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Grand Challenges in Cross Reality

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Abstract—Cross Reality (CR) is a new emerging field based on the current developments in Mixed Reality hardware, especially supported by the broad market penetration of video-based see-through Head-Mounted Displays. It refers to applications that span across different stages (real, Augmented Reality, Augmented Virtuality, Virtual Reality) of the reality-virtuality continuum, where users are interconnected between different stages and/or are able to transition between these stages.

This publication follows the concept of other grand challenges publications and reflects the discussion of various researchers invested in CR. After an initial discussion at the 1st Joint Workshop on Cross Reality at IEEE ISMAR 2023, six topic groups have been identified, leading to 22 challenges, which were discussed in groups over the period of multiple months. The discussion of these challenges should act as a road map for future research in the area of CR.

Index Terms—Cross Reality, Grand Challenges, Reality-Virtuality Continuum.

I. Introduction

Cross Reality (CR) refers to applications that span across different stages of the reality-virtuality continuum (RVC). Examples would be users being fully immersed in a Virtual Reality (VR) environment at one moment and later transitioning to a partially augmented space where virtual elements are overlaid onto the real world, 2D displays could be enhanced into 3D Augmented Reality (AR) spaces, or users in a fully analogue real environment could collaborate with users in VR. A plethora of potential applications arises using a range of stages of the RVC instead of a single stage.

CR is a novel and emerging field driven by current developments in enterprise and consumer Mixed Reality (MR) hardware, which enables interaction with different stages of the continuum using a single device. Although many open questions in the individual areas of AR, VR, and Transitional Interfaces (TI) exist, CR integrates these fields. This presents new challenges (e.g., heterogeneity of technologies, spatial and temporal consistency, standardization) but also offers the potential to mitigate the limitations of each field by leveraging the strengths of others while enabling a whole new category of applications.

This publication follows the example of recent Grand Challenges publications [1]–[4] to highlight current topics in CR. It acts as a roadmap and offers ideas for future research.

Before going into the in-depth discussion of the challenges, we would like to present developments in the research community and industry leading to the current state of CR. We provide a terminology that will be used consistently over the description of the challenges. We explain the detailed methodology used in our research process in the supplementary material.

II. The Evolution of Cross Reality

30 years ago, the umbrella term Mixed Reality was introduced by Milgram and Kishino to classify visual displays between fully real and fully virtual environments [5]. At this time applications at distinct stages of Milgrams' RVC were developed. VR, AR, and a few Augmented Virtuality (AV) prototypes have been investigated in isolation from the other stages. From the 1990s to 2015, AR and VR were—in terms of display technology—mainly going separate ways. VR was primarily focused on projection displays like the CAVE [6] or powerwall installations to allow for a reasonable resolution and a full field of view, while AR was concerned with desktop-based systems (equipped with webcams), smartphones, tablets, and Spatial Augmented Reality. During that period very few publications discussed the changing between or the interconnecting of multiple stages of the RVC. The visionary publications by Billinghurst et al. on the Magic Book prototype demonstrated—for the time, highly sophisticated—the use of multiple RVC stages in a single application [7]–[9]. Other examples of early CR prototypes are given by Benko et al., who demonstrated with VITA a collaborative CR system [10], [11], or by Feiner and Shamash, who introduced the term hybrid user interfaces describing a prototype which extended a 2D display with additional augmentations [12]. Benford et al. discussed early concepts of interconnecting different RVC stages [13]. In 2001 Koleva et al. created an art installation—Desert Rain—where users could transition between real and virtual environments [14]. Lifton et al. introduced the term "cross reality" in 2009 describing the combination of real-world sensor data with virtual environments [15]. Also, prototypes emulating AR with VR have been developed [16]

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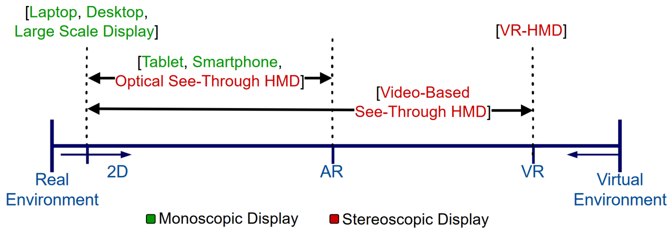

Fig. 1. MR display technologies along the RVC. CR applications interconnect individual stages or allow transition between stages like OSTs with 2D and AR or VSTs covering the full range from 2D to VR.

With the rise of modern Head-Mounted Displays (HMDs) in the second wave of VR starting in 2015, the idea to combine real and virtual spaces has become more and more popular. VR HMDs like the HTC Vive Pro and the Oculus Quest were equipped with cameras mainly used for object avoidance in the real environment (with Vive's Chaperone system) and inside-out tracking (the Oculus Quest). The cameras also allowed low-quality pass-through functionality and API access, although the HMDs were not designed as classical Video See-Through (VST) devices. Different researchers from the HCI and VR/AR community began looking at the possibilities and capabilities for moving along the RVC or interconnecting applications on it. Modern HMDs like the Varjo XR4, the Apple Vision Pro, Samsung Galaxy XR, Steam Frame and the Meta Quest 3 are specifically designed as VST devices and allow applications along the whole RVC, as depicted in Figure 1.

Communities have started building around the topic at six workshops [17]–[22] from 2020 to 2023 at a variety of venues. CR does not really have a home in a single community but asks for collaboration and convergence in different overlapping fields.

A. Terminology

In the field of MR, already many varying definitions have been given for individual aspects like Presence, Immersion, or the term ”MR” itself. In order to avoid confusion, redefinition, or reintroduction of terminology, we consider the current interpretation of terms provided by Skarbez et al. to be the most concise [23]. Thus, we will follow this publication for all MR related terminology and consider MR as the umbrella term for AR, AV and VR. We understand Presence as a combination of Place Illusion and Plausibility Illusion [24] and a system's immersion is the set of valid actions supported by that system [25].

For the more specific term ”cross reality”, which has been introduced in multiple publications [17], [26]–[28], we would like to condense the most important aspects into a clear definition: ”Cross Reality allows users to transition between different stages of the RVC, or interconnects different users at different stages of the RVC”.

CR applications thus allow the use of multiple stages of the RVC as opposed to single-stage applications. Transitional Interfaces (TIs) [7] are an emerging class of CR user interfaces that enable users to freely move along the RVC during their work or collaboration [29]. These interfaces allow users to individually choose and transition between different displays, input/output modalities, and representations of data or functionality that are preferred for the specific task at hand.

When identifying certain points on Milgrams' RVC we use the term ”stage” since it is common in various domains using a continuum.

B. Workshops

We have seen six workshops in the past four years dedicated to the topic of CR at different venues. The first workshops took place at ACM ISS 2020 [17], followed by a second ACM ISS workshop in 2021 [18]. In 2022 two workshops were held, one at ACM AVI [19] and one at IEEE ISMAR [20]. Again in 2023 two workshops took place at IEEE VR [21] and at IEEE ISMAR [22]. The recent ISMAR workshop was targeting to consolidate the different activities and efforts in CR so the main organizers of all previous workshops were asked to join the organizing committee and program committee.

C. Surveys

Many publications related to CR exist, which have been discussed recently in two surveys coming from different angles.

Fröhler et al. focus on CR applications in the context of Immersive Analytics (IA) [27]. They provide categories of different types of CR applications and highlight the use of CR in the area of production.

Auda et al. target a holistic overview, looking mainly at the area of transitional interfaces [28]. They also provide a categorization in the three groups (transitional, substitutional, multi-user) of CR and give an initial overview of potential research gaps.

Each of these surveys can be used as a starting point for getting an overview on the topic of CR and an initial corpus of related literature.

D. Design Spaces

Two design spaces in the area of CR have been published.

Lee et al. [30] focus on visualization transformations between 2D and 3D. They concentrate on IA and choose an initial visualization state and user interaction as starting points, which then leads to a final visualization state with the help of a transformation. Each of these components is described in detail, and potential variants how they can be realized are given.

Wang and Maurer discuss single-user CR applications [31]. They take a device-driven approach and focus on the use of input and output device categories to design transformations for single users or objects between RVC stages.

III. Grand Challenges of Cross Reality

During a Workshop at ISMAR 2023 initial discussion on the Grand Challenges of Cross Reality started, which was continued in offline writing sessions. This publications contains the results of these discussion. A detailed description of the process and the methodological approach can be found in the supplementary material. In overall multiple clusters were identified and refined.

The identified clusters of challenges can be categorized in six topic groups as illustrated in Figure 2. Where the three groups Designing, Developing and Evaluating follow closely the process of human-centered design, two topics are related to the whole development process, which are spatial and temporal coherence and collaboration. The resulting applications themselves provide additional challenges.

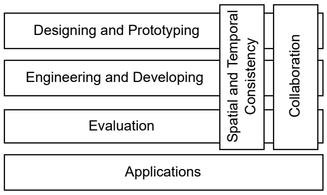

Fig. 2. Topic groups for the grand challenges in CR.

The these topics (Figure 2) and the derived challenges (see Table I) are discussed in the ensuing sections.

Topics		Challenges
DESIGNING AND PROTOTYPING	C1	Design Spaces
	C2	Designing Transitions Along the RVC
	C3	Simulating Realities
	C4	Software Challenges and Technical Limitations
ENGINEERING AND DEVELOPING	C5	Comprehensive Engineering Processes
	C6	Toolkits, Frameworks, and APIs
	C7	Improved Testing Workflows
	C8	Technological Constraints and Requirements
EVALUATION	C9	Complexity of Evaluation Scenarios
	C10	Evaluation of Switches and Transitions
	C11	Transferring Existing Methods to CR
	C12	Diversity in CR Evaluation
SPATIAL AND TEMPORAL CONSISTENCY	C13	Spatial Mapping
	C14	Temporal Fusion
	C15	Information Representation
COLLABORATION	C16	Real-world Use Cases for CR Collaboration
	C17	User Representation and Social Presence
	C18	Object and Environment Representation and Interaction
APPLICATIONS	C19	Generalization of Existing Research
	C20	Onboarding
	C21	Safety and Accessibility
	C22	Ergonomics and Hardware

TABLE I
Overview of the identified grand challenges in CR.

IV. Designing and Prototyping

The designing and prototyping of CR systems and applications is inherently challenging, as it requires sophisticated technical skills, expensive hardware, and time, and it often requires more than one person. The complexity results from the different RVC stages and users involved in CR applications, creating a large space of possibilities. Consequently, the first sub-challenge is to map out these possibilities and introduce an all-encompassing design space. Transitions between stages are key for CR systems and their main characteristic, so we discuss them in depth as the second sub-challenge. Thereafter, we shift our focus from designing to prototyping and start by introducing the simulation sub-challenge with the goal of making the complex systems approachable. Finally, we conclude with the current limitations of prototyping CR as the final sub-challenge of this topic.

A. C1: Design Spaces

Having a detailed design space is crucial for designing and prototyping CR systems, as it clearly maps out the spectrum of possibilities, guiding not only the initial design and ongoing development but also informing research within this area. Researchers have contributed early efforts towards a comprehensive design space for CR, with many of these efforts stemming from systematic explorations of different CR prototypes or concrete factors of CR. The investigation of concrete factors directly informs the design space by exposing specific dimensions and their levels (e.g., levels of substitution, referring to the overlap of physical and virtual space [32]). Beyond these studies and prototypes directly focused on CR, it is crucial to acknowledge that research in the field of VR and AR serves as fundamental building blocks for CR. In fact, many systems published over a decade ago include CR aspects (e.g., the Magic Book from Billinghurst et al. published in 2001 [7]); however, the term had not been established yet, making it difficult to identify fitting research [28].

Efforts to standardize terminology and introduce clear definitions have contributed to a comprehensive design space for CR. In particular, surveys offer valuable insights and often introduce clear definitions and dimensions that can be foundational to a design space. In this regard, the scoping survey on CR systems has introduced three different types of CR systems [28] (i.e., transitional interfaces, substitutions reality, and multi-user systems). Finally, the most concrete step towards a comprehensive design space of CR are smaller, more focused papers that introduce parts of the design space. For example, Wang and Maurer introduced a design space focused on single-user CR [31]. These individual parts break down the overall complexity of striving towards a comprehensive space and make it easier for researchers to tackle the challenge.

Creating a comprehensive design space is crucial for CR systems for several reasons. It allows for detailed exploration of design options, ensuring innovative solutions are considered, and facilitates informed decision-making through a clear evaluative framework. It encourages creativity within set boundaries, enhances teamwork by creating a common project understanding, and guides

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future research by pinpointing areas needing further investigation. The rapid pace of technological change complicates the task of capturing the full scope of design possibilities. It is particularly challenging to determine when the design space is sufficiently comprehensive or to identify which aspects will have the most significant impact in the long term.

B. C2: Designing Transitions Along the RV-Continuum

A fundamental aspect of CR includes progressing through various stages of the RVC to leverage the advantages offered by different stages. This provides the ability to choose the best stage for a given task or context of use and combines those reality stages for a continuous experience. To enable such an experience, it is necessary to move along the continuum, which can be implemented with various transition techniques, which range from rather simple fading effects to complex morphing and fragmentation algorithms [33]. Those techniques can either be applied to the entire environment to change the stage of the user on the continuum [7], [34]–[36] or only for specific objects [37]–[40]. However, a transition may also be necessary to interact with real-world objects [41], [42], collaborators [29], [43] or bystanders [42], [44], [45] in other stages. There is a wide variety of different interaction concepts in the area of immersive technologies utilizing touch, tangible, or gestural interfaces [46], [47], but it has not been explored how these could be utilized for transitions in the context of CR. Different transition techniques could benefit from different interaction concepts; for example, a portal could be opened with a circular motion and a simple fade-out with a short swipe gesture on a controller. However, transitions do not necessarily have to be user-controlled; they can also be initiated automatically. Previous studies have used an automatic transition process [48], [49], yet they have not extensively examined the design aspect of such automation and how to provide a convincing initiation process. Furthermore, it is unclear what happens if transitions are interrupted midway through the process, leaving the user in an intermediate stage.

Previous research has primarily focused on analyzing transition techniques from the viewpoint of the transitioning individual [34]–[36], [50]. However, it is crucial to consider how these transitions are presented to external collaborators. The design should effectively communicate that an individual is currently in motion along the continuum and in which direction.

Another critical consideration is the auditory feedback design when applying transitions. In AR preserving the perception of real-world ambient sounds is often desirable to maintain situational awareness [51], [52]. Conversely, in VR, users are typically isolated from their physical surroundings, experiencing audio exclusively from the virtual environment [53], [54]. This could be achieved through noise-canceling headphones and, if necessary, selective passthrough for ambient awareness. During transitional phases, however, both the auditory cues from the source environment and those of the target environment must be carefully integrated. Thoughtful blending of these audio streams is essential to ensure a seamless and coherent auditory experience that aligns with the visual metaphor of the transition.

To address this challenge, we identify three key areas which are crucial for moving across different RVC stages, blending them together: Transition control strategies, design different perspectives and auditory feedback. Initially, exploring methods to control transitions or enable autonomous reactions is necessary. Subsequent research should focus on identifying interaction concepts and input mechanisms for controlling transitions. As a next step, broadening the perspective beyond the transitioning individual to focus on the visual design of transitions from an external collaborator's standpoint is essential. While current efforts focus on the individual, future work should consider the design from external observers' viewpoints. Another essential aspect to consider is gaining a deeper understanding of how the auditory and visual transition design influences the user.

C. C3: Simulating Realities

Prototyping CR systems presents significant challenges, requiring advanced technical skills, considerable time, and often costly hardware (e.g., displays, projectors, sensors) [28]. To address these issues, previous studies have suggested methods to simulate various levels of virtuality, such as using VR environments and hardware to simulate AR applications [55], a widely adopted practice used in the past decades to leverage the constraints of current AR devices [56]–[58]. Despite current VR devices being arguably more consumer-ready, their use has historically included its downfalls [41]. This substitution approach also raises critical questions about the immersion level (reproduction fidelity and/or extent of presence metaphor) of such simulations [23], highly dependent on the specific level of the RVC [5] the final application aims for.

Additionally, the complexity of these simulations is amplified when dealing with multi-user asymmetric systems [59], a common aspect of CR environments [60], [61]. Recently, this has been addressed by isolating one interface for user experiments, while simulating the other one via a Wizard of Oz (WoZ) server, controlled by the researcher [62]–[64]. This type of simulation allows for a more controlled collaboration scenario, a method already in practice for prototyping single-user AR/VR applications [65], [66]. The complex social aspects inherent to collaboration (e.g., voice and gestures), however, are yet to be fully reproduced using WoZ methods. By replicating an external interruption (i.e., a local person not participating in the CR environment interacting with a user) [63], Gottsacker et al. acknowledge how HMDs can inhibit the interlocutor from making a confident judgment about the mental state of the HMD user.

Determining effective scenarios and assessing the reliability of observations are pivotal concerns. This prompts us to explore whether simplifying these scenarios and using basic methods like paper prototyping and role-playing could be effective for simulating CR systems. In this sense, addressing specific topics is essential for developing practical, efficient, and reproducible simulation strategies for CR system prototyping.

Establishing the fidelity of different levels of reality simulation is imperative. For instance, understanding whether the immersion levels of different simulated realities affect perception. This can be explored by analyzing task performance metrics of novice users in VR-simulated AR versus regular AR, and identifying if there is a threshold immersion level for seamless simulation. It is important to determine when AR HMDs will match the high fidelity of state-of-the-art VR devices. The first step is discerning if state-of-the-art VST (e.g., Apple Vision Pro) is distinguishable from optical see-through to novice users based on resolution, FoV and latency, under controlled experiments. Regarding collaboration, it is necessary to identify which social aspects are not reproducible in current WoZ simulations. Machine Learning models might reproduce social interaction in simulated collaboration scenarios to some extent, but it is fundamental to ensure balanced, fair, ethical, and reproducible behaviors from these models in user studies.

D. C4: Software Challenges and Technical Limitations

The design and prototyping phase is crucial across multiple domains and research fields. It serves as the initial stage to provide the users with information about the CR development process by presenting and testing the possible design space and functionality in terms of visualization and interaction [31], [37], [67]. However, researchers may not have equal access to devices, technologies, environments, scenarios, interaction and visualization modalities, or users with the same human capabilities. Addressing these various dimensions is challenging as CR bridges multiple stages and combines various devices.

One major difficulty arises from the diverse experiences and requirements found across highly diverse domains, which are reflected in the limited existence of a standardized terminology [28] for creating CR design guidelines. CR systems for instance, may need to visualize and analyze computer tomography (CT) data from material science [68]–[70], explore abstract data visualizations [71], [72], provide immersive content for passengers in a vehicle [73], or enable the experience of cultural heritage [74]. Different areas emphasize unique constraints, including visual representations, interaction modalities, spatial characteristics, and environmental context. These constraints result in different established design rules. One example of a commonly used design tool in the field of visualization is ColorBrewer [75]. It helps select effective color schemes and test their impact on printed media and colorblind users, but it lacks the ability to analyze the effect of real-world backgrounds and lighting on colors in CR. Similarly, tools like Figma [76] excel at designing 2D user interfaces but fail to consider CR requirements, such as the spatial distance to the user and transitions between RVC stages. A work that shows a first approach for modeling CR workflows is by Auda et al. [67], which prepares ideas of the unified modeling language (UML) [77] for CR systems. Effective CR tools must guide designers in determining the design space, evaluating immersion and presence, assessing the perceptual impact of colors and transitions, and ensuring accessibility for diverse users (e.g., individuals with limited vision or reduced mobility).

The second major difficulty for prototyping tools stems from technological constraints. Even if standardized terminology and guidelines were available, they could not be applied universally due to the heterogeneity of hardware, performance differences, mobility requirements, and user capabilities. Moreover, while there has been initial work on simulating realities, as discussed in C3, research remains limited. Current prototypes rarely support simulating features that are unavailable on the used devices, nor do they support anticipating the functionalities of upcoming hardware. Further enabling retrofitting of non-immersive workflows, e.g., through complementary interfaces [72], [78], [79], prototype tools can substantially promote a seamless transition across diverse RVC interfaces and enhance further CR development. Given the current landscape, where game engines are the typical CR prototyping environments (e.g., IATK [80], DXR [71], VRception [81], Colibri [82], XRSpotlight [83], and work from Schröder et al. [29]) there are inherent limitations in integrating the real world, retrofitting, support for complex transitions, scientific computations, and simulation of functions due to lack of standardization and hardware compatibility.

The development of design and prototyping tools is currently hindered by the absence of standardized terminology for inherent CR features and the heterogeneity of hardware capabilities. Addressing these limitations allows for a unified design and prototyping tool to guide users through CR design spaces with the appropriate level of immersion, transition, and simulation of features.

V. Engineering and Developing

Creating a CR application inherits many engineering challenges faced during the development of 3D software, AR/VR applications, and networked collaborative tools. The move from prototypes (C4) to real CR applications comes with an amplified set of challenges due to the range of possible configurations of use, and the resulting increase in complexity when spanning different points of the design space (C1). It is the interaction effects that arise when designing for applications that might be single-user or multi-user, spanning various different input and output modalities, at once and across time, that makes the engineering and development of CR applications uniquely challenging. We need comprehensive engineering processes that account for this variety, with a focus on reusable toolkits and frameworks, improved testing workflows, and methods to resolve the various technological constraints and requirements across stages of the RVC.

A. C5: Comprehensive Engineering Processes

To fit modern software development practices that heavily rely on Agile and Lean principles [84], we need to understand how we can develop functional and usable CR systems in an iterative, incremental manner. For this, UX as well as quality assurance efforts must be part of the engineering process—moving from user-experience design to stable and reliable applications in short increments in each cycle. While challenge 4 focuses on software and technical limitations, this challenge discusses the overall engineering process for CR systems.

As CR systems often include deploying user interfaces on multiple devices while coordinating data and work processes across system boundaries, repeatable testing processes that cover functional and non-functional requirements are needed (see challenge 7). Engineering processes must accommodate diverse input modalities, such as controllers, hand tracking, and touch interfaces, as well as heterogeneous tracking technologies. These inputs must be synchronized and shared across devices and users at various stages of the RVC, demanding a robust and responsive network infrastructure. Moreover, sensory feedback mechanisms and input devices may vary across stages of the RVC, requiring adaptive system behavior and corresponding adjustments in usability engineering. Ensuring consistent user experiences across these stages is critical to maintaining usability and system reliability. Often researchers accommodate their interaction to the available hardware.

Advancing the engineering processes to account for the unique demands of CR systems, such as multi-device interaction, dynamic input modalities, and distributed environments can significantly reduce development costs and enhance user acceptance. Ultimately, these improvements will lead to a broader adoption of CR technologies across diverse application areas.

B. C6: Toolkits, Frameworks, and APIs

The inherent heterogeneity of CR applications can perhaps be best addressed through the development of standard, scalable, and platform-independent frameworks. They should include components such as APIs or toolkits to empower developers and researchers to create robust CR applications and conduct studies more efficiently [31], [85]. Many research teams have developed their own versions of such frameworks for specific project threads [86], [87], but their uptake has largely been limited to being within these teams. From the perspective of development environments, platforms like Unity and Unreal offer means to create applications that target a wide ecosystem of devices. The OpenXR standard [88] addresses the need for cross-platform and cross-device frameworks that abstract away low-level implementation detail and allow researchers and developers to focus on high-level features and functionalities.

While development engines and standards like OpenXR help address the creation and translation of basic interactive features across devices and RVC stages, future frameworks must also include methods to effectively connect these stages. This must take place in two forms: creating transitions for a single user traversing stages of the RVCs, and creating networked experiences for multiple users occupying different stages. While some studies have explored the design of transitions in specific contexts [26], [39], [89], recent work has developed a framework for implementing “spatial hypermedia” [90] that enables shared content to adapt to best suit the modality of interaction. By drawing from a range of prior results around CR collaboration and transitions, this work is a valuable example of synthesizing insight into reusable tools that operate on a layer above device-focused frameworks like OpenXR. When considering connections across users and devices, the task of integrating networking into CR applications has largely been left to individual teams and developers, who use general networking frameworks that are not specifically designed with the intricacies of CR in mind. Recent projects such as Colibri [82] address this by offering a platform and primitives to support the rapid development of CR applications. Moving forward, comprehensive frameworks for CR will need to combine device (such as OpenXR), content (such as SpatialStrates), and networking considerations (such as Colibri) to present a unified sandbox for development, that also provides a series of established and reusable primitives for quickly and efficiently creating different forms of single-user and multi-user CR applications [91].

C. C7: Improved Testing Workflows

Software testing is required to improve reliability and stability of software systems [92], and regression testing [93] is utilized to ensure that software still functions after changes to the code base—something that is an inevitable part of developing and maintaining CR applications given constant updates to the software and hardware involved across devices. In practice, comprehensive regression testing requires test automation as manual regression testing is too costly. Test automation approaches for MR applications are being developed [94]–[96], and recent no-code methods show particular promise [97]. However, functional testing frameworks for the CR applications spanning multiple devices simply do not exist. This results in increased costs for development and risks that changes to existing code might break the system. Tools to support testing CR user interfaces are missing, requiring manual tests across devices that can be cumbersome. Developing CR-oriented capture and replay tools can help overcome these limitations, especially if such tests can be automated and integrated into continuous build processes. Non-functional requirement metrics for CR applications are not yet well defined and an open question is if CR applications would require separate metrics or can rely on more traditional performance metrics of MR applications like frame rate, rendering quality or multi-user scalability.

Usability testing of CR systems is difficult as workflows can span multiple devices. In the case of AR stages, these require interactions with a real-world environment that might be inaccessible or too dangerous to be used for testing purposes. For example, CR applications for controlling chemical plants should be tested outside the plant due to inherent dangers of incorrect implementations. A digital twin of the real-world environment could serve as a deployment environment for testing CR applications in a controlled and safe virtual world. To address the difficulties of testing multi-device, multi-user CR applications in real-world conditions, we can draw upon recent community-driven efforts to support immersive experience evaluation [98], and build crowd-sourcing platforms that can be integrated into beta-testing workflows for more ecologically valid evaluations.

D. C8: Technological Constraints and Requirements

The engineering and development of CR systems faces many of the same challenges as broader MR systems today. Technological limitations relating to display [99], tracking [100], interaction [101], and networking [102], [103] are some of the main reasons for the gap between the concepts of MR systems established through research, and their implementation in practice. With each iteration of MR devices, new concerns relating to the privacy and security of users arise, in terms of the data that is collected [104], the sensory information presented [105], as well as the agency of bystanders in this process [106]. MR systems rely heavily on the assumption that users are sighted and able-bodied, and the development of similarly spatial and immersive experiences via other sensory modalities (sound, touch) for input and display is essential to achieve wider accessibility and inclusion [107]–[109]. As a result, more general use of CR systems first requires the wider adoption of MR, for which hardware must be comfortable to use, affordable, and accessible [110].

Beyond these inherited challenges, there are further ideal characteristics specific to CR hardware. As discussed in section II, CR requires devices that are capable of transitions and connections via (1) devices that can traverse the RVC themselves, or (2) ecosystems of devices, used by one or more people, that connect different levels of reality or virtuality.

Researchers have explored the design and prototyping of CR interfaces with these capabilities by either instrumenting existing MR hardware with additional sensors (such as pass-through cameras for transitions between AR and VR) [111], or using one device and modality to simulate multiple others [81]. Both these approaches point to the need for sensory capture and display technologies with improved resolution and fidelity, that enable functional perception of the real world through VR devices, or the virtual world through AR devices (some examples of ongoing efforts include [112], [113]). Devices capable of more seamless transitions along the RVC also require a much greater level of scene understanding of the real world. This is to ensure the system can provide the required level of awareness to help users keep track of their surroundings without sacrificing immersion [42], [114], and better incorporate elements of one's physical environment into the experience [115], [116], enabling operations such as diminishing [105], substitution [117], and blending [118] for consistent CR transitions.

When considering connected ecosystems of devices for CR, the creation of appropriate toolkits and frameworks would significantly improve user and developer experience. The devices themselves, however, must ideally work in tandem with these frameworks to provide cross-device application compatibility at a hardware level—similar to the challenges faced by software development more generally [119]. Networking technologies need to further improve their bandwidth and ability to store multi-modal data on the cloud to facilitate smooth cross-device transitions, and some of these elements are being explored in the context of holographic remote communication [120]. Here it has to be taken into account, that this is of course use-case dependent. Taken together, the future development and adoption of CR applications will likely involve a split approach: on one hand, there is a clear benefit to developing devices that capture and render high-fidelity representations of the real world, and possess a greater understanding of one's physical environment, in order to support different stages of the RVC. On the other hand, a key strength of CR applications is that multiple users can work together using whatever devices they might have access to. Thus, it is important to work towards functional parity across heterogeneous devices through streamlined processing and networking pipelines, that connect back to high-level, cross-device design guidelines that are encapsulated in development frameworks (C6).

VI. Evaluation

Evaluation approaches used in CR research have been based largely on how MR systems are evaluated. In a survey on the evaluation of AR systems, Merino et al. [121] categorized these evaluations along two key areas: technology-centric assessments and human-centric evaluations. In the latter, researchers apply well-established HCI research methods borrowed from other fields, e.g., Psychology or Social Sciences [122]. In line with this [122], the designing, prototyping, and evaluating stages of CR systems are closely related. Therefore, it is not surprising that research on CR systems evaluates the usability of handling CR technologies (C1), how the design of transitions (C2) affects participant's performance, or how the simulation of specific levels of the RVC (C3) influences task load. In general, crossing multiple stages by dynamically utilizing various platforms and environments across the RVC increases the overall complexity. Nevertheless, it also comes with opportunities, as current off-the-shelf devices are equipped with an abundance of sensors that allow for e.g., real-time assessment of physiological signals.

In this section, we first outline the challenges to evaluation introduced by the nature of CR (cf. C1). Then, we put a spotlight on evaluating transitions and switches within CR applications (cf. C2, C3), and finally suggest ways

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to transfer existing evaluation approaches to the space of CR, providing directions for future research.

A. C9: Complexity of Evaluation Scenarios

One of the distinct characteristics of CR systems, compared to other interactive systems (e.g., featuring only a single stage of the RVC), is the dynamic relationship of multiple stages. In a single-stage interface, an experimenter can carefully select measurement modalities to address their research questions and map them to the available hardware used in the experimental situation. In a CR interface, this decision is less straightforward, as tasks are performed across multiple stages, requiring the consideration and integration of multiple measurement modalities.

Depending on the specific scenario, experimenters might have to find trade-off decisions based on environments and modalities, data, and users. To elaborate further, we refer to a typical dependent variable in HCI user studies: cognitive workload. Researchers often rely on post-hoc subjective assessments (e.g., using the NASA TLX [123]), however, an objective real-time assessment (e.g., using eye tracking) might be preferable [124]. HMDs that facilitate CR interfaces often include such eye tracking capabilities. With this, the experimenter can constantly assess relevant eye movements (e.g., pupil dilation) as indicators for cognitive workload, irrespective of the current stage on the RVC.

If the CR interface includes additional hardware (e.g., desktop workplaces), requiring discrete switches between environments (as in ReLive [125]), then the experimenter has to find a trade-off. Regarding environments and modalities with respect to data some components might feature built-in eye tracking devices, others might not. This might result in only partial data availability, decreased data quality (e.g., due to different tracking rates), or post-hoc data fusion. From a practical point of view, having a distinct eye tracking modality in each component is doable but frequent switches between environments can further hamper the experimental flow and require multiple calibration activities. The complexity further increases depending on the number of users: Multiple users might have frequent transitions within and across environments. This might lead to the need for additional experimenters present during the study sessions (cf. user studies on remote collaboration).

Using subjective questionnaires might be considered as an alternative to simplify the experimental situation. While this is a valid point, it might affect data quality [126] (depending on the individual research goal). As an example questionnaires are filled in after an experimental situation, which comes at the risk of participants not being able to remember each condition accurately. This issue becomes even more pronounced in dynamic CR scenarios due to frequent switches and transitions across multiple stages. Moreover, questionnaires are not feasible for all scenarios, as they might further break the flow. Therefore, objective real-time assessment modalities are promising to understand and measure the qualities of a CR interface. Yet, it needs carefully designed experiments to avoid the increased complexity of running, analyzing, and reporting experiments.

TABLE II
Quantitative measures used to evaluate transitions and switches

Quantitative Measure	References
Performance	[34], [36], [37], [40], [134]
Task Load	[34], [36], [37], [40], [134]
Interaction Logs	[34], [134]
Simulator/Motion Sickness	[34]–[36], [40], [133]
Presence	[34], [36]
Usability and User Experience	[35], [36], [133]
Preference	[34]–[37], [133], [134]

B. C10: Evaluation of Switches and Transitions

With the necessity of transitions between different stages on the RVC in CR, see Section IV-B, the question remains how these transitions affect users' understanding, task performance, and experience, and how the transitions themselves can be evaluated. These questions shape the goals and methodologies of CR technology evaluations.

There is only limited exploration of transitions so far, with most of the studies focusing on a quantitative comparative evaluation approach [35], [36], [40], including different quantitative metrics, see Table II. Performance metrics such as completion time, accuracy, or error rate are often used to evaluate the success of the transformation in terms of users' comprehension of the transition. This is often contrasted with perceived task load using the NASA Task Load Index [123] and interaction logs to document participants' interactions with the prototype. Additionally, concepts based on AR and VR research, such as Simulator and Motion Sickness and Presence, are measured using questionnaires such as the Simulator Sickness Questionnaire [127], the Fast Motion Sickness Scale [128], and the Igroup Presence Questionnaire [129]. For a subjective perspective, quantitative methods are also used to measure usability with the System Usability Scale [130], user experience with a short User Experience Questionnaire [131], and user preference using a ranking system. In contrast to the quantitative comparative approach, transitions are also evaluated using qualitative metrics. This has been used for an elicitation study on interaction techniques for manipulating 3D visualizations [132]. In a qualitative comparative approach, it has also been applied to identify advantages and disadvantages of visual transition techniques between AR and VR [35] and between reality and VR [133].

These common approaches leave out the application of switches and transitions to realistic scenarios. This is especially hard to achieve as the switch or transition, which is the focus of the evaluation, is only a small portion of the overall task and study. Currently, there are only limited applications of qualitative exploratory approaches, e.g., in elicitation studies [132]. Nevertheless, there is not yet a

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longitudinal study investigating switches and transitions in a real scenario. For comparative approaches, there is not yet a specific and reliable standardized measure that allows us to quantitatively measure the impact of switches and transitions. This should be targeted by future research by developing and testing suitable objective and subjective measures for the users' understanding and experience.

C. C11: Holistic Evaluation of Cross Reality Systems

Beyond evaluating the discrete transitions between realities, it is crucial to assess the CR system as a whole. This section discusses the broader challenge of adapting established HCI evaluation methods [122] to holistic CR environments, highlighting the unique difficulties posed by their hybrid nature.

While standard task performance metrics (e.g., completion time, accuracy) are frequently borrowed from HCI, their application in CR is not straightforward. A key challenge arises when defining task success in scenarios that span both physical and virtual environments. For example, in a collaborative maintenance task, a user may complete the physical actions quickly but spend several minutes interacting with AR instructions, resulting in highly variable measurements. As an integrated CR approach, the central question becomes whether users can effectively complete their tasks within the hybrid environment. In current research, these tasks mainly consist of gathering information across different stages on the RVC or manipulating objects and data on different stages. However, with increasing research in CR and real life applications these tasks are set to become more complex. For improving system design, it is also necessary to understand how the individual AR, VR, and reality components influence performance. Defining these boundaries between components remains a significant methodological hurdle unique to CR evaluation.

Similarly, while self-reported questionnaires are widely adopted to evaluate subjective concepts like sickness, workload, and engagement, their direct application to CR systems reveals significant challenges rooted in the varying modalities and states involved in RVC. It is difficult to isolate whether reported sickness or cognitive workload stems from virtual elements, real-world interactions, or the mental strain of switching between them. Therefore, a unique challenge for CR is the need for new evaluation instruments specifically designed to measure the user's nuanced experience across the RVC.

To complement subjective evaluations using post-study measures, studies also collect data during the studies [135]–[137]. The methods themselves are not new, but the CR context introduces unique challenges in data interpretation, mainly the stimulus attribution problem. For example, when a sensor like an ECG or EEG detects a spike in arousal or cognitive load, it is challenging to determine the cause. The confounding of physical and virtual stimuli is a core challenge in CR evaluation that is less prevalent in more controlled VR or desktop settings. The fundamental challenge, therefore, lies in developing methods that can effectively disentangle these blended influences to accurately evaluate the user's experience in a hybrid world.

Finally, various application contexts of CR systems determine that the focus of evaluation will differ for training simulations, education and learning, gaming, and collaboration. Blending various stages of the RVC, CR systems are positioned in hybrid environments. It remains a challenge to determine consistent evaluation measures that are able to accommodate distinct characteristics of the interaction techniques, user interfaces, physical surroundings, and application contexts.

D. C12: Diversity in CR Evaluation

There are numerous issues around diversity that empirical evaluations in general have to face. As the evaluation of CR applications is not immune to these challenges as well, we want to highlight three aspects in the context of diversity that are especially relevant to consider and transparently document in future research in CR. This allows readers to better assess the relevance and limitations of a study as well as identify research gaps. (1) Diversity within the user groups. This includes diversity in experiences with technologies such as AR and VR, but also diversity of age, gender and cultural background [47]. All these factors can influence how well users can and want to adopt CR applications [138]–[140]. To avoid this, the CR community needs to proactively look for diversity in multiple factors in their empirical evaluations and clearly state limitations based on a lack of such diversity to encourage further research in this area. (2) Diversity in task scenarios. Usage context is key in determining the most suitable interaction method [47], visualization or transition for a CR scenario [35], [133]. By evaluating the strengths and weaknesses of different interaction techniques in various scenarios, we can better select appropriate interaction techniques for real-world applications. (3) Diversity of measures. While there is a diverse field of measures that can be utilised in empiric evaluation, there is a clear preference of certain measures, as a recent review of the related field of IA shows [136]. According to this analysis, most studies evaluate user performance and user experience. This is in line with the measures commonly used in the evaluation of switches and transition identified in VI-B and the evaluation methods borrowed from HCI, discussed in Section VI-C. It is advantageous to consider a broader spectrum of factors, such as novelty, social acceptance, and robustness under diverse conditions [138], [140], [141].

VII. Spatial and Temporal Consistency

In contrast to traditional VR and AR problems, CR systems are by nature incapable of fully matching stages of the RVC. It is therefore the greatest challenge for such applications to provide most rational perceptual coherence among individual user's simulations, instead of targeting identity among AR/VR matrices. The user is always situated in reality, the further they move towards virtuality, the more their perception split into two realities. At the VR stage less spatial and temporal synchronization is required compared to AR due to the visual isolation from the real environment. The grand challenge is to investigate perceptual priorities for these coherences and contingencies. Besides this aspect CR opens up many possible variables, which can offer great freedom for example to create novel interactions but also come at the cost of increased complexity which have to be either kept in sync or fused upon transition. This is further complicated by the asymmetric capabilities of devices at different RVC stages. Here we discuss approaches to fuse and map spatial and temporal mismatches as well as the representation of information.

A. C13: Spatial Mapping

Communicating and transitioning between stages on the RVC requires careful synchronization between physical and virtual spaces and their inherent properties, such as acoustics or visual representation. Yet, each stage offers distinct capabilities that are not easily synchronized or go beyond a 1-to-1 mapping.

The foundation for spatial mapping is the available extent of world knowledge [23] (e.g., room geometry, material properties, coordinates, lighting, acoustics). While we expect that tracking technology will continue to improve, CR systems must decide between representing virtual content perfectly to fit the real world (e.g., virtual objects matching inferior visibility of real objects in AR for the sake of immersion) and benefiting from the capabilities of virtuality—which may also change depending on the user's current stage. CR systems are able to use this trade-off to implicitly communicate interaction possibilities, for example by purposefully breaking the immersion to indicate the extended affordances of virtual objects. In addition, while prior work has focused on mapping spaces in terms of their room geometry and coordinates (e.g., [142]), capturing and integrating other properties such as lighting and acoustics needs further investigation.

Another challenge is the calibration of different spaces to establish a consistent environment across systems and users. This is, in part, due to technological restrictions. Each tracked device establishes its own coordinate system despite often using the same data (e.g., the real world for inside-out tracking). Non-tracked devices such as desktops still need custom fiducial markers to be spatially registered. However, a 1-to-1 mapping between virtual and physical space may also be undesirable or cannot simply be established. For example, VR environments offer exceptional freedom in changing the user's environment (e.g., using non-euclidian spaces [143]), yet this may not be easily synchronized with the real world, making the mapping between stages challenging. Prior work has already investigated the mapping of dissimilar physical spaces for remote collaboration using AR (e.g., [111], [144]), which could be investigated for mapping dissimilar CR spaces (e.g., between collaborators and entities in different stages [142]). Besides looking at a pure spatial mapping between these spaces, Yang et al. also investigated user placement for telepresence in dissimilar spaces [145]. However, these mappings may lead to confusion when switching between stages. Here, too, further research is needed, for example by making use of consistent spatial landmarks.

Further challenges are presented by mapping individual entities between stages. While entities in VR can be entirely virtual and therefore not bound by the laws of physics, CR systems may also have to consider virtual objects that are semantically linked to real objects (e.g., digital twins or substitutional reality [117]) and may therefore be limited in how the user can interact with these entities. Often, this interaction is unidirectional: Mapping the movement of a real object onto a digital object simply requires the appropriate tracking; mapping the movement of a virtual object to a real object is much harder. This difference may not be obvious and needs to be clearly communicated—otherwise we risk users leaning on non-existing walls.

B. C14: Temporal Fusion

A challenge in CR is the temporal synchronization of the involved entities in the scenario which are potentially located at different stages of the RVC in a geographically co-located or dislocated setting. Typically AR and VR devices aim to have the lowest possible latency, to reduce the risk of cybersickness in VR and to have an accurate registration in AR. Both stages demand for a high precision, which is especially important for AR. This low-latency/high-precision requirement is traditionally challenging at individual stages, but it becomes even more complex if multiple displays and other devices have to be synchronized. In many CR scenarios multiple displays are involved. In VESADs for example it is pointed out that real-time synchronization between virtual and real displays is extremely important [146]. Similarly Kawakita and Nakagawa [147] encountered a latency-related problem while synchronizing a real-world TV broadcast with additional content displayed via AR around and beyond the TV screen.

Latency in general is a topic widely discussed and investigated under different point of views. Depending on the use-case it can be highly relevant. For successful CR applications a variety of suggested solutions could be combined to achieve a low-latency CR environment. With HMDs it is common to implement prediction [148] to hide latencies and reduce cybersickness. The research community dealing with Networked Virtual Environments (NVEs) developed different topologies and algorithms to hide latencies from users. Here a recent survey provides a good overview [103]. The game development community started early with algorithms for latency hiding [149]. In single object manipulation by simultaneous users jitter poses for example a greater problem than a constant even higher latency [150] here a jitter reduction is suggested

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by introducing a constant latency. All of these approaches come with drawbacks for example in precision and affecting the spatial synchronization. Thus, ideally an adaptive handling of latency and precision should be achieved based on the demands of the scenario. To successfully handle this trade-off in CR a collection of such approaches should be available as a framework.

Besides the temporal synchronization of multiple different devices synchronization over time can be interesting in CR applications. VR setups allow for example recording and replay of data [125]. Replaying of tracking data can be valuable for later analysis for example in user studies. Here VR is also used for replaying data used in an AR setting. Displaying recorded sessions in VR can be used to replay as well transitions and interactions between RVC stages.

Another aspect in temporal synchronization is the potential of asynchronous interactions as discussed by Fender and Holz [151]. They describe a causality-preserving approach merging real and virtual content.

C. C15: Information Representation

As different devices and stages have different capabilities, considering different representation strategies of the same information in different stages and on different devices may be necessary [152]. To maintain recognizability, such a representation should be transitioned and therefore linked semantically when traversing different stages. Transitioning established visualizations like scatter plots over different stages to utilize their capabilities might be rewarding but needs further research. Spatial and relative visual consistency are important for improving recognizability when transitioning representations over different stages. The spatial synchronization of coordinate systems in two-dimensional environments like desktop environments and three-dimensional environments like MR applications is another challenge.

VIII. Collaboration

CR systems offer the potential to enable entirely new forms of collaboration, especially compared to established collaborative tools such as 2D video conferencing. These new forms extend far beyond mimicking physical face-to-face meetings using avatars in VR. For example, Billinghurst et al. demonstrated as early as 2001 how collaboration between two CR users can be facilitated by enabling their transitions between reality, AR, and VR and also between different scales [7]. Schröder et al. built a CR system, in which users could individually switch between desktop-based, AR, and VR views of their workspace during a dyadic urban design task [29]. In their user study, a wide variety of CR collaboration styles unfolded with many different reasons for users to use transitions during collaboration, including the current task, distribution of roles, time pressure, personal preferences, interpersonal relationships, and simply the enjoyment of new technologies [29]. This resonates with the comprehensive review of collaborative MR systems by Ens et al., who consider transitional CR interfaces as an important foreseeable direction for future groupware [59].

Designers of future collaborative CR can benefit from the extensive body of work in CSCW (Computer-Supported Collaborative Work) from the pre-CR era, e.g., [153]–[157]. For example, the concept of workspace awareness [156] is valuable for understanding CR collaboration. It reminds designers to provide sufficient cues about other team members' presence, identity, actions, and intentions, including what they are working on, what they can currently see, what they are looking at, and what they are reaching for. Also, Johansen's widely recognized time-space matrix [153] (see Table III) helps to classify the kind of collaboration a system is built for. Should it facilitate bridging geographical divides, temporal divides, or perhaps both?

TABLE III
Traditional time/space matrix based on [153]

		Time	
		Synchronous	Asynchronous
Space	Co-located	same time, same place	different time, same place
	Remote	same time, different place	different time, different place

However, this matrix needs to be substantially revised to account for CR collaboration [27]. For instance, the notions of "same place" and "different place" are ambiguous in CR because two VR users may be perceptually separated by being immersed at opposite ends of a large virtual environment, despite being physically co-located within a few meters. Conversely, users can perceive each other as if they were virtually co-located in the same room, even when separated by thousands of kilometers geographically [27]. To account for this, Schröder et al. differentiate between physical vs. sensory proximity [158]. They also move beyond the dichotomy of synchronous vs. asynchronous in the time dimension [158] and, based on neuroscientific research, distinguish temporal proximity at different scales: milliseconds, seconds to minutes, and circadian rhythms (e.g., days) [158]. Other work in CR challenges linear notions of time by creating causality-preserving asynchronous reality [151]. Acknowledging that time and space become non-trivial concepts in CR is key to understanding its full potential for collaboration. While CSCW research from the pre-CR era can guide the design of future collaborative CR to some extent, there is a great need to revise established concepts and thinking beyond simple dichotomies [29], [59], [157]. This will enable researchers to address the following three grand challenges of CR collaboration.

A. C16: Real-world Use Cases for CR Collaboration

A challenge lies in identifying use cases where CR collaborative systems can outperform existing collaborative tools. New capabilities offered by CR collaborative systems compel us to reinvent traditional use cases, provide new super-powers to collaborators, discover new use cases enabled by CR, and globally create innovative ways of collaborating that effectively leverage collaboration.

This challenge is particularly pronounced for CR collaborative systems, as these inherently offer enhanced functionality, such as the ability to switch between different environments. For example, a CR system may transition a participant from a VR world to an AR environment to share a common location with another participant. Will these new capabilities enhance or hinder the user experience? Therefore, it is essential to identify the relevant criteria and heuristics for evaluating CR collaboration. Radu et al. [159] address this by categorizing AR collaboration needs in collocated spaces. Their approach emphasizes the primacy of collaboration itself. CR applications benefit from the flexibility to transition seamlessly between VR and AR, potentially making them more useful. However, there is a risk of promoting inappropriate use cases, as noted by Sriworapong et al. [160], where a simple 2D representation would suffice. How can we systematically identify real-world use cases where collaborative CR provides genuine value rather than serving as a technological curiosity? How can such technologies be effectively integrated into real-world workflows? What applications are practical, and in which contexts do they make the most sense?

This issue already exists with VR collaboration systems, which generally provide a diminished experience compared to face-to-face collaboration. VR collaboration platforms such as Meta Horizon[1], Big Screen Remote Desktop[2], Spatial[3] and Virbela[4], among other prominent examples, have demonstrated the potential of MR collaboration. However, they are by no means competitors to mainstream platforms like Zoom or Teams, despite the lack of spatial interplay of video-based remote collaboration [161]. One study by Sriworapong et al. [160] demonstrates that in certain collaborative use cases, 2D environments can outperform immersive VR when the VR environment does not offer unique advantages and, in fact, requires additional training to be used effectively.

The value of CR collaboration for real-world applications is highly context-specific. Which properties are decisive for success or failure in practice? This will be a challenge for future work in CR collaboration. To begin, we consider the following criteria as a starting point for characterizing CR collaborative systems.

1) Spatial dimensions, tasks, and entities involved, along with their interactive modalities, vary depending on the heterogeneity of superpowers among collaborators
2) Spatial sound and its impact on collaboration, especially in larger groups
3) Variations in social presence arise from differences in collaborators' realities, rather than from basic communication or representation
4) Accuracy of direct interactions, such as manipulation, and the colocation of entities sharing the CR shared space
5) Time management during collaboration and seamless transitions between different modes, such as synchronous, asynchronous, and challenging hybrid modes
6) Keep other, less obvious trade-offs in mind, such as travel costs and time, cognitive load and stress, energy consumption (e.g., travel versus computation, wireless versus fiber optics, monocular smart glasses versus fully-fledged stereoscopic HMDs), the use of drones for inspection, et cetera

This list is not all-encompassing, but should be seen as a first step. The challenge must be to develop and codify a set of criteria and heuristics for when CR collaboration makes sense. Research in this area should set out to create formal criteria for requirements for when to use CR for Collaboration based on research conducted similar already in the AR space [159] and explore experiments in line with VR collaboration research that has shown to be superior to video applications. [162].

B. C17: User Representation and Social Presence

This challenge is concerned with finding a sweet spot between the realism of embodied avatars versus more abstract or metaphorical user representation. Not every CR system requires high-fidelity fully-articulated representations of users as avatars. In fact, their benefit greatly depends on the context of use, such as users' tasks, the different collaborators' individual stages of the RVC, available devices and their screen sizes. We need to understand when and where embodiment is necessary and where simpler means of user representation are fully sufficient. For example, when are simpler awareness cues such as abstract representations of gaze and gestures enough?

During asynchronous or remote collaboration, collaborators embed avatars of different complexities depending on the nature of the task [163], from sharing view focus or virtual hands only [164] to photorealistic full-body avatars [165]. The balance between personal closeness and professional relation, and between embodied avatars and disembodied 2D abstract representations by texts or only voice must be taken into account. Social MR networks require higher levels of realism to enhance the sense of presence, co-presence, body ownership and self-perception [166]. During certain object-centered tasks, realistic full-body avatars may provide similar levels of interpersonal communication compared to face-to-face collaboration [167]. Ghamandi et al. [168] proposed a taxonomy of human-human MR collaborative tasks, listing different actions and properties which may be used as criteria for estimating the user representation and social presence needs of a collaborative CR system.

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[1] https://horizon.meta.com/
[2] https://www.bigscreenvr.com/remotedesktop
[3] https://www.spatial.io/
[4] https://www.virbela.com/

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In a CR environment, participants can also be remote to each other or in partially distributed groups as well. Thus, user representation between remote and co-located collaborators must also be considered. Can CR enable systems that overcome the divide between remote and co-located participation (“the Remote Challenge”) in partially distributed teams and hybrid collaboration? Remote participants are known to contribute less or be ignored more. Can CR help to overcome this? How can CR collaboration overcome the problem of being co-located or not? Work has been done to explore ways of describing these hybrid collaboration environments and coupling styles in partially distributed teams through the Domino framework [157]. This could act as a starting point to explore this challenge, but ultimately, work must be conducted to define criteria for requirements to achieve meaningful CR hybrid collaboration.

C. C18: Object and Environment Representation and Interaction

Collaboration, whether in the real world or virtually, traditionally assumes that all collaborators need to perceive the same shared task space consistently. In shared CR spaces, the inherent use of heterogeneous devices transitioning between different environments at any given time presents a challenge: ensuring that an object within a shared task space remains identifiable as the same object across all realities. This issue is analogous to the problem described in C15, section 8.3.

While consistent representation, manipulation, and functionality are essential, they may differ between heterogeneous CR devices. Depending on collaborative use cases, task spaces may also be distributed symmetrically or not. Thus, a challenge exists for any CR collaboration application in how it represents objects and environments between users.

The reality of the objects and environments involved in the collaboration also impacts CR systems. If a single virtual shared environment is used by all collaborators, the perception of collaborators themselves will be based on the same context. If that shared environment is a synchronous reconstruction of the real environment of one collaborator, remote collaborators will share a degraded perception of this environment and will have none to poor interaction means. Use cases constrain contexts and force the nature of shared objects and environments. For example, children’s heart surgery benefits from pre-operatory training with printed or virtual replicas of real hearts obtained from previous imagery or interventions [169]. The virtual replica of a patient’s heart must be highly accurate for training efficiency. Newman et al. [170] showed that the degree of realism of a virtual replica impacts the experience and that maximizing realism strengthens VR system. CR system designers and developers should establish requirement criteria for shared CR spaces to enhance the resulting experience.

If tasks are symmetrical and CR devices are identical between collaborators, collaborators have access to isofunctional perceptions and interactions of shared environments and objects. In the case of heterogeneous CR devices, keeping isofunctional perceptions or interactions may only be partially possible or completely unfeasible. Asymmetrical tasks imply that each collaborator plays a specific role using the perception and interaction techniques provided by his CR device. A multimodal approach would ensure that heterogeneous CR devices provide a consistent experience despite the use of heterogeneous modalities and capabilities. Modular modules would enable a set of modalities depending on each CR device’s capabilities. These modules would communicate together to enable an interaction design and to provide consistent representations and interactions between CR devices as part of a CR system.

Depending on the accuracy required by the task, the CR system would modulate interaction techniques, slowing them down for precision tasks and speeding them up for tasks requiring less accuracy. A critical challenge in using this contextual tuning is balancing the capabilities of CR devices during operation. The complex issues of equity versus equality can be illustrated by considering the representation of objects. One could argue that, for the sake of equality, each object’s representation should default to the lowest common denominator. However, a more equitable approach involves the specific management of limited CR devices to ensure that all users have an equal footing. This means that, even if representations on more advanced CR devices offer higher definition in terms of detail and interactivity, equity is maintained by providing fair access and experience across all devices.

IX. Applications

There is a wide range of applications impacted by the potential of CR to revolutionize various industries, including healthcare and education [171], [172], Training and Simulation [173], [174], Production and Manufacturing [175], [176], Tourism and Cultural Heritage [177]–[179], Remote Collaboration and Assistance [179]–[181], Urban Planning and Transportation [73], [81], [175], as well as Gaming and Entertainment [182]. With the recent release of HMDs designed for everyday use and advances in VST quality, HMD manufacturers are driving innovation further into the area of CR applications. However, when migrating this technology from laboratories into everyday applications there are also specific challenges faced [183], [184]. For example, real-world physical environments are less predictable, introducing factors such as connectivity issues, natural lighting, and unexpected bystanders. This section provides a structured and in-depth examination of four key challenges that must be addressed to successfully integrate CR into everyday applications.

First, we explore the challenge of generalizing existing research. The integration of various stages of the RVC significantly increases complexity and constraints, making it particularly difficult to derive broadly applicable findings. Second, we discuss the need for effective onboarding mechanisms to support novice users. These mechanisms must provide accessible explanations or tutorials tailored to the specific stages of the RVC and their combination. Third, we examine potential safety and accessibility concerns, which vary across different stages and must be carefully addressed when bringing CR to a diverse population. Finally, we analyze ergonomics and hardware limitations, as user comfort and long-term usability are critical considerations for the successful deployment of CR in everyday scenarios.

A. C19: Generalization of Existing Research

A key goal of apllied research is to convert findings into real-world applications, ensuring that results and design considerations are applied in future developments. However, generalizing research outcomes from controlled laboratory studies to real-world scenarios in the field of CR presents unique challenges. CR introduces multiple layers of complexity compared to traditional VR or AR research [27]. This complexity arises from stage-specific constraints, such as the need for robust registration in AR [185], [186] or the isolation of users from the real world in VR. Additional complexity arises from variations in environmental factors, as the spaces in which the applications are used can differ significantly from one user to another, potentially leading to issues such as registration errors or variations in brightness [187]–[189]. In CR multiple stages can be used to solve tasks [35], [36] which can add additional complexity for the task design. Collaboration in CR is also not limited to one stage but can span across different stages, often involving multiple collaborators in multiple stages [29], which is discussed in more detail in section VIII. Furthermore, CR hardware must support these different stages, adding to the setup complexity and limiting its availability, which presents its own challenge (see section V).

Given all these factors, researchers often need to isolate specific aspects of CR in their studies, which can lead to compromises in study design.

When CR applications are brought into real-world contexts, these complexities and constraints reappear, making it difficult to generalize findings from case studies to practical applications. As a result, it remains unclear how much these constraints affect the applicability of research findings in real-world CR environments. To address this challenge, further research is needed to examine these restrictions in more detail and to assess their implications for real-world applications. This will aid in improving the generalization of research findings. In addition, developing guidelines or providing tools to manage this complexity will be essential for the successful application of CR research in practical settings.

B. C20: Onboarding

Introducing a CR application to a broader population is challenging, as it involves various new output and input devices [31], [89], [190], diverse interaction modalities [40], [78], [191], and novel user interfaces [192], [193]. Therefore, onboarding mechanisms are necessary to assist novice users in interacting effectively with CR applications [194]. Designing a robust onboarding system is particularly challenging because each stage of the RVC has unique characteristics, requiring tailored onboarding mechanisms to address both the distinct qualities of each stage and the complexity of multiple device combinations. Furthermore, user skill levels and experience can vary between stages within an application, necessitating a flexible and adaptive onboarding system.

However, CR also offers unique opportunities for onboarding, as the process can span across several stages rather than being restricted to one. For example, VR is inherently isolating, making it challenging for a trainer to assist users due to restricted communication and limited perception. However, CR can facilitate a gradual transition to VR, allowing onboarding to occur between real and virtual environments [133]. Beyond visual aspects, further research is essential to explore how CR can enhance the onboarding process, for example by using input devices to facilitate transitions from familiar interfaces and hardware to new ones. In addition, future research should focus on developing onboarding mechanisms that support users navigating CR applications with a variety of device types, interaction modalities, and interfaces.

C. C21: Safety and Accessibility

Safety concerns are paramount in CR environments, particularly when transitioning between various stages of VR and AR. In VST systems, latency (discussed in more detail in C14), and warping present significant risks, especially in high-stakes environments such as pedestrian zones or workplaces involving machinery, where delayed or distorted visual feedback can lead to collisions [195] and accidents. These risks are especially prominent in medical contexts, where the use of VST displays is often prohibited due to the lack of reliable backup solutions in the event of technical failure or display malfunction.

Beyond physical safety, security issues, including authentication [196], are becoming increasingly relevant in CR applications. This encompasses not only traditional user authentication but also the verification of both real and virtual content. Ensuring secure transitions between virtual and real spaces, such as during off-boarding from digital content, is crucial [48]. Privacy concerns, closely related to security, are further exacerbated by the immersive and pervasive nature of MR technologies.

Accessibility, another critical challenge, becomes more complex with the introduction of advanced user interfaces that are tailored to different stages of MR interaction. The complexity of these interfaces can hinder accessibility, particularly for vulnerable populations such as the elderly [197]. However, this challenge also presents opportunities for innovation in UI design, which can enhance accessibility for all users [198]–[200]. Ongoing research is actively addressing these challenges, with frameworks being developed to create universally accessible MR environments

[201], as outlined in current research agendas [202], and highlighting the current status quo [203].

D. C22: Ergonomics and Hardware

Ergonomics in CR systems presents a significant challenge, particularly concerning user comfort and long-term usability. One of the primary concerns is cybersickness, a well-documented issue that can significantly impact the user experience and limit the duration of MR sessions [187], [204]–[206]. This issue becomes especially relevant in CR scenarios that combine VR with real-world contexts, such as in AR, where VST HMDs are commonly employed. They offer the flexibility to fully occlude the physical environment in VR while allowing real-world perception when needed. However, capturing, processing, and rendering the real-world scene introduces additional system delay [207]. Combined with limitations in display and camera technologies, such usage can contribute to cybersickness. Many HMDs suffer from issues such as limited field of view, low resolution, and latency, all of which contribute to a suboptimal user experience. While state-of-the-art devices, such as the Apple Vision Pro, have mitigated these problems, but have by no means fully solved them. These perceptual limitations, along with others related to hardware design, have been documented for decades, yet remain unresolved in many modern devices [208], [209].

Another challenge arises from the diversity of input hardware when using different stages of CR. Applications may require multiple interaction hardware, for example, using a touch-sensitive display with a touchpen in one stage and a six-degree-of-freedom controller in another, or switching between a desktop view with mouse input and VR view with handheld controller. Transitions between input modalities can disrupt the interaction flow and reduce user comfort. Addressing these limitations with novel interaction techniques will be crucial for improving both the usability and accessibility of CR systems in the future. For example, Wentzel et al. [210] introduce a method for “peeking” between 2D desktop and 3D VR interfaces which allow users to view and interact with the desktop from VR, and vice versa, without fully switching input devices.

X. Conclusion

This paper has discussed the 22 grand challenges of CR which were grouped in 6 different greater topics (Designing and prototyping, engineering and developing, evaluation, spatial and temporal consistency, collaboration and applications). We have focused on conceptual and technical problems of the current state of the art and excluded MR challenges that concentrate exclusively on a single stage of the RVC as well as larger meta topics related to commercialization like privacy and social implications. Some challenges are of course also relevant for single stages like the lack of standardization of hardware but are exaggerated when multiple stages are used within a single application.

In the following we take an overarching perspective. Heterogeneity in various ways poses one of the biggest issues in CR. Heterogenous technologies with different capabilities are available in different stages and make it hard to provide simulation environments (C3) and engineer CR applications (C5). Representation and interaction (C15) in collaborative scenarios are hindered by heterogenous hardware as well as the creation of real-world use cases (C16). Spatial heterogeneity must be resolved by spatial mapping (C13) in case of multi-user or even single user applications when transitioning (C2) between stages. The used hardware in CR is diverse and enhances the problem of interaction which is often tailored to a device and application category (C22).

Synchronization and consistency are crucial to provide a coherent experience between different stages of the RVC. Temporal consistency (C14) is for example relevant when multiple devices or users are interconnected. In representation of information (C15) objects or environments (C18) we argue for equity over equality in terms of consistency. Standardization is missing in many aspects relevant for CR. Standardized frameworks not only allowing transitions between stages but also interconnecting stages and devices are not available (C6). A similar problem arises when it comes to test automation, such approaches are available in MR but would have to be adapted to support CR. The high variability of interconnection of stages increases this problem (C7).

A vast space of possibilities for connecting different stages with multiple users or transitioning between is challenging and hinders standardization. Detailed design spaces often only look at a subset of combinations (C1). This space of possibilities and the nature of the diverse domains involved in CR call for standardized development approaches and terminology and common terminology (C4). Combining multiple devices in CR in calls for new toolkits and frameworks (C8).

This variability in potential setups adds to the complexity evaluating such systems (C9), where it is not sufficient to investigate a single stage. The experiments have to span multiple stages including the effects of transitioning between them (C10). The complexity is further enhanced by stage-specific constraints (C19). In such scenarios it is challenging disentangle blended influences coming from multiple devices and stage transitions (C11).

The degree of representation fidelity differs typically on the stage (in AR often abstract in VR closer to realism) but also on the application. This affects CR in many aspects like user representation (C17), information representation (C15) and object and environment representation (C18) adding additional complexity.

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