What is Mixed Reality?

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ABSTRACT

What is Mixed Reality (MR)? To revisit this question given the many recent developments, we conducted interviews with ten AR/VR experts from academia and industry, as well as a literature survey of 68 papers. We find that, while there are prominent examples, there is no universally agreed on, one-size-fits-all definition of MR. Rather, we identified six partially competing notions from the literature and experts' responses. We then started to isolate the different aspects of reality relevant for MR experiences, going beyond the primarily visual notions and extending to audio, motion, haptics, taste, and smell. We distill our findings into a conceptual framework with seven dimensions to characterize MR applications in terms of the *number of environments*, *number of users*, *level of immersion*, *level of virtuality*, *degree of interaction*, *input*, and *output*. Our goal with this paper is to support classification and discussion of MR applications' design and provide a better means to researchers to contextualize their work within the increasingly fragmented MR landscape.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *HCI theory, concepts and models*;

KEYWORDS

Augmented reality; conceptual framework; expert interviews; literature review; mixed reality; taxonomy; virtual reality.

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1 INTRODUCTION

This paper is motivated by many discussions with colleagues, researchers, professionals in industry, and students active in the HCI community, all working on Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) projects. These discussions showed that, while MR is increasingly gaining in popularity and relevance, and despite the relative popularity of Milgram & Kishino's Reality–Virtuality Continuum [44], we are still far from a shared understanding of what MR actually constitutes. Many see MR as a synonym for AR. Some consider MR strictly according to the definition given by Milgram & Kishino [44], i.e., a superset of AR in terms of a "mix of real and virtual objects within a single display." Yet, others consider MR distinct from AR in the sense that MR enables walking into, and manipulating, a scene whereas AR does not. Some do not even attempt, or want, to specify what MR is. What adds to the confusion is that key players like Microsoft are pushing MR as a new technology, first, with HoloLens, then expanding to a range of Windows Mixed Reality devices, along with the Mixed Reality Toolkit to build applications for these devices.

What does this paper do? The goal of this paper is to work towards a shared understanding of the term MR, the related concepts and technologies. Many researchers base their understanding of MR on the Reality–Virtuality Continuum [44], which they consider the go-to source for a widely accepted definition of MR. Yet, as we will show with expert interviews and a literature review reported in this paper, it is not a universally agreed notion. As the authors noted themselves, the core limitation of the continuum is the fact that it is restricted to *visual* features. Broadly speaking, MR originated from computer graphics, hence common notions of MR are mostly restricted to graphical aspects. Yet, technological capabilities, design practices, and perceptions of MR have evolved since the continuum was first proposed in 1994, and discussions about MR have become increasingly difficult. We therefore found it necessary to identify the different working definitions of MR that are used "in the wild", how they differ and relate, and what their limitations are. We hope that our effort will allow the community to work towards a more consistent understanding of MR and apply it in different contexts, e.g., to better characterize MR experiences using such distinguishing factors as single-user or multi-user, same or different environments, different degrees of immersion and virtuality, and implicit *vs.* explicit interactions.

*What does this paper **not** intend to do?* The goal of this paper is **not** to find *the* definition of MR, or even to develop a new one. First, there are already several definitions in the literature and in use, and another one would only add to the confusion. Second, it is not realistic or constructive to try to impose a definition onto an active community. Finally, MR is a rapidly developing field and it is not clear whether a single definition would be sufficient to cover all its aspects.

This paper offers two core contributions:

(1) We compile six widely used working definitions of MR. These have been derived from interviews with ten experts and a literature review of 68 sources. We provide an overview of the status quo, showing that there is no one-size-fits-all definition for a concept as broad as MR, but that there are indeed different, competing types of MR to be distinguished.

(2) We provide a conceptual framework for organizing different notions of MR along seven dimensions—*number of environments*, *number of users*, *level of immersion*, *level of virtuality*, *degree of interaction*, *input*, and *output*. This framework enables more precise capture of the different types of MR in order to reduce confusion, helps with the classification of MR applications, and paints a more complete picture of the MR space.

Who is this paper for? First and foremost, this paper is intended for anyone who wants to learn about the current state of MR. Given the proliferation of MR technologies and increased interest among new developers, designers, researchers, and in particular students, our work aims to facilitate their participation in the existing MR community. It is our attempt to enable people with differing understandings to better communicate which notions of MR they are working with, with the goal of improving reasoning and reducing misunderstandings, including in peer review processes. Moreover, this paper provides researchers already working in the field of MR with a way to think about their work, and hopefully one that enables them to better contextualize, evaluate, and compare their work, as well as identifying opportunities for further research. In our interviews, experts noted that, even though notions are fading and might not distinguish, or even use, the terms AR/MR/VR anymore in the future, it is important to have a common vocabulary.

In the following, as the background for this paper, we will first revisit the Reality–Virtuality Continuum as one of the most popular notions of MR, and from the literature identify aspects of reality beyond the visual that are relevant for MR. Next, we go into the details of our expert interviews and literature review. As part of our findings, we present six notions, or *working definitions*, of MR and the extent to which they are being used. Finally, based on the aspects of reality and working definitions, we propose a conceptual framework and illustrate its use by classifying two MR applications mentioned in interviews and the literature.

2 FIRST THINGS FIRST: MILGRAM ET AL.'S CONTINUUM

Similar to the goal of this paper, in the early 90s, Milgram et al. noticed that "Although the term 'Augmented Reality' has begun to appear in the literature with increasing frequency, we contend that this is occurring without what could reasonably be considered a consistent definition" [45]. Hence, they developed the *Reality-Virtuality Continuum*—first described in [44]—as a means to facilitate a better understanding of AR, MR, and VR and how these concepts interconnect.

The continuum has two extrema: a fully real environment, the real world, and a fully virtual environment, i.e., VR. Everything in between—*not* including the extrema (cf. [44], Fig. 1)—is described as MR. Types of MR can be AR, which is a mostly real environment augmented with some virtual parts, and *Augmented Virtuality* (AV), which is "either completely immersive, partially immersive, or otherwise, to which some amount of (video or texture mapped) 'reality' has been added" [45]. In particular, according to this definition, VR is not part of MR and AR is only a subset of MR.

Today, this continuum is still probably the most popular source when it comes to definitions of MR, with 3553 [44] and 1887 [45] citations on Google Scholar, as of August 2018. Yet, it stems from the beginning of the 90s and technological capabilities as well as the capabilities of MR have significantly evolved. One shortcoming of the continuum is that it is mostly focused on visual *displays*. The authors note that "although we focus [...] exclusively on mixed reality visual displays, many of the concepts proposed here pertain as well to analogous issues associated with other display modalities[, f]or example, for auditory displays". This, however, means that novel developments like multi-user or multi-environment MR experiences cannot be fully covered. Moreover, despite its popularity and being one of the main frameworks guiding MR researchers (as will become evident in our expert interviews and literature review), we will find that the continuum is neither a universal nor *the* definition of Mixed Reality.

3 ASPECTS OF REALITY

Many experts and researchers the authors have talked to (and many of whom are familiar with the continuum) initially only consider the visual—i.e., virtual 3D models added to a real environment—and a single display when describing or discussing MR. However, in the context of this paper, we are also particularly interested in exploring which aspects beyond the purely visual are considered MR, and in which ways these have already been addressed. From the literature, we have identified five other aspects of reality that can be simulated in a virtual environment, or translated from the physical into the digital to align two environments:

Audio. "Auditory displays" are a possible extension to the Reality–Virtuality continuum mentioned in [44]. An early example is *Audio Aura* [51], which augments the physical world with auditory cues instead of 3D models. Dobler et al. [18] and Çamcı et al. [13] combine visual and audio elements to enable sound design in VR or MR.

Motion. It is not possible to augment the physical world with motion in a digital way. Yet, motion is an important aspect for aligning physical and virtual realities, e.g., by manipulating 3D models based on motion capture [14, 47].

Haptics. A variety of research has looked into haptics as input, e.g., in the form of tangible user interfaces [81], and output, such as [71], who describe a "device that lets you literally feel virtual objects with your hands". A third variant are passive haptics (e.g., [32]) that can be used to enhance virtual environments.

Taste/Flavor. First steps have been taken into the direction of simulating the experiences of eating and tasting. [52] create a virtual food texture through muscle stimulation while [60] have successfully simulated virtual sweetness.

Smell. Another key human sense is smelling. Previous work [12] has looked into smell in virtual environments as early as 1994 while [59] inquired into authentic (virtual) smell diffusion. Hediger & Schneider [24] discuss smell as an augmentation to movies.

4 EXPERT INTERVIEWS

To get a better understanding of accepted notions of Mixed Reality and in which ways they potentially differ—and therefore as a foundation for our conceptual framework of Mixed Reality—we have interviewed a total of ten AR/MR/VR experts ($\mathcal{I}$1–$\mathcal{I}$10) from academia and industry.

We recruited experts from academia (5) and industry (5) we identified based on their experience and leadership in the AR/VR field. All interviewees had at least two years of experience and eight had 8+ years of experience working with AR, MR, and/or VR technologies. Our interviewees were: a full professor, an associate professor, an assistant professor, a post-doctoral researcher, an AR consultant, a UX engineer for a popular AR/VR headset, an R&D executive, the CTO of an AR/VR company, the CEO of an AR company, and the head of an AR lab. Their backgrounds included HCI, computer vision, technology-enhanced learning, wearable computing, media arts, architecture, design, AR training and maintenance, and entertainment. Each expert received a $20 gift card for their participation.

The interviews started with a short briefing about the background of our research and comprised a total of 16 questions. These questions were designed to uncover differences in perceptions of AR/MR/VR and relevant aspects beyond the visual, and to inquire into understandings of current and potential future definitions. First, we asked interviewees how they usually explain AR, VR, and MR to their students or clients and moreover asked for specific examples they typically use—if any—to illustrate what AR/MR/VR *are* and *are not*. Next, we inquired into what interviewees see as the relevant aspects of reality that should be considered in the context of MR and furthermore gave three examples, for each of which they should state and explain whether it is MR or not: *(1)* listening to music; *(2)* Tilt Brush, where the motion of the user's hands is translated from the physical into the virtual world; and *(3)* Super Mario Bros.™, where Mario (in the virtual world) jumps when the user pushes a button in the physical world. Here, the idea was to provide examples of "increasing controversy" in order to explore the boundaries of MR and what the experts think constitutes a (minimal) MR experience, e.g., whether a simple augmentation or translated motion is enough. Following this, we asked whether it will still make sense to explicitly distinguish between AR, MR, and VR five or ten years from now. The final questions asked the experts to explain whether it is useful to have a single definition of MR at all and if so, which would be the most useful in the context of HCI research.

What is AR?

The interviewees named a set of relevant characteristics for AR experiences, not all of which are compatible. The *merging of 3D graphics with the real world* and *spatial registration in the physical environment* were mentioned as requirements five times each. $\mathcal{I}$2 explained AR as the *combination of the human, the digital, and the physical world*, so that AR cannot be considered independent of the user. Another two experts supported this by mentioning the necessity that *the user has to be in control.* $\mathcal{I}$3 stressed that virtual content must be able to *interact with the real world* while $\mathcal{I}$6 stated that AR, unlike VR, always happens *in the physical space you are currently in.* Two experts provided rather broad explanations by stating that AR is any *contextual digital overlay* or *augmenting your reality in any way* (which specifically stand in contrast to spatial registration). $\mathcal{I}$7 and $\mathcal{I}$10 provided less technical explanations by stressing that AR means augmenting or creating *experiences* by enhancing human perception.

Examples. As for examples they typically use to constitute what AR *is* and *is not*, the most prominent was Pokémon GO. It was given as an example for AR three times; yet, the original version also served as a negative example thrice due to the missing spatial registration. Other examples for AR included Terminator (2×), AR training and maintenance (e.g., Steven Feiner's work; 2×) Google Glass, Snapchat, FB AR Studio, and Pepper's ghost. $\mathcal{I}$10's understanding was that AR is not bound to technology and, therefore, books can be AR if they augment your interactions with the world. Besides Pokémon GO, further examples for what does not constitute AR were sports augmentations on TV (3×), "anything that's just HUD or 2D contextual" (2×), again Google Glass (2×), the Pokémon GO map view (because despite its contextual nature it is fully virtual), (static) paintings, and VR.

Generally, it seems that experts have differing understandings of what constitutes AR. For some, simple overlays already qualify as long as they are contextual (e.g., Google Glass) while others explicitly require spatial registration in space and/or interactions with the physical space—from both, users and virtual content.

What is VR?

Unlike with AR, experts were more in agreement about what constitutes VR. Eight mentioned that the defining characteristic is a *fully synthetic* or *fully virtual view* while one described it as *a completely constructed reality*. Moreover, the *necessity for head tracking or a head-worn display* and *full immersion* were mentioned five and four times, respectively. J2 and J6 specifically noted that VR features an *isolated user*, i.e., there is a lack of social interaction. Two experts described VR as *"the far end of the MR spectrum"* (J4, J7), while three mentioned the *ability to visit remote places* as an important characteristic (J6, J7, J10).

Examples. Two experts (J4, J5) referred to watching 360-degree content on a headset as an example for VR. Moreover, 360-degree movies, Tilt Brush, architectural software, flight simulators, virtual museums, movies like The Matrix, CAVEs and Sutherland's Ultimate Display [78] were mentioned once each. Contrary, watching 360-content on a mobile device like a smartphone was given as a non-VR example by J4 and J5 (due to the missing head-worn display). "Simple" desktop 3D on a screen and anything happening in the space you're in (i.e., the real world) were given once and twice respectively.

Overall, our experts largely agreed that a fully virtual view, full immersion and head-worn technology are what constitutes VR as opposed to AR. Therefore, their characterization of VR is mainly based on hardware and graphical aspects. However, also social aspects were explicitly mentioned.

What is MR?

Experts had more difficulties to specify what constitutes MR, with a number of contradicting statements, which illustrates our motivation for writing this paper. They described *eight* characteristics, of which *everything in the continuum* (incl. VR), *"strong" AR* (i.e., like AR, but with more capabilities)[1], and *marketing/buzzword* were mentioned three times each. Two experts each referred to *AR plus full immersion*, i.e., the possibility to do both, AR and VR in the same app or on the same device. The remaining explanations were *"MR is the continuum"* (J2), the *combination of real and virtual* (J6), that MR is *bound to specific hardware* (e.g., HoloLens; J6), and *"the same as AR"* (J9). Two experts explicitly expressed regret over the fact that the term is also used for marketing purposes nowadays (J1: "It's all marketing mumbo-jumbo at this point."). Moreover, J4 pointed out that "only academics understand the MR spectrum". J10 said that they had not thought enough about MR conceptually, but that they usually see it as "realities that are mixed in a state of transition" and sometimes use AR and MR interchangeably.

Examples. In comparison to AR and VR, interviewees also struggled with giving specific examples for what is and is not MR. Three experts referred to HoloLens as a specific example for MR while J8 mentioned diminished reality and projection-based augmentation. J5 chose Pokémon GO as a whole, i.e., the combination of catching a Pokémon in AR plus the VR map view. J10 chose windows in a house as their example, since they mediate a view, but can also alter your experience with noises and smells if open. In terms of what does not constitute MR, J1 and J9 mentioned anything that is not AR (or registered in space) and gave Google Glass as an example. Moreover, J6 referred to just overlays without an understanding of the physical environment, in the sense that in MR, a virtual chair would be occluded when standing behind a physical table. J3 did not consider HoloLens and RoboRaid as MR, because neither is capable of full immersion, but said that these come closest to their idea of MR.

As above, there are major differences in experts' understanding of MR. Generally, four themes become apparent so far: MR according to Milgram et al.'s continuum, MR as a "stronger" version of AR, MR as a combination of AR and VR (potentially bound to specific hardware or devices), and MR as a synonym for AR.

What are relevant aspects of reality?

Since discussions about AR, MR, and VR usually evolve around graphics and visuals—J8 noted that we are "visually dominant creatures"—we also asked interviewees for other aspects of reality that are relevant for MR, or could be in the future. Five experts each said that MR should consider *(spatial) audio* and *haptics* while three said *any of the user's senses* or *any physical stimulus*, and two each *interactions*, and *anything sensors can track*. *Smell* was mentioned twice. Aspects that were mentioned once included: *other participants* (i.e., the 'social aspect', J3), *geolocation* (J5), *motion* (J7), *temperature* (J8), as well as *wind* and *vibrotactile feedback* (J9). To provoke thinking more about aspects beyond visual and the "boundaries" of MR, we furthermore asked the interviewees to reason for each of the following examples why it is or is not MR.

Listening to Music. Seven of the experts stated that listening to music is not MR, the most prominent reason given being the *lack of a spatial aspect* (5×). Additionally, J3 noted that it is *not immersive enough* while J7 stated that music is

[1]For instance, J8 described AR as "the poor man's version of MR."

not MR when it is just a medium to replace the live experience and does not react to (i.e., mix with) the environment. Yet, three of the experts were undecided. One stated that you "could technically say it's MR", but that the "visuals are still very important". J10 stated that it depends on your "state of mind" and whether you are "carried away by the music".

Tilt Brush. The idea here was to inquire into whether the translation of the motion of the user's hands into the motion of the virtual controllers (i.e., adding a "part" of the real to the virtual world) is enough to constitute MR in the experts' opinions. Almost unanimously, they argued that Tilt Brush is VR rather than MR. The main reasons given were that *no part of the physical world is visible* (6×), that *motion is simply an input to interact with the virtual reality* (4×), and the *high level of immersion* (3×). J2 explicitly stated that "just input is not sufficient to constitute MR". J7 argued that it is MR, because VR is a type of MR according to the continuum and because *the interaction is visible* even though the controllers are virtual.

Super Mario Bros.™ This was maybe the most provocative of the examples. The experts were unanimously convinced that pushing a button on a video game controller is not MR, even though technically a motion is translated from the physical into a virtual world. Four experts reasoned that it is just input. A missing spatial aspect and "if this is MR, then everything is" were mentioned three times each. J6, J8, and J9 said that it would be MR if Mario were standing in the room, though, while J7 and J8 referred to the gap between real world and GUI.

Generally, this shows that *spatial registration* seems to be one of the core features of MR. Many experts argued that listening to music becomes MR as soon as the music reacts to the environment. Moreover, it seems that a *certain minimum of the physical environment needs to be visible.* For instance, J5, J6, and J8 noted that Tilt Brush would be MR if the user's actual hands were visible instead of virtual controllers. Finally, while interactions (both with other users and the virtual parts of the environment) were mentioned as an important aspect of reality for MR, *simple input is not sufficient* to constitute MR.

Will there still be AR/MR/VR in the future?

Regarding the future of the different concepts, four experts said that five or ten years from now, we *will not* distinguish between AR, MR, and VR anymore. In their opinion, this will be mainly due to the fact that different hardware/devices will merge and be capable of everything (J4, J5, J6, J10) and that people will internalize the differences with more exposure to the technology (J2). Yet, another four experts said we *will still* distinguish between the concepts (or at least two of them, e.g., AR/MR vs. VR) while two were undecided. For instance, J7 argued that the gap between devices and therefore also between AR and VR will remain. Yet, they also specifically noted that differences are fluent and human perception, not devices, should be the deciding factor for distinction. J1 and J9 stated that in the future, we might distinguish based on applications rather than technology.

Is a single definition useful?

Six experts stated that it would be useful to have a single definition of MR, while two said it would not, J8 said it does not matter, and J5 was undecided. Two experts (J1, J2) explicitly noted that context matters and it is important in conversations to make one's understanding of MR clear. J7 stressed the importance of a coherent frame of reference. J2 also pointed out that "definitions are temporary", while J3 and J5 mentioned that the term "Mixed Reality" is at least partly marketing.

Regarding a suitable definition for the specific context of HCI research, J7 proposed the notion of MR encompassing everything according to the continuum, including VR, and stressed that it is time to "fix the broken definitions from the past". Similarly, J9 proposed an extensible version of the continuum. J2 noted that they would like to see more "consistent definitions for everything in the context of MR". Three experts explicitly stated that a single definition would be very useful for the community. J1 compared the situation to that of the different competing definitions of grounded theory. Additionally, J5 stated that a definition of MR for HCI must include interactions since "interaction is a very big part besides the rendering". J10 noted that it might be worthwile to move away from technology-based to an experience-based understanding. Per J8, different understandings lead to better research since they help to identify gaps.

Results (so Far)

For a start, we have learned that experts struggle when it comes to defining AR and MR, while the distinction from VR is more clear and mainly based on visual as well as hardware aspects. So far, it seems that spatial registration and the possibility to see at least some part of the physical environment constitute defining features of MR, while "simple" input (e.g., through motion capture) does not, in the experts' opinion. While the majority of interviewees considered a single definition of MR useful—also in the context of HCI research—they as well generally agreed that this is unlikely (J4: "Never going to happen.") and we might not even use the terminology anymore in the future. Furthermore, interactions, geolocation, and temperature were mentioned as relevant aspects of reality for MR that were not in our initial list, but will be incorporated.

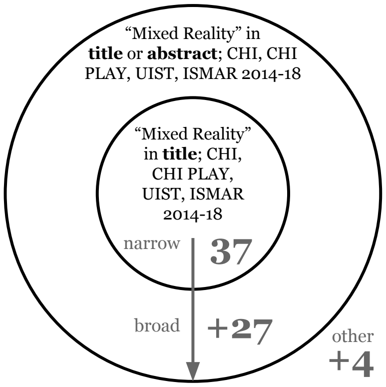

Figure 1: Our paper selection strategy for the literature review. We identified 37 relevant papers in round one and 27 in round two, and added four other sources for a total of 68.

From the interviews we can derive a preliminary list of working definitions of MR, which were explicitly or implicitly used by the experts and which we will refine and extend based on the upcoming literature review:

MR according to the Reality–Virtuality Continuum. In this case, the term "MR" is used based on the definition in [44] or [45]. It can either include VR or not. (𝒥1, 𝒥2, 𝒥7)

MR as a Combination of AR and VR. In this case, MR denotes the capability to combine both technologies—AR and VR—in the same app or on the same device. (𝒥3, 𝒥5)

MR as "strong" AR. This understands MR as a more capable version of AR, with, e.g., an advanced understanding of the physical environment, which might be bound to specific hardware. (𝒥4, 𝒥6, 𝒥8)

MR as a synonym for AR. According to this working definition, MR is simply a different term for AR. (𝒥9, 𝒥10)

5 LITERATURE REVIEW

To get a more thorough understanding of existing notions of MR "in the wild", we decided to conduct an additional literature review. From a total of 68 sources we were able to extract six different notions of MR, including the four working definitions identified during the expert interviews.

Method

We focused on four primary sources known for high-quality Mixed Reality research: *(CHI)* the ACM CHI Conference on Human Factors in Computing Systems; *(CHI PLAY)* the ACM SIGCHI Annual Symposium on Computer-Human Interaction in Play; *(UIST)* the ACM Symposium on User Interface Software and Technology; and *(ISMAR)* the International Symposium on Mixed and Augmented Reality. These were selected since there are already systematic MR reviews focused on ISMAR [16, 91] and we intended to build the bridge to premier HCI venues. Hence, we added UIST and, informed by [73], CHI and CHI PLAY. To find the most relevant papers from these conferences, we based our search on two popular academic databases—dblp[2] and Scopus[3]—as well as a two-tier strategy (Figure 1).

In a first round, we selected all papers from the above venues that featured the term "Mixed Reality" in their titles. We restricted the search range to 2014–2018 (inclusive), i.e., the past five years, in order to ensure that we extract only notions with reasonable currency. This corresponded to the dblp search term `"mixed reality" venue:X: year:Y:` with $X \in$ {`CHI, CHI_PLAY, UIST, ISMAR`} and $Y \in$ {`2014`, ..., `2018`}. Papers from companion proceedings were manually excluded from the results.

In a second round, we extended our search to papers from the four venues between 2014 and 2018 that featured the term "Mixed Reality" in their abstracts (but potentially not in their titles). This corresponded to the Scopus search term `(TITLE-ABS-KEY("mixed reality") AND CONF (chi OR uist OR ismar)) AND DOCTYPE(cp) AND PUBYEAR > 2013 AND PUBYEAR < 2019`. Again, papers from companion proceedings were excluded.

The process of reviewing an individual paper was as follows. We first identified the authors' understanding of MR by finding the part of the paper in which the term was defined. In case no explicit definition (or at least explanation) was given, we derived the authors' understanding implicitly from the described contribution. If the authors cited one or more other sources from which they seemingly derived their understanding of MR, those sources were added to the stack of papers to be reviewed—if they referred to MR at some point themselves (which was not the case for [1, 2, 8, 20, 46]). Also, for each paper, we updated a citation graph (Figure 2) showing which papers rely on which references for their understanding of MR.

Overall, we reviewed 37 papers in round one and an additional 27 papers in round two. Moreover, we added four other sources known to us that deal with the definition of MR [7, 11, 27, 34], which makes a total of 68 reviewed sources. In the following two sections, we will first present existing notions of MR, which we synthesized from the above literature review in combination with the expert interviews. Subsequently, we will describe other findings from the literature review based on the identified notions.

6 EXISTING NOTIONS OF MIXED REALITY

Based on the literature review and expert interviews combined, we were able to derive *six notions of MR*. To synthesize these, we performed *thematic coding* of all definitions and

[2]https://dblp.org/
[3]https://www.scopus.com/

explanations extracted from the various papers as well as experts' answers to the interview questions[4]. The resulting themes are the identified notions of MR. It has to be noted that the notions are not mutually exclusive and partly overlap. We tried to classify papers according to the most relevant notion, e.g., a paper that technically has an understanding according to the continuum and references [44] could still be mainly focused on the collaborative aspect of MR. An unambiguous classification was, however, not always possible and therefore, six papers were classified into two notions each [11, 17, 57, 69, 70, 73].

1—Continuum

This is the "traditional" notion of MR **in accordance with the Reality–Virtuality Continuum** defined in [44] and [45]. That is, a mix of real and virtual objects within a single display on a spectrum between a fully real and a fully virtual world. This mix can constitute AR, which is a mostly real world with some virtual objects, or Augmented Virtuality (AV), which is a mostly virtual world with some real objects, according to [44]. Within this notion, some consider VR (the far end of the spectrum) to be a part of MR, while others do not, including the original definition.

Example. One example for this notion—as mentioned by two of our interviewees—would be a version of Tilt Brush in which the user, instead of virtual controllers, sees their real hands incorporated into the otherwise virtual environment. Another example is [50], in which the authors describe MR as "the 'merging of real and virtual worlds' on a display".

Sources. [7, 9–11, 15, 21, 23, 26, 28–31, 33, 35, 37, 39, 43, 44, 50, 57, 64, 70, 73, 79], 𝓘1, 𝓘2, 𝓘7 (35.3% of reviewed sources, 3/10 interviewees).

2—Synonym

Many papers we encountered simply treated **MR as a synonym for AR**. This means that the authors used the terms interchangeably for a system or experience that was clearly AR, or provided a definition of AR to explain their understanding of MR.

Example. To give just one example, [36] state that "Mixed Reality (AR/MR) interfaces allow displaying virtual information to the human senses while users explore the real world", which is essentially a definition of AR and is also reflected in the usage of "AR/MR" to abbreviate Mixed Reality.

Sources. [13, 22, 25, 36, 40, 48, 49, 54, 66, 67, 72, 82–84, 86, 89], 𝓘9, 𝓘10 (23.5% of reviewed sources, 2/10 interviewees).

[4]The complete analysis and raw data are available via https://github.com/mi2lab/What-is-MR.

3—Collaboration

The third notion we encountered defined **MR as a type of collaboration**. In this case, MR describes the interaction between an AR and a VR user that are potentially physically separated. Also, this notion includes the mapping of spaces, i.e., for a remote user, the environment of a local AR user is reconstructed in VR.

Example. In [63], the authors link physical project rooms and virtual spaces. They refer to Dix et al. [17], who "argue that mixed reality relies on the cognitive process of mapping (drawing connections between) multiple spaces". As another example, Benford et al. [6] develop a taxonomy based on collaboration scenarios. They introduce "the idea of *mixed realities* as new forms of shared space that span these dimensions and that integrate the local and remote and the physical and synthetic".

Sources. [6, 17, 56–58, 63, 68, 69] (11.8% of reviewed sources, 0/10 interviewees).

4—Combination

Some authors understood **MR as a combination of AR and VR**, i.e., the whole of a system combining distinct AR and VR parts that interact with each other but are not necessarily tightly integrated, or an app or device that can switch between AR and VR as necessary.

Example. One example for this notion is [53], in which the authors present a system that uses 360 images for walking through a store (in VR) and displays individual products using marker-based AR. An additional example is Pokémon GO, as understood by 𝓘5, i.e., the combination of catching a Pokémon in AR and a map overview that is fully virtual.

Sources. [53, 55, 69, 80, 85], 𝓘3, 𝓘5 (7.4% of reviewed sources, 2/10 interviewees).

5—Alignment

Another notion is that of **MR as an alignment of environments**. This means a synchronization between a physical and a virtual environment or the alignment of a virtual representation with the real world, respectively. Again, such a system combines distinct physical and virtual parts and in that sense partly overlaps with *4—Combination*, but the environments do not necessarily have to be AR and VR. It is also similar to *3—Collaboration*, however, without the collaboration aspect and the environments usually not being physically separated.

Example. One example is given in [69] in terms of a system translating motion from the real world into fully immersive VR (via Leap Motion). Another is [87], where Kinect observes real building block towers on an earthquake table and synchronizes their state with digital towers in a projection. They state that MR "bring[s] together the physical and virtual worlds by sensing physical interaction and providing interactive feedback". These stand in contrast to statements by 𝒥1 and 𝒥2, who said that just input is not sufficient to constitute MR.

Sources. [3, 4, 11, 17, 42, 61, 62, 69, 73–75, 77, 81, 87, 90] (23.5% of reviewed sources, 0/10 interviewees).

6—Strong AR

The last notion we identified is the one considering **MR as a "stronger" version of AR**. It is mainly characterized by an advanced environmental understanding as well as interactions, both of the user with virtual objects and the virtual objects with the environment. This potentially means that MR is bound to a specific hardware or device that is able to provide the necessary functionality. However, this notion also presumes that "regular" AR by definition is not capable of this and therefore, MR is an evolution of AR.

Example. In [88], the authors do not refer to a specific definition and instead implicitly assume MR as what HoloLens can do, where "virtual contents can directly interact with the physical environment". HoloLens was also mentioned by 𝒥6 as a device to which MR is currently restricted. As another example, [27] states that in contrast to AR, in MR it is possible to interact with the virtual content.

Sources. [27, 34, 41, 70, 88], 𝒥4, 𝒥6, 𝒥8 (7.4% of reviewed sources, 3/10 interviewees).

7 OTHER FINDINGS

While identifying existing notions of MR was the main objective of our literature review, in the following we report additional findings regarding the considered aspects of reality, the distribution of notions used among conferences, and which sources were cited for definitions of MR.

Aspects of Reality Considered

As mentioned before, discussions about AR, MR, and VR are largely focused on graphical aspects, e.g., how to spatially register 3D objects in the real world or how to display digital information. Therefore, to complement our own initial list and interviewees statements, we have analyzed which aspects of reality became salient during the literature review.

Among the 68 reviewed sources, the most prominent aspect was *motion*, or *interactions* in general, which was explicitly mentioned as a relevant characteristic of MR by 11 (16.2%) of the papers [3, 11, 23, 25–27, 54, 69, 70, 77, 87]. Examples for this are MR experiences that rely on Leap Motion [69] or tangible UIs [70]. In contrast, what would not count is, e.g., Pokémon GO since the user interacts purely via an HUD (cf. 𝒥2: "just input is not sufficient to constitute MR").

Additionally, four papers each (5.9%) were concerned with *(geo)location* [4, 17, 42, 63] and *haptics*, or the *tactile sense* [36, 56, 70, 81].

notion →	**1**	**2**	**3**	**4**	**5**	**6**	total
CHI	3	7	4	1	4	1	20
CHI PLAY	3				4		7
UIST	3	1		2		2	8
ISMAR	5	8		2	2		17
other	10		4		6	2	22
total	24	16	8	5	16	5	74

Table 1: Distribution of reviewed papers across the four main venues considered as well as other sources, and use of the existing notions of MR by the different venues (6 papers classified twice, thus total=74).

Two papers we reviewed (2.9%) considered *sound*, or the *auditory sense*, as an aspect of reality relevant to MR. Finally, Sharma et al. [73] state that "Broadly, all games that connect virtual and physical reality [...] in some meaningful way through sensors, networks, computers, and databases are mixed realities".

This makes a total of 22 sources (32.4%), or roughly one third, who considered aspects of reality beyond graphics to describe MR experiences while the remaining 46, or 67.6%, focused purely on vision.

Which conferences use which working definitions?

Overall, we reviewed 19 papers published at CHI (27.9% of the total 68), 6 (8.8%) from CHI PLAY, 7 (10.3%) from UIST, 17 (25.0%) from ISMAR, and 19 (27.9%) from other venues (cf. Table 2).

Notion *1—Continuum*, i.e., MR according to Milgram et al.'s continuum, was the most used (24/68, 35.3%) and the only one used across all venues, but mostly by ISMAR (5/17, 29.4%) and "other" (10/19, 52.6%).

MR as a synonym for AR (*2—Synonym*) was the second-most used notion (16/68, 23.5%) and appeared mostly in CHI (7/19, 36.8%) and ISMAR (8/17, 47.1%).

MR as alignment of environments (*5—Alignment*) was the understanding of 16 out of 68 papers (23.5%) and was mostly used by "other" (6/19, 31.6%) and CHI PLAY papers (4/6). No UIST papers referred to this notion.

MR as collaboration (*3—Collaboration*) was exclusively used by CHI (4/6) and "other" sources, and a total of 8 times (8/68, 11.8%).

Notion *4—Combination* appeared five times out of 68 papers (7.4%) and was referred to by UIST and ISMAR papers twice, respectively, and once by a CHI paper.

Finally, the notion of MR as "strong" AR (*6—Strong AR*) was used only 5 times (5/68, 7.4%), i.e., twice by UIST and "other" sources and once by a CHI paper.

The most-used notions per venue were *2—Synonym* for both, CHI (7/19, 36.8%) and ISMAR (8/17, 47.1%). CHI PLAY papers mostly referred to *5—Alignment* (4/6). *1—Continuum*

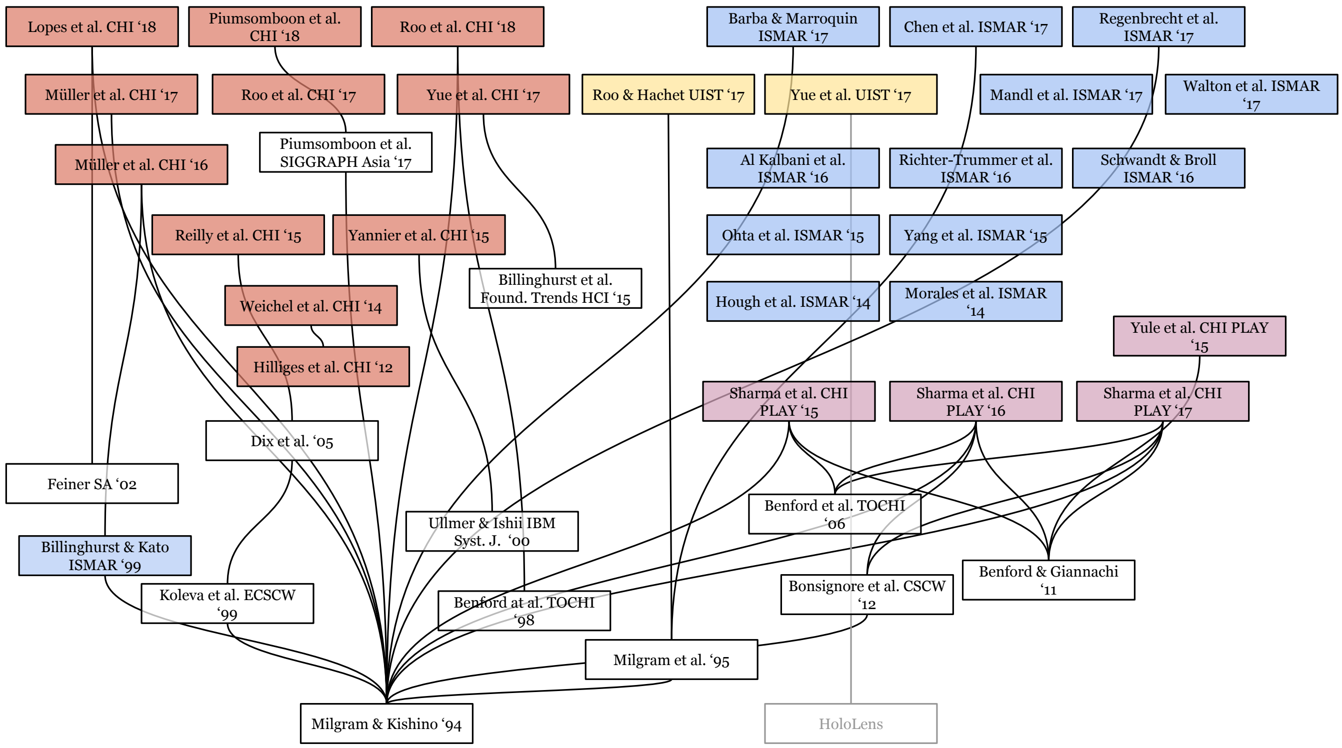

Figure 2: The citation graph derived from round one of the literature review, with clusters of CHI (light red), UIST (light yellow), ISMAR (light blue), and CHI PLAY (light pink) papers.

was the most consistently used notion across all venues and was the most-used among UIST (3/7, 42.9%) and "other" sources (10/19, 52.6%). The remaining notions, *3—Collaboration*, *4—Combination*, and *6—Strong AR* were not among the most-used for individual venues.

Generally, this suggests two things. First, even though the Reality–Virtuality Continuum is considered the go-to definition of MR by many and was indeed the most-used notion overall, it was still only referred to by just over a third of the reviewed papers, which highlights the fragmentation of the MR landscape and the lack of a predominant notion. Second, the use of different notions seems to be not uniformly distributed across venues. For instance, CHI might be more about collaboration and CHI PLAY (i.e., MR games) more about aligning distinct environments. However, the sample size is too small for findings to be conclusive.

Which papers are cited as definitions of MR?

Another goal of our literature review was to investigate which specific sources are used as references to explain or define one's understanding of MR. Overall, 34 of the 68 papers (50.0%) referenced one or more sources for explaining or defining MR, and provided a total of 49 of such references. Yet, only a majority of the reviewed CHI (12/19, 63.2%) and CHI PLAY (5/6, 83.3%) papers do so, while the numbers of papers with respective references lies below 50% for UIST, ISMAR, and "other" (Table 2). This lack of references could have three reasons. Authors might use an intuitive understanding of MR or consider it common sense and therefore do not see the need to provide a reference, or authors might have an understanding of MR that is not yet covered by existing literature.

Venue	Papers total	w/ MR reference(s)	%
CHI	19	12	63.2
CHI PLAY	6	5	83.3
UIST	7	3	42.9
ISMAR	17	6	35.3
other	19	8	42.1
total	68	34	50.0

Table 2: Overview of the use of references to explain or define a source's understanding of MR.

Overall, 22 sources were referenced[5] a total of 49 times, with 13 in round one of the literature review and seven in round two (two papers appeared in both). The most popular

[5] [2, 4–6, 8–10, 17, 20, 25, 29, 30, 33, 37, 43–46, 57, 77, 81], and HoloLens.

reference was Milgram & Kishino [44], with 20 citations, followed by Benford & Giannachi [5] with five citations, all of which came from CHI PLAY papers. Transitively, however, [44] would be referenced by an additional 5 (round one, cf. Figure 2) plus 2 (round two) papers. This means that 27 of the 34 papers (79.4%) providing at least one reference are in some way connected to Milgram & Kishino's paper.

Venue-wise, the reviewed CHI papers referenced a total of 13 unique sources; Milgram & Kishino [44] was the most-referenced with six citations. CHI PLAY papers cited four sources a total of 14 times, with the aforementioned Benford & Giannachi [5] being the most popular. Only three UIST papers provided references. Milgram & Kishino [44], Milgram et al. [45], and HoloLens were cited once each. ISMAR papers referenced four different sources a total of six times, again with Milgram & Kishino [44] being the most-cited, as was also the case for "other" sources with 6 citations.

Two papers provided four references to explain or define their understanding of MR, two provided three references, five provided two references, and 25 provided a single reference. The citation graph for round one of the literature review is shown in Figure 2.

Overall, this suggests that if an academic paper cites an explanation or definition of MR, it is very likely that it is derived from Milgram & Kishino [44]. Still, more than 50% of the reviewed sources do not rely on the Reality–Virtuality continuum or do not provide a reference at all. Therefore, the continuum *is* the single most popular notion of MR, but is far from being a universal definition in a fragmented landscape. This highlights the need for a more systematic approach to understand, organize, and classify the different notions.

8 A CONCEPTUAL FRAMEWORK FOR MIXED REALITY

So far, we have found that the MR landscape is highly fragmented. We interviewed ten experts from academia and industry, who made partly contradicting statements. Based on their answers and a literature review with 68 sources, we could identify six existing notions of MR. Even though the majority of experts agreed that a single definition would be useful and important—especially in the context of HCI research—our aim was not to find the one definition of MR. Rather, we acknowledge that different people will always use different notions, depending on their context. The important thing is to make this context clear and provide a coherent framework for better communicating what one's understanding of MR is. This is what we do in the following.

Dimensions

After analyzing the differences between the six notions, we initially derived five dimensions. With this, we aimed at finding a minimal framework that still allows us to classify all notions unambiguously.

Number of Environments. This dimension refers to the number of physical and virtual environments necessary for a certain type of MR. For instance, if an AR and a VR user are in the same room, the VR experience would be treated as a separate environment.

Number of Users. The number of users required for a certain type of MR. More than one user is only strictly required for notion *3—Collaboration*, but, of course, is also possible for other kinds of MR.

Level of Immersion. This dimension refers to how immersed the user feels based on the digital content they perceive. This is not a linear relationship with level of virtuality. For instance, a head-worn MR display might show a huge amount of digital content that does not interact with the environment and therefore might not feel immersive.

Level of Virtuality. The level of virtuality refers to how much digital content (whether or not restricted to a specific sense) the user perceives. For instance, visually, VR is fully virtual while the real world without any augmentation is not. In this sense, this dimension is similar to the Reality–Virtuality Continuum, which is, however, specifically concerned with displays [44].

Degree of Interaction. Interaction is a key aspect in MR, which can be divided into implicit and explicit [38]. While all types of MR require implicit interaction, e.g., walking around a virtual object registered in space, explicit interaction means intentionally providing input to, e.g., manipulate the MR scene. The only notion explicitly requiring this is *6—Strong AR*, but, of course, can be realized with other types of MR. What does specifically not fall into this category are GUIs that are separate from the MR scene (as is the case in Pokémon GO).

Two additional, lower-level dimensions should be specified that are independent of particular MR notions. Based on our earlier review of "aspects of reality", these dimensions are *input* and *output* (to specific senses).

Input. This dimension refers to input (besides explicit interaction) that is used to inform the MR experience. Such input includes *motion* (e.g., tracked by Leap Motion [69]), *(geo)location*, *other participants*, and in a more general sense *anything sensors can track*.

Output. This dimension considers output to one or more of the user's senses in order to change their perception. As we have seen, in most cases of MR, this is exclusively *visual* output, but can also encompass *audio*, *haptics*, *taste/flavor*, *smell*, as well as any other stimuli and sensory modalities like temperature, balance, etc.

Dimension	# Environments		# Users		Level of Immersion			Level of Virtuality			Interaction		Input	Output
value	*one*	*many*	*one*	*many*	*not*	*partly*	*fully*	*not*	*partly*	*fully*	*implicit*	*explicit*	*any*	*any*
1—Continuum	✔		✔		✔	✔	✔		✔	✔	✔		✔	✔
2—Synonym	✔		✔		✔	✔			✔		✔		✔	✔
3—Collaboration	✔	✔		✔		✔	✔		✔	✔	✔	✔	✔	✔
4—Combination	✔		✔			✔	✔		✔	✔	✔		✔	✔
5—Alignment		✔	✔		✔	✔	✔	✔	✔	✔	✔		✔	✔
6—Strong AR	✔		✔			✔			✔		✔	✔	✔	✔

Table 3: Our conceptual framework for classifying MR experiences along seven dimensions, showing a classification of the six notions of MR that were derived from expert interviews and a literature review.

In addition to the notion of MR, it is important to specify these two dimensions for specific MR experiences since many consider MR on a purely visual basis. Yet, different types of output and input can imply entirely different requirements, particularly in terms of the necessary hardware.

In Table 3, we have classified the six notions of MR according to these dimensions. For instance, *1—Continuum* spans a whole range of MR experiences and has therefore been classified as all possible types of immersion, but does not cover cases that feature no virtual content whatsoever. Contrary, when understanding MR as alignment of environments (*5—Alignment*), one of the environments can be completely without virtual content. The individual dimension's values we have chosen are sufficient for this purpose, but can be adjusted for more fine-grained classification. For instance, many MR application use a mix of implicit and explicit interactions to various degrees. While watching 360-degree photos involves purely implicit interaction, explicit interaction can, e.g., vary from simple clicks on digital objects to changing the environment using gestures.

How to use the conceptual framework

To conclude this section, we want to illustrate the use of our conceptual framework with two examples.

Yannier et al. [87]. The authors present a system in which a Kinect observes real building block towers on an earthquake table (environment 1) and automatically synchronizes their state with virtual towers in a projection (environment 2). They state that "Mixed-reality environments, including tangible interfaces, bring together the physical and virtual worlds by sensing physical interaction and providing interactive feedback". This experience is based on MR as *alignment* of environments.

According to Table 3, it can be classified as featuring: *many environments*, *one to many users*, a level of immersion that is between *not immersive* and *partly immersive*, a level of virtuality that is both, *not virtual* (environment 1) and *fully virtual* (environment 2), and *implicit and explicit interaction* (since the building blocks can be directly manipulated).

Moreover, the MR experience provides *visual* output and receives *motion* as input, as tracked with a Kinect.

Pokémon GO according to Interviewee № 5. According to I5, the whole of Pokémon GO, i.e., the combination of the fully virtual map view and the AR view in which one can catch Pokémon, is an MR experience. Hence, the considered notion is that of MR as a *combination* of AR and VR.

According to Table 3, it can be classified as featuring: *one environment* (since everything happens on one device and in one specific real-world location), *one user*, a level of immersion that is between *not immersive* and *partly immersive*, a level of virtuality that is both, *partly virtual* (AR view) and *fully virtual* (map view), and *implicit interaction* (since explicit interaction happens via an HUD).

Moreover, Pokémon GO provides *visual* as well as *audio* output and receives the user's *geolocation* as input.

9 DISCUSSION & FUTURE WORK

We have identified six existing notions of MR and from these derived a conceptual framework, which is an important step into the direction of being able to more thoroughly classify and discuss MR experiences. While existing taxonomies or conceptual frameworks are well suited for specific use cases or aspects of MR, they do not intend to cover the complete landscape as described in this paper: [44, 45] are essentially included in the dimension "level of virtuality", while [29] only considers visualization techniques and provides a taxonomy specific to image guided surgery; [65] conceptualizes MR in terms of transforms, which allows for a more detailed classification in terms of explicit interaction.

We also need to acknowledge the limitations of our work. First, it is rather academia-centric. Even though we recruited half of our interviewees from industry and they directly informed several of the notions of MR, there is a chance that we missed other notions that exist beyond academia. Second, while our literature review included 68 sources, there is always more literature to be reviewed, in order to get an even more thorough understanding of the MR landscape. Third, the conceptual framework was derived based on the six identified notions. It is possible that other, yet undiscovered, notions of MR cannot be unambiguously classified based on the current framework and might require more dimensions (e.g., "number of devices", with more advances in shared and cross-device MR experiences [76], if distinctions between devices are still important in the future). As boundaries blur, the framework could also be extended to classify experiences that do not fit current definitions of AR/MR/VR.

Future work, therefore, should encompass more research into non-academic notions of MR, e.g., through more industry expert interviews or extended reviews of commercial applications. In addition to experts, interviews with novice users could as well yield valuable insights. Also, while our literature review was broadly targeting the HCI domain, future reviews should be extended to *ACM SIGGRAPH*, *IEEE VR* and *VRST*, since they feature the most MR papers in dblp after the already analyzed conferences.

10 SO, WHAT IS MIXED REALITY?

The answer is: *it depends.* MR can be many things and its understanding is always based on one's context. As we have shown in this paper, there is no single definition of MR and it is highly unrealistic to expect one to appear in the future. However, as was also stressed in the interviews with ten experts from academia and industry, it is extremely important to be clear and consistent in terminology and communicate one's understanding of MR in order to avoid confusion and ensure constructive discussion. Experts noted that definitions are temporary and notions like AR/MR/VR might not be used in the future anymore, but that it is important to have a common vocabulary. We hope to provide useful support for this with the six working definitions and the conceptual framework with seven dimensions synthesized from the interviews and a literature review of 68 sources.

In this sense, the notion of an MR experience has analogies to groupware, which required conceptual frameworks like the Time/Space Matrix [19] for better characterization. As there are many types of collaboration, it is necessary to clarify whether collaboration happens synchronously or asynchronously and in the same or in different locations. Our conceptual framework can enable better communication and reasoning when talking about MR experiences.

With this paper, we wanted to reduce misunderstandings and confusion, within as well as beyond the HCI community. Our hope is to provide researchers (and practitioners, for that matter) with a means to think and talk about, as well as contextualize, evaluate, and compare, their work.

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