users to naturally and easily change roles in MR collaborative experiences.

Transitional interfaces in MR remote collaboration systems will enable users to start conversations in VR, then transition to AV or AR as a user starts sharing a part of or entire physical environment he or she is in. This is analogous to modern video conferencing solutions supporting integration and transition between audio and video calls, and even text messages.

Transitions in MR remote collaboration can also happen in other dimensions of the design space, aside from Artificiality. For example, in the Time dimension, an MR collaboration session could start as asynchronous collaboration, then move into a synchronous live session, and fall back again to asynchronous as the conversation calms down. It could also transition from a small group to a larger one, starting as a 1-to-1 session with more people joining as the conversation grows. Transitions can also happen between colocated and remote collaboration in the Space dimension. For instance, a user leaving a colocated MR conversation could continue by transitioning to remote collaboration as they depart; or conversely, a participant could initialize a MR collaboration session remotely on her way to the place where a colocated MR collaboration will be held. The Symmetric-Asymmetric dimension also provides a space for transition. For example, in an asymmetric 360/3D broadcasting session the streamer can choose to interview one of the viewers, asking him or her to also share his physical surroundings turning into a symmetric collaboration between the streamer and the interviewee.

4.3. Empathic Collaboration

One of the key elements of collaboration is to understand each other and build empathy. To define empathy, Austrian psychotherapist Alfred Adler (1870-1937) uses a quote from an anonymous author, "One must see with the other person's eyes, hear with his ears, and feel with his heart" [117, 118]. Based on this notion, we envision MR collaboration will grow from seeing the reality of another to feeling the reality of another.

From the survey, we observed that the main focus of many shared experience and telepresence systems has been on capturing, sharing and presenting a remote person and his or her physical surroundings, with focus on the audiovisual sensory channel. Advances in imaging and audio technology have made it much more feasible and affordable to capture a person's physical environment, and their appearance in high quality. As the technology matures enough for capturing and sharing the outward appearance of physical entities, we envision MR collaboration will grow and expand to share invisible features and status of the physical reality. Such extension could be applied to sharing internal status of people or sharing multi-sensory features of physical surroundings.

For over twenty years, researchers in Affective Computing [119] have been exploring how computers can capture and recognize emotion, although primarily in single user systems. More recently, the field of Empathic Computing [105] is

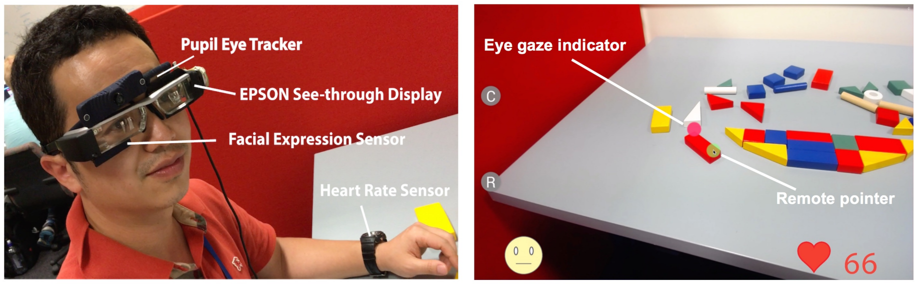


Figure 11: Empathy Glasses sharing facial expression, heart rate, and gaze [120].

concerned with developing systems that will enable people to share how they are feeling with each other in real time. For example, the Empathy Glasses [120] are a pair of AR glasses that enable a local user to share their gaze, facial expression and heart rate with a remote collaborator (Figure 11). A user study with these glasses found that gaze sharing significantly improved the feeling of connection between remote collaborators.

In addition to sharing gaze [106] and facial expressions [120], it would be interesting to further investigate how sharing physiological measures, such as heart rate, body temperature, skin conductivity, or even brain activity, might help with building empathy between collaborators. There are several early projects emerging in the collaborative VR space that experiment with sharing users' physiological measures, such as heart rate and skin conductivity [121]. We expect such efforts will expand into the MR space as well. Beyond merely capturing and sharing numerical readings of such physiological measures [120], analysing these measures and recognising the mental, cognitive, and emotional state of a collaborator's mind could lead to deeper understanding between collaborators. Advances in machine learning techniques will contribute towards summarizing and organizing such massive amount of physiological information into digestible representations.

In addition to sharing the internal state of collaborators, another interesting research direction would be capturing and sharing non-visible multi-sensory features of the physical environment and applying them to interaction between collaborators. For example, haptic interfaces have been actively investigated in VR systems both for single user experiences and multi-user collaboration [122], which could also be applicable to MR collaborative systems [88]. Early explorations on combining other sensory interfaces with MR systems [123], such as olfactory and gustatory experiences, also envision their application in MR collaboration. Advances in display technology, real time space capture, natural gesture interaction, robust eye-tracking and emotion sensing/sharing are enabling the creation of systems for empathic tele-existence. These are systems that allow remote collaborators to move from being observers to participants and having shared experiences together.

4.4. Collaboration Beyond the Physical Limits

MR has the potential to alter our perception making space-time malleable, giving us the flexibility to alter ones reality. Recent research has been exploring the manipulation of realities to create experiences beyond that we could encounter in the real world. This knowledge also extends to new ways that we can collaborate beyond the limits of a face-to-face meeting. Here we give examples of emerging MR research that enhance collaboration beyond the physical limitation.

One area recently emerging is the manipulation of the user's scale in the collaborative environment. Our survey identified only a few works that introduced the concept of scale in MR [75, 99, 124], but we see the concept growing beyond it's more established roots in VR. This research area extends from the Multi-scale Collaborative Virtual Environment [125], which explores collaboration between city planners working at different scales to complement each users actions in a virtual environment. Other research has studied techniques for collaboration at different scales [126, 127] including a co-manipulation technique across AR and VR [124].

Early MR works that explored multi-scale collaboration combined AR and VR technologies and mostly focused on co-located collaboration. For example a system by Kiyokawa [75] supported user transitions between VR and AR and collaborated across multiple scales. The MagicBook [99] overlaid AR content on a physical book for one user while another user could scale down in VR to collaboratively explore the scene at different scales.

Recent multi-scale MR research has emphasized remote collaboration. For example, Piumsomboon et al. [128] demonstrated a system that shared an AR user's 3D reconstructed environment with a VR user who could be in a regular scale or a giant scale. As the VR user scaled themselves down into a miniature form, they immersed in a 360-video shared by the AR user instead. Another work by Piumsomboon et al. [24] discussed multi-scale telepresence support by equipping an Unmanned Aerial Vehicle (UAV) with an adaptive stereo camera. Adjusting the eye separation of the virtual camera can then create an illusion of growing to a giant in the real world.

In another area, we observe the rise of research that leverages the physicality of objects in the surrounding environment to create more realistic experiences in VR [129, 130, 131], or to provide augmented virtuality experiences [132]. For example, TurkDeck [133] experimented using real people to create dynamic physical constraints in a room with real props to facilitate the VR user with haptic and tactile feedback in virtual environment (VE). Sra et al. [134] proposed a procedurally generated VE from the real environment by capturing a 3D reconstruction of a real indoor scene, detecting the obstacles and walkable areas, and generating a VE that matches the physical space. Mutual Human Actuation [130] proposed using a pair of users to simulate opposing forces, motions, and actions for an asymmetric experience in different VEs but in a shared co-located physical space.

We believe that there will be more research and development that not only blurs the the boundary between physical and virtual realities but pushes the limit beyond what is possible in the real world.

4.5. Social and Ethical Implications

To date, much of the work in collaborative MR, as surveyed in this paper, has looked at enabling and understanding novel methods of communication and collaboration, focusing on technical, usability and human factors issues. However, little focus has been put into the social aspects of collaborative MR. Social MR is rapidly advancing in the entertainment and social networking areas (e.g., enabling filters and augmentations of one's face), and substantial resources are invested in this area by different companies. Novel collaborative MR technologies may enable new forms of social interactions. However, their impact on user behavior in social situations remains mostly unclear. It was shown that AR has the power to elicit negative feelings such as unfairness [135], shame [136] or loneliness [137]. Digital traces may be left in the physical world and need to be considered [138]. Furthermore, conflicts between technology features and prevailing social norms might emerge, and are likely to lead to increased uncertainty and tensions among users [139]. Thus, research should examine how the design of social MR systems might affect the relations between its users in order to better design safe and acceptable social MR experiences.

Social acceptance is another commonly known social issue for MR interfaces, especially when implemented in a wearable form [67]. Wearing AR glasses can evoke negative feelings in bystanders, who may perceive the technology as a violation of their privacy and private space [140]. While there is some prior research on investigating social acceptance of MR interfaces [68, 141], most of these studies are limited to single user MR applications used in public spaces.

Finally, privacy is one of the main concerns of any type of communication technology. Modern social networking services have built in features and functions for ensuring privacy, such as filtering shared information depending on social proximity (e.g., Facebook allows limiting audience when posting). While MR collaborative interfaces can also borrow methods from existing social networking services, further investigation is needed on privacy issues unique to MR. For example, there are early experiments on investigating how the level of details of an avatar [142] or virtual objects [143] could be filtered based on social proximity. However, these works face evaluation challenges in the real world, as MR collaboration systems are still not widely adopted.

5. Conclusion

Collaborative MR systems have only recently advanced to the point where researchers can focus deeply on the nuances of supporting collaboration, rather than needing to focus primarily on creating the enabling technology. To demonstrate this, we have provided an overview of systems, from the earliest seminal works to the most recent developments. These have not only demonstrated the feasibility of MR technologies to support collaboration, but also evidenced new ideas of how collaborative work can be accomplished. This overview reveals that existing frameworks for describing groupware and MR systems are not sufficient to characterize how collaboration occurs through this new medium. Further, our findings suggest that MR systems have continued to adopt new advances to create imaginative systems that push the edges of what has been previously explored in CSCW.

We believe that MR technology will continue to mature rapidly over the coming years, and there are going to be new and fruitful directions for researchers to explore. In this regard, we hope our work can be used as a starting point and as a call to action for researchers who have been working primarily in either the areas of CSCW or in collaborative MR. MR researchers need to continue to deepen their understanding of the basic theories and lessons from decades of CSCW work. CSCW researchers have the opportunity to help set the direction for what collaboration will look like in the future. Our work is just a starting point and more work must be invested in revising frameworks of collaboration to help describe, categorize and identify new opportunities for technology that expand our sense of what it means to be together.

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Appendix - Papers Included in Review, with Coding

Year	Author		Space	Time	Symmetry	Artificiality	Focus	Scenario
1995	Ahlers et al.	[110]	remote	sync.	asymm.	mostly physical	workspace	remote expert
1996	Rekimoto	[13]	colocated	sync.	symm.	mostly physical	object	shared workspace
1998	Benford et al.	[64]	remote	sync.	symm.	mostly digital	person	shared experience
1998	Billinghurst et al.	[15]	colocated	sync.	symm.	mostly physical	workspace	shared workspace
1998	Ohshima et al.	[87]	colocated	sync.	symm.	hybrid	workspace	shared workspace
1998	Szalavari et al.	[144]	colocated	sync.	symm.	hybrid	object	shared workspace
1998	Szalavari et al.	[96]	colocated	sync.	symm.	mostly physical	workspace	shared workspace
1999	Bauer et al.	[82]	remote	sync.	asymm.	mostly physical	workspace	remote expert
1999	Butz et al.	[145]	colocated	sync.	symm.	hybrid	workspace	shared workspace
1999	Fraser et al.	[91]	remote	sync.	symm.	mostly digital	environment	shared workspace
1999	Höllerer et al.	[90]	remote	sync.	asymm.	mostly physical	environment	remote expert
1999	Kato & Billinghurst	[100]	remote	sync.	asymm.	mostly physical	workspace	remote expert
1999	Kiyokawa et al.	[75]	colocated	sync.	asymm.	mostly digital	workspace	shared workspace
2000	Schmalstieg et al.	[146]	both	sync.	both	hybrid	workspace	shared workspace
2000	Starner et al.	[98]	colocated	sync.	asymm.	mostly digital	environment	shared expereince
2001	Billinghurst et al.	[99]	colocated	sync.	symm.	hybrid	object	shared experience
2001	Reitmayr & Schmalstieg	[147]	colocated	sync.	symm.	hybrid	environment	shared workspace
2002	Billinghurst et al.	[148]	colocated	sync.	symm.	hybrid	workspace	shared workspace
2002	Cheok et al.	[97]	colocated	sync.	asymm.	hybrid	workspace	shared workspace
2002	Kiyokawa et al.	[149]	colocated	sync.	symm.	mostly digital	person	shared workspace
2002	Mogilev et al.	[150]	colocated	sync.	symm.	mostly physical	workspace	shared workspace
2002	Prince et al.	[101]	remote	sync.	asymm.	hybrid	person	telepresence
2002	Regenbrecht et al.	[151]	colocated	sync.	symm.	hybrid	object	shared workspace
2002	Schmalstieg et al.	[152]	colocated	sync.	symm.	mostly digital	workspace	shared workspace
2003	Brown et al.	[95]	remote	sync.	symm.	hybrid	environment	shared expereince
2004	Barakonyi et al.	[84]	remote	sync.	symm.	mostly physical	person	telepresence
2004	Benko et al.	[18]	both	both	symm.	mostly digital	environment	shared workspace
2004	Fussell et al.	[32]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2004	Regenbrecht et al.	[102]	remote	sync.	symm.	mostly digital	workspace	shared workspace
2005	Grasset et al.	[153]	remote	sync.	asymm.	hybrid	environment	shared experience
2006	Regenbrecht et al.	[103]	both	sync.	asymm.	mostly digital	workspace	shared workspace
2006	Stafford et al.	[154]	remote	sync.	asymm.	hybrid	environment	remote expert
2007	Chastine et al.	[155]	both	sync.	both	hybrid	workspace	remote expert
2007	Knoerlein et al.	[88]	colocated	sync.	symm.	mostly physical	environment	shared experience
2007	Minatani et al.	[156]	remote	sync.	symm.	mostly digital	person	shared workspace
2007	Pauchet et al.	[104]	remote	sync.	symm.	mostly digital	workspace	shared workspace
2007	Tang et al.	[41]	remote	sync.	symm.	mostly digital	workspace	shared workspace
2008	Chastine et al.	[157]	remote	sync.	asymm.	mostly digital	workspace	remote expert
2008	Stafford et al.	[158]	remote	sync.	asymm.	mostly physical	environment	remote expert
2009	Huynh et al.	[89]	colocated	sync.	symm.	hybrid	workspace	shared workspace
2009	Nilsson et al.	[86]	colocated	sync.	symm.	hybrid	workspace	shared workspace
2009	Piekarski & Thomas	[159]	remote	sync.	asymm.	mostly physical	environment	remote expert
2010	Tang et al.	[42]	remote	sync.	symm.	mostly digital	person	shared workspace
2011	Alem & Li	[160]	remote	sync.	symm.	mostly physical	workspace	remote expert
2011	Wang & Dunston	[111]	both	sync.	symm.	hybrid	workspace	shared workspace
2012	Barden et al.	[161]	remote	sync.	symm.	mostly physical	environment	shared experience
2012	Gauglitz et al.	[22]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2012	Gurevich et al.	[79]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2012	Junuzovic et al.	[81]	remote	sync.	symm.	mostly physical	workspace	shared workspace
2012	Kasahara et al.	[70]	colocated	both	symm.	hybrid	object	coannotation
2012	Oda & Feiner	[162]	colocated	sync.	symm.	hybrid	workspace	shared workspace
2012	Poelman et al.	[61]	remote	both	asymm.	mostly physical	environment	remote expert
2012	Tecchia et al.	[46]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2012	Yasojima et al.	[163]	colocated	sync.	symm.	mostly digital	object	shared workspace

to be continued...

Year	Author		Space	Time	Symmetry	Artificiality	Focus	Scenario
2013	Adcock et al.	[107]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2013	Beck et al.	[164]	both	sync.	symm.	mostly digital	environment	telepresence
2013	Bleeker et al.	[165]	remote	sync.	symm.	mostly digital	workspace	shared workspace
2013	Huang & Alem	[47]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2013	Huang & Alem	[166]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2013	Huang et al.	[167]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2013	Jo & Hwang	[168]	remote	sync.	asymm.	mostly physical	environment	remote expert
2013	Kim et al.	[169]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2013	Kim et al.	[170]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2013	Lanir et al.	[19]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2013	Sodhi et al.	[44]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2014	Adcock et al.	[171]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2014	Benko et al.	[74]	colocated	sync.	symm.	hybrid	person	shared experience
2014	Datcu et al.	[172]	remote	sync.	asymm.	hybrid	workspace	shared workspace
2014	Gauglitz et al.	[45]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2014	Gauglitz et al.	[108]	remote	sync.	symm.	mostly physical	workspace	remote expert
2014	Kasahara & Rekimoto	[78]	remote	sync.	asymm.	mostly physical	environment	remote expert
2014	Kim et al.	[83]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2014	Rae et al.	[173]	remote	sync.	asymm.	mostly physical	workspace	telepresence
2014	Zillner et al.	[174]	remote	sync.	symm.	hybrid	person	shared workspace
2015	Adcock & Gunn	[175]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2015	Amores et al.	[176]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2015	Higuchi et al.	[80]	remote	sync.	symm.	mostly physical	person	telepresence
2015	Kratz et al.	[177]	remote	sync.	asymm.	mostly physical	environment	telepresence
2015	Le Chénéchal et al.	[178]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2015	Lin et al.	[179]	colocated	sync.	symm.	mostly digital	workspace	shared workspace
2015	Lukosch et al.	[37]	remote	sync.	asymm.	mostly physical	object	remote expert
2015	Nagai et al.	[180]	remote	sync.	asymm.	mostly physical	environment	shared experience
2015	Oda et al.	[92]	remote	sync.	asymm.	hybrid	object	remote expert
2015	Tait & Billinghurst	[20]	remote	sync.	asymm.	hybrid	environment	remote expert
2016	Alizadeh et al.	[94]	remote	sync.	symm.	hybrid	person	shared workspace
2016	Fakourfar et al.	[21]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2016	Gupta et al.	[181]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2016	Higuch et al.	[182]	remote	sync.	symm.	mostly digital	environment	remote expert
2016	Irlitti et al.	[71]	colocated	async.	symm.	hybrid	object	coannotation
2016	Le Chénéchal et al.	[124]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2016	Mueller et al.	[183]	colocated	sync.	symm.	mostly physical	environment	shared workspace
2016	Nuernberger et al.	[184]	remote	both	asymm.	mostly physical	object	remote expert
2016	Orts et al.	[93]	remote	sync.	asymm.	mostly digital	person	telepresence
2016	Pejsa et al.	[185]	remote	sync.	symm.	hybrid	person	telepresence
2017	Gao et al.	[186]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2017	Gugenheimer et al.	[76]	colocated	sync.	asymm.	mostly digital	environment	shared workspace
2017	Lee et al.	[55]	remote	sync.	asymm.	mostly physical	environment	remote expert
2017	Lee et al.	[106]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2017	Onishi et al.	[85]	remote	sync.	asymm.	mostly physical	person	telepresence
2017	Piumsomboon et al.	[187]	remote	sync.	asymm.	mostly physical	environment	remote expert
2017	Piumsomboon et al.	[116]	remote	sync.	asymm.	mostly digital	environment	shared workspace
2017	Piumsomboon et al.	[105]	remote	sync.	asymm.	hybrid	workspace	remote expert
2018	Aschenbrenner et al.	[188]	remote	sync.	asymm.	mostly digital	environment	remote expert
2018	Gugenheimer et al.	[77]	colocated	sync.	asymm.	mostly digital	environment	shared experience
2018	Kim et al.	[189]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2018	Lee et al.	[23]	remote	sync.	asymm.	mostly physical	environment	remote expert
2018	Piumsomboon et al.	[128]	remote	sync.	asymm.	mostly physical	workspace	remote expert
2018	Piumsomboon et al.	[109]	remote	sync.	asymm.	hybrid	person	remote expert
2018	Poretski et al.	[139]	colocated	sync.	symm.	mostly physical	object	shared experience
2018	Ryskeldiev	[190]	remote	sync.	asymm.	mostly physical	environment	coannotation
2018	Speicher et al.	[191]	remote	sync.	asymm.	mostly physical	workspace	shared workspace