The Actuality-Time Continuum: Visualizing Interactions and Transitions Taking Place in Cross-Reality Systems

Anonymous

ABSTRACT

In the last decade, researchers contributed an increasing number of cross-reality systems and their evaluations. Going beyond individual technologies such as Virtual or Augmented Reality, these systems introduce novel approaches that help to solve relevant problems such as the integration of bystanders or physical objects. However, cross-reality systems are complex by nature, and describing the interactions and transitions taking place is a challenging task. Thus, in this paper, we propose the idea of the *Actuality-Time Continuum* that aims to enable researchers and designers alike to visualize complex cross-reality experiences. Moreover, we present four visualization examples that illustrate the potential of our proposal and conclude with an outlook on future perspectives.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

1 INTRODUCTION

While Virtual Reality (VR), Augmented Virtuality (AV), and Augmented Reality (AR) are often researched as independent technologies, the lines between them have become increasingly blurry. Nowadays, VR-head-mounted displays (HMDs) can integrate physical objects into the user's experience, transforming these headsets into AV devices on demand. In particular, researchers have demonstrated prototypes that can include physical keyboards for natural typing [22, 23, 39], furniture to avoid collisions [1], and bystanders to allow for interaction [13]. Moreover, new hardware enters the market that empowers users to transition between different degrees of virtuality, for example, between video see-through AR and immersive VR as seen on recent devices such as the Varjo XR-3[1].

Consequently, it turns out that terms such as VR, AV, or AR are too inflexible to capture the various altering Mixed Reality (MR) experiences that users can enjoy today. Currently, there is no well-established term that references the degree of virtuality a user currently experiences, except for the extremes: reality and virtuality. In this context, we argue for introducing the term *actuality* to better describe the current *"reality"* of a user similar to previous suggestions [9]. The English word *actuality* derived from the Latin word *actualitas* translates to *"in existence"* or *"currently happening."*. Hence, it could be used to describe the *"current reality"* of a user. The state in which the world is in for this particular user [34]. In this line of thought, it could be used to refer to a specific degree of virtuality; thus, the word actuality would be suitable to describe the actual experience of users – the current world that they perceive that coexists with physical reality in which the user is present inevitably [43].

In the future, such a designated term could be useful due to an increasing number of prototypes that enable users to experience not only one particular manifestation like AR or VR but also allow them to transition between these manifestations seamlessly over time. Systems that allow for this kind of experience formed a new research field recently: cross-reality systems. Simeone et al. defined them as systems that *"envision (i) a smooth transition between systems using different degrees of virtuality or (ii) collaboration between users using different systems with different degrees of virtuality"* [33]. By nature, cross-reality systems are rather complex as they involve multiple actualities, and often there is more than one user that experiences them. For example, researchers have proposed cross-reality systems that allow users experiencing different actualities to collaborate and play together [15, 19]. As a result of the increasing complexity, it becomes hard for researchers to describe these systems and to communicate the interactions and transitions between actualities that take place.

A helpful concept to describe and understand cross-reality systems is the Reality-Virtuality Continuum introduced by Milgram and Kishino [24]. However, while this continuum can clarify one particular experience for a user at a defined point in time, it remains challenging to depict transitions between different actualities over time (e.g., a user transitioning from reality into a VR experience [36]). Therefore, we added a time dimension to the Reality-Virtuality Continuum. This allows one to visualize how entities transition between different actualities along the continuum. We argue that visualizing transitions along the continuum over time offers several benefits, including structuring and communicating novel cross-reality prototypes and comparing cross-reality experiences. We named the resulting continuum the *"Actuality-Time Continuum."*

Our goal is to synthesize a way for the community to describe cross-reality systems and experiences on an abstract level. Therefore, we first argue for the term *"actualities"* to depict one specific experience along the continuum from Milgram. Next, we describe ways to advance the continuum to visualize transitions over time. Fundamentally, we suggest adding a time dimension to the original continuum. This can help one to understand how users perceive actuality changes over time. However, we do not limit ourselves to this; we propose including multiple users on the continuum to describe mutual influences among them when using a cross-reality system. We demonstrate our idea by presenting four visualization examples that are inspired by previously published research prototypes. Finally, we conclude with an outlook on future perspectives.

Contribution Statement. As cross-reality research is getting increasingly complex, we introduce a simple visualization concept that empowers one to depict the interplay of cross-reality system users, their individual experiences, involved objects, and possible transitions along the Reality-Virtuality Continuum. Through the resulting Actuality-Time Continuum, we can visualize interactions between present entities and transitions that occur over time.

2 RELATED WORK

In this section, we first present different cross-reality systems and highlight relevant aspects of these systems that contribute to their complexity. Then, we revisit the reality-virtuality continuum introduced by Milgram and Kishino [24] and debate extensions of the continuum. We discuss the term actualities and how we think it could support structuring the domain of cross-realty systems and interactions.

[1]Varjo XR-3 Mixed Reality headset, `https://varjo.com`, last retrieved on July 18, 2023.

2.1 Cross-Reality Systems

According to Simeone et al. [33], cross-reality systems can be classified into two types: 1) systems that implement a transition between different actualities, and 2) systems that support multiple users experiencing different actualities.

Single Users Transitioning Between Different Actualities A transitional interface is a cross-reality system designed to enable users to transition on the Reality-Virtuality Continuum [12]. Thereby, users of transitional interfaces can experience changing actualities (e.g., switching from AR to VR). For example, the *MagicBook* from Billinghurst et al. supports reading it as a normal book but also offers an AR mode (i.e., augmented with virtual objects) or serves as a companion for a VR experience [4, 5]. Oftentimes, transitional interfaces involve more than two actualities, making them rather complex systems. For example, one reality by Roo and Hachet supports six different actualities [28].

Multiple Users Experiencing Different Actualities Users experience different actualities for purposes auch as collaboration [7,26], bystander inclusion in virtual experiences [13–15,23,38], or the opposite to have an isolated experience [30]. As different users can perceive different actualities simultaneously, each user's perspective can differ and therefore needs to be understood by, for example, collaborators [10]. In this context, clear communication of the different actualities and their interplay is needed to understand, structure, and further develop corresponding scenarios and manage their complexity.

Virtual experiences that use a VR-HMD often result in an isolated experience as bystanders are not included in the experience nor are they able to perceive the same actuality as the HMD user [2]. Therefore, many approaches investigated the inclusion of bystanders that do not use a device to join a certain virtual experience. Several approaches included real-time images of the bystanders into VR experiences by using external cameras [23, 38] or using external touch displays mounted on an VR-HMD to allow interaction between reality and VR [14, 15]. To address a larger group of bystanders, projection-based setups were employed [17, 18]. With the help of projectors, bystanders can also be an interactive part of a virtual experience through inside-out tracking [40]. In contrast to shared experiences, isolated experiences have the goal of detaching users from their current actuality. Ruvimova et al. introduced an approach to isolate office workers via VR with the goal of reducing distractions in an open office space [30]. Similar to bystanders that are not involved in the experience, two different actualities are created – one for the person in VR and one for the persons that remain in reality.

Common to all these approaches is that all persons have their own actuality that is formed through the used technology. Bystanders that are visually integrated into the virtual experience are still in reality which is their actuality. Using a 2D display or projections to interact with a Virtual Environment (VE) differs in terms of perception compared to head-mounted VR. Involving several actualities makes it hard to describe these systems and the created shared experience due to the different perspectives. Here, we see the need for abstraction to obtain a high-level view of these scenarios. In summary, cross-reality systems can get complex due to multiple users, transitions, and interactions. Therefore, we revisit the Reality-Virtuality Continuum as it serves as the conceptional foundation of different classes of such systems.

2.2 The Reality-Virtuality Continuum

At the time of writing, almost 30 years have passed since Milgram and Kishino introduced the Reality-Virtuality Continuum in 1994 [24]. Up to this point, the work has had a profound impact, coining terms that are frequently used in the field. According to *Google Scholar*, the work has over 8000 citations, which highlights its relevance. Just three years ago, the paper had around 3000 fewer citations [35], which demonstrates the rapid growth of interest in this topic. The introduced concept of the Reality-Virtuality Continuum that spans between *Reality* (on the left) and Virtuality (on the right) allows the classification of different technology classes, such as AR and AV.

On this continuum, *Reality* refers to the real world, in which every entity in the scene is real and subject to the laws of physics. On the other end, *Virtuality* refers to the VE, in which each entity exists only virtually [24]. Each point on this continuum between *Reality* and *Virtuality* refers to an experience that mixes different amounts of the two. While this is useful to depict the properties of MR systems like conveying information about the degree of reality and virtuality and, thus, can be used to categorize systems into classes like AR and VR, the continuum does not allow to communicate changes within these systems that 1) occur over time and 2) change the degree of virtuality. Therefore, we propose to extend the Reality-Virtuality Continuum by adding a time domain to the continuum. Through the time domain, the continuum could enable one to describe time-dependent cross-reality interactions and systems and accurately depict the user's experience. We call the resulting continuum the *"Actuality-Time Continuum."* In the following, we introduce the term actualities in greater detail as it has the potential to describe experiences along the Reality-Virtuality Continuum more precisely and therefore can help to shape future communication of cross-reality systems and interaction.

Increasing Number of Actualities With cross-reality systems, the ongoing trend towards systems supporting more than one manifestation (e.g., AR or VR) continues. Further, these systems can implement seamless transitions on the continuum, for example, to allow users to transition from the real world into VR [20, 30, 37] or to integrate parts of reality into their VR experience [8, 16, 23]. Hence, the existing term *manifestation* is too inflexible to reflect such experiences and, more importantly, does not allow to describe changes in these experiences over time. Thus, we argue for using the term *"actuality"* to depict the current experience of a user. The term *actuality* goes back to the concept of *"potentiality and actuality"* introduced by Aristoteles [32]. In short, Aristoteles stated that potentiality is a not yet realized possibility of all possibilities that can happen and an actuality is the realization of a specific potentiality – the actual thing that became real. The English word *actuality* is derived from the Latin word *actualitas*, which translates to *"in existence"* or *"currently happening."* In other words, the state the world is in for a user [34]. In this sense, we could use the term actuality to describe the *"current reality"* of MR users – the things that currently seem to be facts for them.

For example, we can consider two users – one using VR and one standing nearby. The actuality for the VR user would be a virtual, digital experience, while for the bystander, the actuality is reality. Moreover, when a user transitions, for example, from reality to VR, we can say that the actuality of that user changes over time. Our definition is in line with the suggestion of Eissele et al. who propose to use the word *actuality* for describing different virtual experiences [9].

3 The Actuality-Time Continuum

The Reality-Virtuality Continuum helps one to classify not only the actuality of a single user but also multiple interacting users. For example, a single user is completely in VR. This user would be somewhere on the right-hand side of the continuum. When two users collaborate in AR and VR [7], we would add the AR user somewhere on the left-hand side of the continuum. A bystander just watching the AR and VR users remains in the real world. The bystander would be shown on the far left of the continuum. However, the current research and technology trend leads to investigating possibilities of switching the actuality on the fly. For instance, when the world around the user influences the experience, there is a short period during which the user's actuality can no longer be described as a single position on the Reality-Virtuality Continuum. An example of such a scenario would be a bystander interacting with a VR user, causing the real world to fuse with the virtual world [38]. Another example is collision prevention [3, 27, 41]).

To empower researchers and designers to quantify their scenarios fully, we set out to establish a new concept for visualizing how people transition between actualities throughout an interaction. Thus, in the following, we present an extended continuum in which we argue that it is necessary to add a time dimension to quantify what a user might experience throughout an interaction. We then use this concept to implement a tool that allows others to generate their scenarios' visualizations easily. We envision that this will help to better envision novel experiences, foster discussion of possible alternative options, and share new solutions with others.

3.1 Conceptual Design

In the following, we introduce three questions that guided our concept, discuss their implications, and introduce our approach to tackle accompanying research challenges.

How can one manage the complexity of scenarios involving multiple actualities? The key for researchers, designers, and developers is to manage the complexity of their cross-reality scenarios to understand the impact on the user. Therefore, an abstraction that fits various scenarios and their dynamic behavior is needed. This abstraction must take into account involved entities, objects, and environments. In particular, the perspectives of users or bystanders might differ enormously while experiencing different actualities [13]. The perceived influences on a user can even come from more than one actuality, inevitably leading to increased complexity. This makes it difficult to comprehend individual experiences and their impacts on the perceiving person (e.g., communication between VR and the real world [6, 11, 14, 15, 31]). Further, depicting dynamic changes within these scenarios is vital to managing complexity and understanding the interplay between users, objects, and the environment.

How can one compare and articulate research or experiences involving multiple actualities? Comparing novel experiences to previously introduced research from the literature can be cumbersome due to complexity or a difference in the underlying hypotheses or research questions. Furthermore, relevant aspects can often be hidden inside the research prototypes. Transitions along the continuum over time add yet another layer of complexity. To approach these issues, we suggest visualizing experiences along the Reality-Virtuality Continuum to gain insight into involved users' experiences, where they manifest on the continuum, and how transitions can occur (i.e., when and how transitions affect the user's experience). This can help researchers to better understand the influences on the user and to articulate new ideas to others in order to obtain feedback on future design decisions that incorporate some form of the interplay among multiple actualities. Still, we believe that visualization should be abstract enough to allow for comparing a wide array of scenarios.

How can the Reality-Virtuality Continuum be utilized to analyze scenarios involving multiple actualities? Currently, it is not entirely clear where on the continuum specific research projects of systems are located. For example, two VR systems could be classified close to the VR side of the continuum. It remains unclear to what extent, for example, the enrichment of a VR experience through a real-world object shifts it on the continuum towards AV. Quantifying ranges on the continuum might help with comparing and classifying future experiences, systems, or research prototypes, making them more comparable and easier to understand. Knowing how far a transition on the continuum goes might help in understanding its impact on transitioning users and their experiences and perceptions.

3.2 Components of the Visualization

The concept's general structure consists of three elements: the actuality someone experiences (e.g., reality, AR, or VR), the time, and the entities (e.g., users, objects, or environments). Here, the actuality is represented on the x-axis and the time on the y-axis. As a result, we obtain the *Actuality-Time Continuum*. Here, two or more entities on the *Actuality-Time Continuum* stand in a specific relationship to each other. This allows one to represent various interactions between entities on the continuum over time. Now, we can visualize the interplay of entities experiencing different actualities or transitions between them (see **??**).

3.2.1 Actualities on the Continuum

To describe the actuality that a user experiences, we use the Reality-Virtuality Continuum. We placed this continuum on the x-axis to depict the actuality of entities. The actuality of users that are positioned furthest on the left is reality, whereas the actuality of users furthest on the right is the purely virtual world.

3.2.2 Time

Exploring previous literature, we realized that the use of the Reality-Virtuality Continuum poses challenges when expressing the mix of elements from Reality and Virtuality over time. Therefore, we added a y-axis to our visualization that runs from top to bottom representing time. Here, we took great inspiration from sequence diagrams that are part of the unified modeling language (UML) [29]. We did not specify a definitive time measurement unit for this axis to avoid restrictions regarding specific scenarios. Hence, the time was specified in steps rather than hours, minutes, or seconds. This provides more flexibility and the ability to visualize various scenarios with the Actuality-Time Continuum. This allows us to change the actuality dynamically by moving along the continuum at different times.

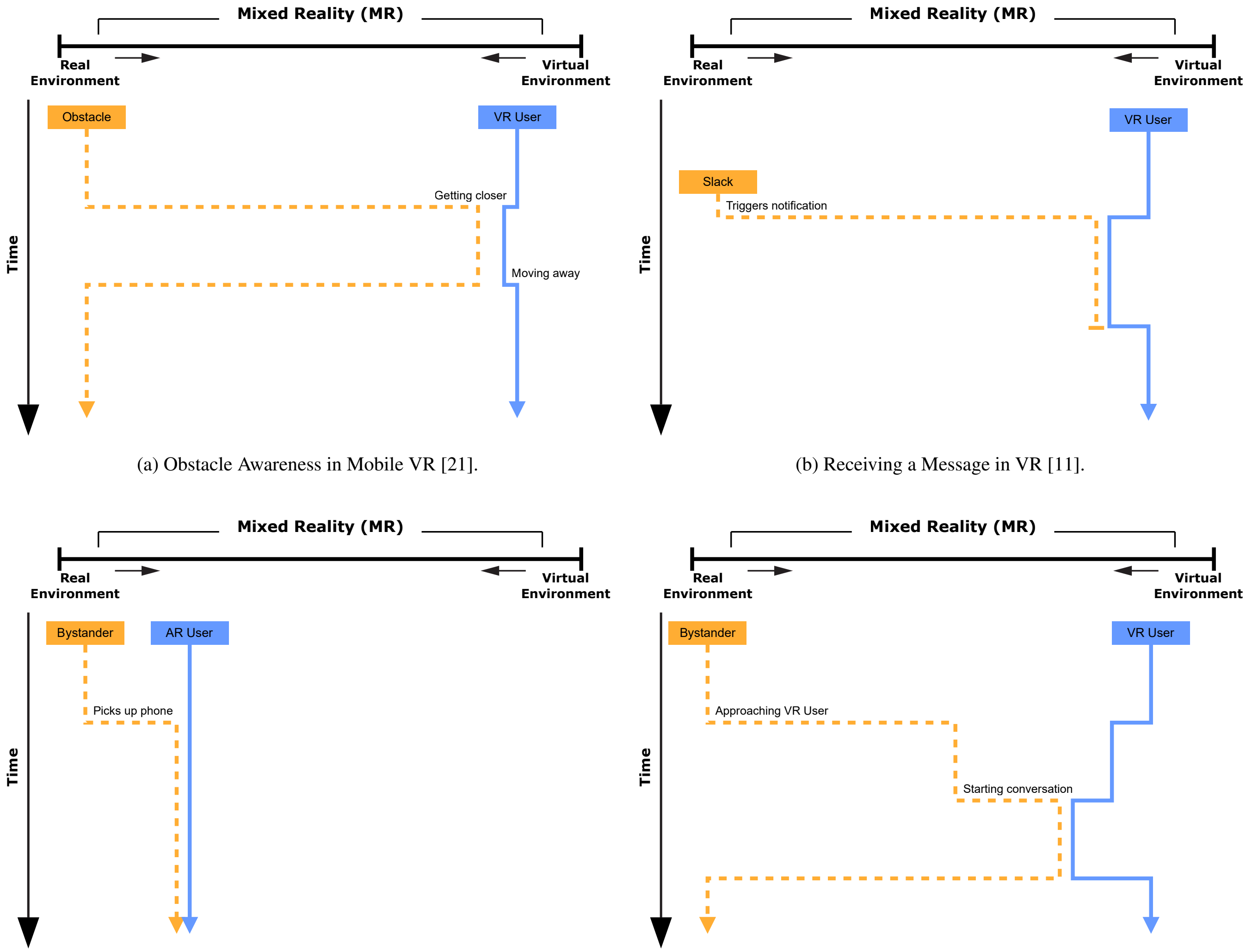
3.2.3 Entities

We have identified two types of entities that can temporarily influence the experience: *Subjects* and *Objects*. The difference between both entities is that subjects have ways to perceive their environment, while objects have no perception. Hence, subjects can experience their environment and therefore an actuality exists that describes their current experience. However, besides this difference, subjects and objects also have attributes in common. Primarily, both can either exist physically in the real environment, digitally in the VE, or in both environments simultaneously. In many scenarios, subjects are users and bystanders [23, 25, 38]. Bystanders can engage with the user, but their presence alone can already impact the perceived actuality. Objects can impact or enrich the interaction, or may be important for the user's safety (e.g., visualizing walls around the user).

4 Visualization Examples

To illustrate our abstract visualization concept, we highlight four different examples inspired by previous cross-reality prototypes (see Fig. 1). The first two are single-user-focused examples in which the main influence is due to the environment or remote people. The other two are co-located multi-user examples in which a bystander influences the AR or VR user.

Obstacle Awareness in Mobile VR The first example was extracted from *SafeXR* by Kang et al. [21]. To make a mobile VR user aware of obstacles, they used built-in smartphone sensors to extract features from real-world objects and alert the user. The system was tested using a mobile VR game (see Fig. 1a). Overall, their approach demonstrated a promising solution for enhancing user safety in immersive VR environments.



(a) Obstacle Awareness in Mobile VR [21].

(b) Receiving a Message in VR [11].

(c) Bystander Joins an AR Experience [42].

(d) Bystander Approaches a VR User [23].

Figure 1: Four example visualization using the Actuality-Time Continuum. The examples are inspired by previously proposed cross-reality systems.

Receiving a Message in VR The second example is inspired by Ghosh et al. [11]. Here, a Slack message was presented visually in VR. The message was presented on existing surfaces based on the user's location and viewing direction. This method successfully integrated a traditional messaging interface into the VR experience, demonstrating a novel way to receive notifications in a VR environment. For the visualization, see Fig. 1b.

Bystander Joins an AR Experience We extracted the third example from the work of Xu et al. [42]. In this paper, a non-HMD user could use a smartphone to join the same AR experience as an HMD user experiencing virtual content in AR. The virtual AR content was synchronized between the HMD and the smartphone to present a joint experience in AR and enable interaction (see Fig. 1c). This highlighted the potential for cross-platform engagement and co-experience, effectively integrating non-HMD users.

Bystander Approaching a VR User The fourth visualization is inspired by work from McGill et al. [23]. In this example, a bystander approaches a VR user. When the bystander enters the same tracking space as the VR user, the former fades into the virtual view. When the VR user chooses to engage with them, they are rendered fully opaque (see Fig. 1d). This interaction technique underscores an intriguing way to incorporate real-world entities into the VR environment, thereby bridging the gap between virtual and physical presence.

5 Conclusion

In this paper, we introduced the concept of the Actuality-Time Continuum. This extended continuum allows one to position multiple entities on the Reality-Virtuality axis and use the new time axis to visualize their interplay over time. The positioning of entities now allows one to visualize the actuality of them their relationships with others and also transitions between different manifestations (e.g., AR or VR). Our visualization can be used to explore alternatives during the development process, discuss ideas with others, or compare different cross-reality systems. We hope that our work sparks discussion on how to describe complex cross-reality systems in an intuitive way. In this context, we used the term *"actuality"* – Latin for *"in existence"* or *"currently happening"* – to name our extension of the Reality-Virtuality Continuum [24].

REFERENCES

[1] C. Afonso and S. Beckhaus. How to not hit a virtual wall: Aural spatial awareness for collision avoidance in virtual environments. In *Proceedings of the 6th Audio Mostly Conference: A Conference on Interaction with Sound*, AM '11, p. 101–108. ACM, New York, NY, USA, 2011. doi: 10.1145/2095667.2095682

[2] J. Auda, U. Gruenefeld, and S. Mayer. It takes two to tango: Conflicts between users on the reality-virtuality continuum and their bystanders. In *In the Proceedings of the International Workshop on Cross-Reality (XR) Interaction*, XR '20, 2020.

[3] J. Auda, M. Pascher, and S. Schneegass. Around the (virtual) world: Infinite walking in virtual reality using electrical muscle stimulation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–8. ACM, New York, NY, USA, 2019. doi: 10.1145/3290605.3300661

[4] M. Billinghurst, H. Kato, and I. Poupyrev. The magicbook - moving seamlessly between reality and virtuality. *IEEE Computer Graphics and Applications*, 21(3):6–8, 2001.

[5] M. Billinghurst, H. Kato, and I. Poupyrev. The magicbook: a transitional ar interface. *Computers & Graphics*, 25(5):745 – 753, 2001. doi: 10.1016/S0097-8493(01)00117-0

[6] L. Chan and K. Minamizawa. Frontface: Facilitating communication between hmd users and outsiders using front-facing-screen hmds. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '17. ACM, New York, NY, USA, 2017. doi: 10.1145/3098279.3098548

[7] M. L. Chenechal, T. Duval, V. Gouranton, J. Royan, and B. Arnaldi. Vishnu: virtual immersive support for helping users an interaction paradigm for collaborative remote guiding in mixed reality. In *2016 IEEE Third VR International Workshop on Collaborative Virtual Environments*, 3DCVE '16, pp. 9–12. IEEE, 2016. doi: 10.1109/3DCVE.2016.7563559

[8] A. P. Desai, L. Peña-Castillo, and O. Meruvia-Pastor. A window to your smartphone: Exploring interaction and communication in immersive vr with augmented virtuality. In *2017 14th Conference on Computer and Robot Vision*, CRV '17, pp. 217–224. IEEE, 2017. doi: 10.1109/CRV.2017.16

[9] M. Eissele, O. Siemoneit, and T. Ertl. Transition of mixed, virtual, and augmented reality in smart production environments - an interdisciplinary view. In *2006 IEEE Conference on Robotics, Automation and Mechatronics*, pp. 1–6, 2006. doi: 10.1109/RAMECH.2006.252671

[10] M. Feick, A. Tang, and S. Bateman. Mixed-reality for object-focused remote collaboration. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*, UIST '18 Adjunct, p. 63–65. ACM, New York, NY, USA, 2018. doi: 10.1145/3266037.3266102

[11] S. Ghosh, L. Winston, N. Panchal, P. Kimura-Thollander, J. Hotnog, D. Cheong, G. Reyes, and G. D. Abowd. Notifivr: Exploring interruptions and notifications in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1447–1456, 2018. doi: 10.1109/TVCG.2018.2793698

[12] R. Grasset, J. Looser, and M. Billinghurst. Transitional interface: concept, issues and framework. In *IEEE/ACM International Symposium on Mixed and Augmented Reality*, ISMAR '06, pp. 231–232. IEEE, 2006. doi: 10.1109/ISMAR.2006.297819

[13] J. Gugenheimer, E. Stemasov, J. Frommel, and E. Rukzio. Sharevr: Enabling co-located experiences for virtual reality between hmd and non-hmd users. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, p. 4021–4033. ACM, New York, NY, USA, 2017. doi: 10.1145/3025453.3025683

[14] J. Gugenheimer, E. Stemasov, H. Sareen, and E. Rukzio. Facedisplay: Enabling multi-user interaction for mobile virtual reality. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '17, p. 369–372. ACM, New York, NY, USA, 2017. doi: 10.1145/3027063.3052962

[15] J. Gugenheimer, E. Stemasov, H. Sareen, and E. Rukzio. Facedisplay: Towards asymmetric multi-user interaction for nomadic virtual reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, p. 1–13. ACM, New York, NY, USA, 2018. doi: 10.1145/3173574.3173628

[16] J. Hartmann, C. Holz, E. Ofek, and A. D. Wilson. Realitycheck: Blending virtual environments with situated physical reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–12. ACM, New York, NY, USA, 2019. doi: 10.1145/3290605.3300577

[17] A. Ishii, M. Tsuruta, I. Suzuki, S. Nakamae, T. Minagawa, J. Suzuki, and Y. Ochiai. Reversecave: Providing reverse perspectives for sharing vr experience. In *ACM SIGGRAPH 2017 Posters*, SIGGRAPH '17. ACM, New York, NY, USA, 2017. doi: 10.1145/3102163.3102208

[18] A. Ishii, M. Tsuruta, I. Suzuki, S. Nakamae, J. Suzuki, and Y. Ochiai. Let your world open: Cave-based visualization methods of public virtual reality towards a shareable vr experience. In *Proceedings of the 10th Augmented Human International Conference 2019*, AH '19. ACM, New York, NY, USA, 2019. doi: 10.1145/3311823.3311860

[19] P. Jansen, F. Fischbach, J. Gugenheimer, E. Stemasov, J. Frommel, and E. Rukzio. Share: Enabling co-located asymmetric multi-user interaction for augmented reality head-mounted displays. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20, p. 459–471. ACM, New York, NY, USA, 2020. doi: 10.1145/3379337.3415843

[20] S. Jung, P. J. Wisniewski, and C. E. Hughes. In limbo: The effect of gradual visual transition between real and virtual on virtual body ownership illusion and presence. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces*, VR '18, pp. 267–272. IEEE, 2018. doi: 10.1109/VR.2018.8447562

[21] H. Kang and J. Han. SafeXR: alerting walking persons to obstacles in mobile XR environments. *The Visual Computer*, 36(10):2065–2077, Oct 2020. doi: 10.1007/s00371-020-01907-4

[22] P. Knierim, V. Schwind, A. M. Feit, F. Nieuwenhuizen, and N. Henze. Physical keyboards in virtual reality: Analysis of typing performance and effects of avatar hands. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, p. 1–9. ACM, New York, NY, USA, 2018. doi: 10.1145/3173574.3173919

[23] M. McGill, D. Boland, R. Murray-Smith, and S. Brewster. A dose of reality: Overcoming usability challenges in vr head-mounted displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, p. 2143–2152. ACM, New York, NY, USA, 2015. doi: 10.1145/2702123.2702382

[24] P. Milgram and F. Kishino. A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, 77(12):1321–1329, 1994.

[25] J. O'Hagan, J. R. Williamson, and M. Khamis. Bystander interruption of vr users. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays*, PerDis '20, p. 19–27. ACM, New York, NY, USA, 2020. doi: 10.1145/3393712.3395339

[26] S. Orts-Escolano, C. Rhemann, S. Fanello, W. Chang, A. Kowdle, Y. Degtyarev, D. Kim, P. L. Davidson, S. Khamis, M. Dou, V. Tankovich, C. Loop, Q. Cai, P. A. Chou, S. Mennicken, J. Valentin, V. Pradeep, S. Wang, S. B. Kang, P. Kohli, Y. Lutchyn, C. Keskin, and S. Izadi. Holoportation: Virtual 3d teleportation in real-time. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, UIST '16, p. 741–754. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2984511.2984517

[27] I. Podkosova and H. Kaufmann. Preventing imminent collisions between co-located users in hmd-based vr in non-shared scenarios. In *Proceedings of the 30 th International Conference on Computer Animation and Social Agents*, pp. 37–46. CASA 2017, 2017. talk: CASA 2017, Seoul, South Korea; 2017-05-22 – 2017-05-24.

[28] J. S. Roo and M. Hachet. One reality: Augmenting how the physical world is experienced by combining multiple mixed reality modalities. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, p. 787–795. ACM, New York, NY, USA, 2017. doi: 10.1145/3126594.3126638

[29] J. Rumbaugh, I. Jacobson, and G. Booch. Unified modeling language reference manual, the, 2004.

[30] A. Ruvimova, J. Kim, T. Fritz, M. Hancock, and D. C. Shepherd. "transport me away": Fostering flow in open offices through virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–14. ACM, New York, NY, USA,

2020. doi: 10.1145/3313831.3376724

[31] R. Rzayev, S. Mayer, C. Krauter, and N. Henze. Notification in vr: The effect of notification placement, task and environment. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, CHI PLAY '19, p. 199–211. ACM, New York, NY, USA, 2019. doi: 10.1145/3311350.3347190

[32] J. Sachs. Aristotle–motion and its place in nature. 2005.

[33] A. L. Simeone, M. Khamis, A. Esteves, F. Daiber, M. Kljun, K. Čopič Pucihar, P. Isokoski, and J. Gugenheimer. International workshop on cross-reality (xr) interaction. In *Companion Proceedings of the 2020 Conference on Interactive Surfaces and Spaces*, pp. 111–114, 2020.

[34] S. Soames. Actuality: Actually. *Aristotelian Society Supplementary Volume*, 81(1):251–277, 2007. doi: 10.1111/j.1467-8349.2007.00158.x

[35] M. Speicher, B. D. Hall, and M. Nebeling. What is mixed reality? In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–15. ACM, New York, NY, USA, 2019. doi: 10.1145/3290605.3300767

[36] D. Sproll, J. Freiberg, T. Grechkin, and B. E. Riecke. Poster: Paving the way into virtual reality - a transition in five stages. In *2013 IEEE Symposium on 3D User Interfaces*, 3DUI '13, pp. 175–176. IEEE, 2013. doi: 10.1109/3DUI.2013.6550235

[37] F. Steinicke, G. Bruder, K. Hinrichs, A. Steed, and A. L. Gerlach. Does a gradual transition to the virtual world increase presence? In *2009 IEEE Virtual Reality Conference*, VR '09, pp. 203–210. IEEE, 2009. doi: 10.1109/VR.2009.4811024

[38] J. von Willich, M. Funk, F. Müller, K. Marky, J. Riemann, and M. Mühlhäuser. You invaded my tracking space! using augmented virtuality for spotting passersby in room-scale virtual reality. In *Proceedings of the 2019 on Designing Interactive Systems Conference*, DIS '19, p. 487–496. ACM, New York, NY, USA, 2019. doi: 10.1145/3322276.3322334

[39] J. Walker, B. Li, K. Vertanen, and S. Kuhl. Efficient typing on a visually occluded physical keyboard. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, p. 5457–5461. ACM, New York, NY, USA, 2017. doi: 10.1145/3025453.3025783

[40] C.-H. Wang, S. Yong, H.-Y. Chen, Y.-S. Ye, and L. Chan. Hmd light: Sharing in-vr experience via head-mounted projector for asymmetric interaction. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20, p. 472–486. ACM, New York, NY, USA, 2020. doi: 10.1145/3379337.3415847

[41] P. Wozniak, A. Capobianco, N. Javahiraly, and D. Curticapean. Towards unobtrusive obstacle detection and notification for vr. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, VRST '18. ACM, New York, NY, USA, 2018. doi: 10.1145/3281505.3283391

[42] S. Xu, B. Yang, B. Liu, K. Cheng, S. Masuko, and J. Tanaka. Sharing augmented reality experience between hmd and non-hmd user. In S. Yamamoto and H. Mori, eds., *Human Interface and the Management of Information. Information in Intelligent Systems*, pp. 187–202. Springer International Publishing, Cham, 2019. doi: 10.1007/978-3-030-22649-7_16

[43] M.-S. Yoh. The reality of virtual reality. In *Proceedings Seventh International Conference on Virtual Systems and Multimedia*, pp. 666–674, 2001. doi: 10.1109/VSMM.2001.969726