A Design Space for Single-User Cross-Reality Applications

Nanjia Wang
University of Calgary
Calgary, Canada
nanjia.wang1@ucalgary.ca

Frank Maurer
University of Calgary
Calgary, Canada
frank.maurer@ucalgary.ca

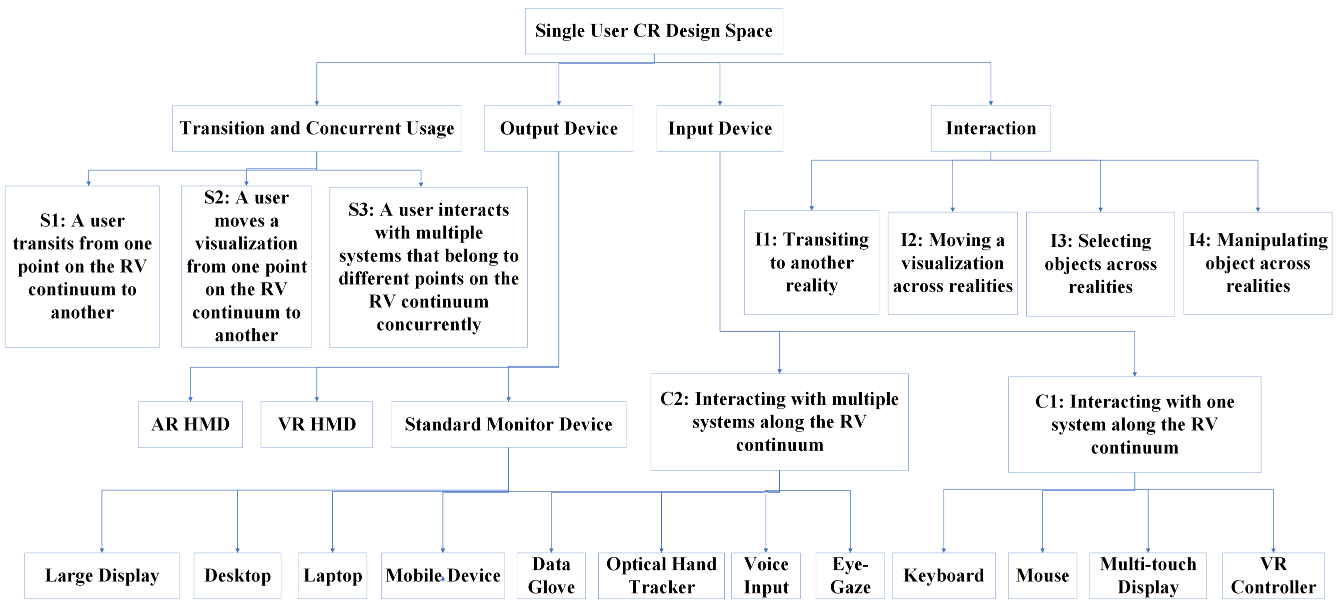

Figure 1: A design space of single-user CR application

ABSTRACT

Cross-reality (CR) applications allow users to utilize tools for problem solving that reside on different points of the Milgram reality-virtuality spectrum. Design guidelines for such applications are missing. In this paper, we are proposing a design space focusing on single-user Cross Reality applications as a tool for guiding research and development projects.

CCS CONCEPTS

• **Human-centered computing** → **Interaction design theory, concepts and paradigms**; **Mixed / augmented reality**; **Virtual reality**; **HCI theory, concepts and models**.

KEYWORDS

cross reality, augmented reality, virtual reality, mixed reality, design space

AVI 2022, June 6–10, 2022, Frascati, Rome, Italy

ACM ISBN 978-1-4503-9719-3/22/06…$15.00
https://doi.org/10.1145/3531073.3531116

ACM Reference Format:
Nanjia Wang and Frank Maurer. 2022. A Design Space for Single-User Cross-Reality Applications. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces (AVI 2022), June 6–10, 2022, Frascati, Rome, Italy.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3531073.3531116

1 INTRODUCTION

Single user cross reality applications allow a user to move between different points of Milgram's reality-virtuality (RV) spectrum, utilizing environments that best fit a specific task or purpose. Cross Reality (CR) usage will likely increase significantly in the near future due to progress in peripheral devices, multisensorial rendering, computational power, and enhanced 5g networking capabilities. Although studies have been conducted in the field of Cross Reality, a framework used to classify CR application designs has not been created.

Researchers have spent decades exploiting the benefits and potentials on different points along Milgram's RV continuum[23]. However, most studies that have been conducted focus on a single point on the RV continuum or compare the advantages and disadvantages of the system on different points of the RV spectrum. With the breakthroughs in technology in recent years, the barrier that restricted applications to a single space on the RV spectrum no longer exists. Therefore, an increasing number of studies are starting to explore a system that connects multiple points on the

RV spectrum. Cross-Reality (CR) was defined as *"transition between or concurrent usage of multiple systems on the RV continuum"*[2].

However, the design space for CR application is huge since it involves making design decisions impacting application components residing on multiple points of the RV spectrum, such as Virtual Reality (VR) or Augmented Reality (AR). Each point in the RV spectrum raises many questions regarding user-friendly design of information presentation, interactions and appropriate available technology use. Due to the multi-space nature of CR, some studies look into collaborations that involve users using systems at different points along the RV continuum[13][12]. However, Wang et al. proposed that CR can support the individual user by moving visualizations across the Milgram continuum[32]. Moreover, this combination of display-based visualization, AR, VR, and more could potentially overcome disadvantages and enhance the advantages of systems at different spaces of the RV continuum for a single user[28]. Application developers have to make many design choices for CR systems but lack structured guidance on what choices to make. This paper presents a design space focusing on single-user Cross Reality applications that target state-of-the-art personal technologies that are commercially available and accessible for everyday users. Our design space focuses on personal devices such as AR HMD, VR HMD, desktop, laptop, tablet, etc. We propose this design space as the groundwork and tool that the CR research community can use to discuss, guide research, and develop applications that cross between points of the RV spectrum.

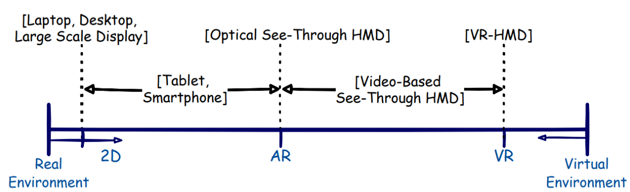

Figure 2: Technologies along the RV continuum[26]

2 RELATED WORK

The RV continuum proposed by Milgram describes the degree of the virtuality of a single display system. On one end is a real environment where the user can only see real objects in the physical world[23]. On the other end, a user is completely immersive in a virtual environment where only virtual objects can be seen. Pointecker et al. presented a generic CR architecture that lists technologies in different spaces of the RV continuum, as shown in the figure 1 [26]. Riegler et al. used the example of different technologies on the RV continuum such as 2D screen, AR, and VR to demonstrate the advantage of each point individually[28]. Wang et al. proposed research questions: how can a single user naturally interact with a CR application and how can users a seamless transition from one point of the RV spectrum to another [32]. To the best of our knowledge, no research discussed a design space for cross-reality applications nor do any evidence-based guidelines for designing such applications exist. In the following, we will start to address the former, focusing on single-user applications while leave collaborative applications for future work.

3 DESIGN SPACE

We propose a high-level design space for a single-user CR application with four dimensions. The first dimension describes the central concept of CR: transition or concurrent usage. The second dimension discusses the visual output devices, which focus on HMDs. The third dimension distinguishes between the choice of input devices used by CR applications. Last but not least, the fourth dimension discusses interactions involved in a single-user CR application. Figure1 gives an overview on the design space.

3.1 Transition and Concurrent Usage

In this first dimension, three main scenarios(S) can be derived from the definition of CR for single-user applications:

- **Scenario 1 (S1): A user transits from one point on the RV continuum to another** Applications that fall into S1 use a single HMD, or a HMD with secondary visual output devices on other points along the RV continuum. A use case is an application that allows users to do analytical work with 2D and 3D visualizations on both computer monitors and a VR headset. For example, the user works with 2D visualizations on a computer that connects to a standard display. When the user needs to work with 3D visualizations, s/he could put on a VR headset and do analytical work in a virtual environment. In this case, the action "put on VR headset" is an example of user transition from the physical world to the virtual environment. However, the transition that requires the user to put on or take off an HMD, instead of wearing it continuously, is not considered a seamless transition. Seamless user transition from one point of the RV spectrum to another (i.e., transitioning from the real environment to virtual environment) is feasible with video pass-through HMD such as Varjo XR-3 or optical see-through HMD such as Microsoft Hololens 2 since the device itself does the transition without the effort and time to put it on and off the HMD[15][24].
  Standard 2D monitors, AR HMDs, and VR HMDs could support analytical work differently[20][33][1]. The transition from one point on the RV continuum to another could bring benefit to the user since it allows the user to effortlessly switch to the environment that is most suitable for the task.
- **Scenario 2 (S2): A user moves a visualization from one point on the RV continuum to another:** The first use case in S1 falls into S2 if both 2D and 3D visualizations are initially being analyzed on a 2D monitor and the user moves the visualization from the monitor to the virtual environment. Wang et al. proposed a research idea that moves information from a 2D monitor to the VR/AR environment to overcome the limitation of the physical 2D display[32]. Schwajda et al. proposed transformation initialization, target layout in 3D space, and transformation parameters as three influential areas to be considered to seamlessly transit information from a 2D display to AR[30]. In that study, when the user selects a visualization and pulls the controller away from the 2D display, a copy of the visualization will first spawn in AR space in a 2D form that aligns with the 2D visualization shown in the 2D display. Then the 2D visualization

in AR space will transform into a 3D visualization. A natural and seamless transition of information from a standard display to AR space using optical see-through HMD is based on enabling hand gesture interaction so that users can perform a "grab" action pull the visualization out of the 2D display into AR 3D space. When the visualization hits the boundary of the 2D display, it should disappear from the 2D display and appear in AR space to simulate the illusion that visualization is being moved from a 2D monitor to physical space by hand. Alternatively, it could stay visible on teh monitor and, essentially create a copy in the physical space.

- **Scenario 3 (S3): A user interacts with multiple systems that belong to different points on the RV continuum concurrently:** S3 must involve the concurrent usage of devices/systems in at least two different spaces on the RV spectrum. It is challenging for users to interact with systems too far away from each other on the RV continuum, such as using a desktop while wearing a VR HMD. There are quite a few studies on the concurrent usage of systems located at the space between 2D and AR on the RV continuum[23]. The study conducted by Reipschlager and Flemisch et al. combined an AR HMD with the 2D interactive display. The result indicates that this concurrent usage could reduce the perception issue of the 2D display and better support dense data analysis[27]. Langner et al. explored utilizing the concurrent usage of AR HMD and multiple mobile devices (i.e., tablets) for data visualization[19]. Mayer et al. proposed the idea of using a planar surface mobile device as a cutting plane that interacts with volumetric data in mixed reality (MR) environment[21]. The proposed design utilizes planar devices categorized into simple or smart handheld devices (HHD). A simple HHD, like a tablet, is a tangible interface that provides haptic feedback and is utilized as an additional control for MR devices. Therefore, the application that combines MR HMD with simple HHD does not fall into S3 as the HMD is the only device displaying digital information. However, a smart HHD such as a tablet has computing power and displays visualizations categorized as the 2D device on the RV continuum. Thus, the design proposed by Mayer et al. that utilizes a concurrent usage of MR HMD and smart HHD falls into S3.

3.2 Output Devices

This dimension focuses on display devices used for CR since only few studies are related to multisensory output in this field. Our design space focuses on three types of visual output devices in this dimension based on three spaces on the RV spectrum: standard monitor, AR HMD, and VR HMD. A CR application should utilize at least two types of output devices in this dimension.

- **Standard Monitor Device** The standard monitor in our design space is defined as a device with a display utilizing a 2D array of pixels to represent information or visualization and does not give the user the illusion that the computer-generated content exists in the same space as the user. A large variety of devices have been included in this category, such as desktop and laptop monitors, tablets, and large displays. Devices that fall into this category contribute non-negligible benefits to CR applications. For example, a state-of-the-art standard monitor has high readability and resolution, allowing to fine-grained details [28]. In addition, the user can operate the desktop with familiar ways of interaction. Furthermore, the standard monitor device with touch input provides haptic feedback. Portable devices with standard monitor reduce the location constraint and provide more flexibility[26]. Many studies have been conducted on combining standard monitor devices with AR or VR HMD in S3 using visualizations in AR space, enhancing information on the standard monitor device, or using the standard monitor device as a tangible input device to interact with visualizations in AR and VR space[21][11][27][19][22][6][4]. However, only few papers or studies are related to S1 and S2[32][30].
- **AR HMD** AR is in the center of the RV continuum. Since an AR environment integrates real and virtual environments, the devices that fall into this category are naturally suitable for CR applications. The AR HMDs utilized in CR applications can be categorized into optical see-though HMD and video pass-through HMD.
  Optical see-through HMD shows data and visualizations on a transparent or semi-transparent display[31]. The user who wears optical see-through HMD can see and interact with standard computing devices, which makes it suitable for applications in S1, S2, and S3. However, optical see-through does have limitations, such as low contrast and a narrow field of view (FoV) [9][16][26]. These limitations significantly impact the range of transition in S1 and S2 since users are not able to be visually isolated and be fully immersed in a computer-generated environment as created by VR HMD. The state-of-the-art optical see-through HMD supports the transition between real and AR spaces. The limitation caused by low contrast and a narrow FoV will be overcome in the near future. Compared with optical see-through such as Hololens 1, more advanced AR HMD such as Hololens 2 have a significant increase in FoV from 30° by 17.5° to 43° by 29°. Magic Leap 1, as an alternative product to Hololens 2, has a Fov of 40° by 30°[14]. The contrast ratio has been increased to around 70 percent for Hololens 2 [10]. This advancement in AR technology will enable optical see-through devices to provide S1 and S2 transition from the real environment to a space near the VR environment. Video pass-through HMD uses multiple wide-angle cameras affixed to the HMD to capture live video and render it in the display [26][25]. This type of technology enables the applications that utilize video pass-through HMD to support S1 and S2 transition between any realities on the RV continuum. However, the technology is not mature yet. Pfeil et al. built a video pass-through HMD prototype by attaching ZED Mini to an HTC Vive and found issues related to distance perception[25]. Oculus Quest 2, as a newer device, has embedded video pass-through functionality, but the live video rendered on display has low resolution which does not provide the user the perception of the real world. Urho claims that the video pass-through HMD made

by Varjo can render live video of the physical world on display close to the quality of what the user could see through the transparent display of an optical see-through HMD[15]. This HMD could be utilized in any CR application.

- **VR HMD** VR HMD is on one end of the RV continuum in which the user will be fully immersed in VR space visually. Due to this characteristic, only one study has been found in S3 that utilizes VR HMD since the user can not interact with other computing devices invisible to her while wearing a VR HMD [21]. In addition, it is challenging for the user that is fully immersed in a VR space to interact with the 2D device. However, research related to the transition perspective utilizing VR HMD in S1 and S2 still has great potential.

3.3 Input Device

We classify input devices into two categories based on the number of systems along the RV continuum designed to interact within a single application. Input devices are usually designed for a specific space on the RV continuum. Category one (C1) represents **input devices that interact with only one systems along the RV continuum**. For example, the mouse and keyboard are commonly used to interact with desktops and laptops[29]. Touch screen interaction was introduced in the 1990s and is now widely utilized by laptops and mobile devices. Touch user interface even became a state-of-the-art input method for mobile devices with the invention of multi-touch displays[5]. The digital pen as an input device invented in 1955 is now another common input device of laptops and mobile devices[8]. The controller is the standard input device for VR devices that have 6 degrees of freedom tracking. A VR controller usually has joysticks, buttons and touchpads integrated into it[3]. However, many input devices could be utilized in multi-space on the RV continuum. Category two (C2) represents **input devices that interact with multiple systems along the RV continuum in an application**. Data gloves can recognize hand gestures and provide a more accurate and natural interaction experience than a static keyboard and mouse, which has been utilized in computer, AR, and VR applications[18][34][17]. The optical hand tracker is another input device that supports gesture tracking. The latest VR and AR HMD, such as Oculus Quest 2 and Mircosoft Hololens 2, has an integrated optical hand tracker. The optical hand tracker such as Leap Motion could be attached to a desktop, laptop, or older VR HMD (Oculus Rift) to enable natural gesture interaction[5][7]. Voice input devices are commonly embedded in personal devices discussed in this paper, including VR HMD, AR HMD, desktop, and mobile devices. Eye-gaze input devices are usually embedded in the latest VR and AR HMDs[11][31][3]. Eye-gaze input devices such as Tobii EyeX can be attached to desktops and laptops to support eye-gaze interaction[5].

Based on the definition of CR, a CR application should support transition or concurrent usage in at least two spaces of the RV continuum. Since different spaces on the RV continuum have different input modalities that are suitable. Researchers and designers need to make a choice or find the balance between the two types of input implementation. The first type of implementation (T1) is mono-interaction. This implementation aims to avoid switching the way of interaction when users interact with the system in different spaces of the RV continuum. The second type of input implementation (T2) is multi-interaction. Users interact with systems in different spaces of the RV continuum in a way that is the most efficient in each space. The CR application that implements T1 could utilize C1 input devices or multiple C2 devices that share the same type of interaction. For example, a CR application that utilizes a Microsoft Hololens 2 and a personal computer with a Leap Motion Controller enables users to interact with both systems using hand gestures. The prototype presented by Reipschlager and Flemisch et al. utilizes a digital pen that communicates with both, an AR HMD and a 2D display, to create annotations. In this study, the digital pen is an example of a C1 device[27]. In the use case described in S2, that user transit visualizations between the 2D monitor and AR HMD, a potential choice of input is utilizing mouse and keyboard for interaction with the 2D display while utilizing controller or hand gesture control for interaction with AR HMD. Thus, the user could interact with the 2D display with a familiar and conventional way of input and interaction with visualization in AR space with input that is adapted to spatial operation. In this case, both input devices are categorized in C2 since they interact with devices in one space on the RV continuum.

Whether an input device is categorized in C1 or C2 is based on how it is used in the system. Both the prototype presented by Langner et al. and the prototype presented by Mayer et al. utilize a tablet as an input device. In Langner's prototype, the touch input from the tablet only affects the visualization shown on the tablet. Meanwhile, the tablet utilized in Mayer's study could interact with visualizations shown on the tablet and in MR space[19][21].

3.4 Interaction

This dimension is dedicated to CR interactions that are inspired by 3D interaction techniques in mixed reality. The first interaction (I1) is **transiting to another reality** as describe in S1. Interaction 2 (I2) is **moving a visualization across realities** which is essential functionality for the application that falls into S2. I2 is implemented in Schwajda's study in which users could move graph-based data from a planar display to AR space[30]. I2 needs to be enabled by another important interaction (I3) in CR, which is **selecting objects across realities**. For example, to move a visualization from a standard display into AR space as described in Schwajda's study, the user should select the visualization in the 2D display from the AR space. **Manipulating object across realities** (I4) is an interaction technique closely related to applications that fall into S3. In the study by Mayer, the user could use a 2D device (tablet) to manipulate a visualization in AR and VR space[21].

4 CONCLUSION

We present this design space based on state-of-the-art commercial accessible personal technologies. We looked at four dimensions of the single-user CR application. We hope this design space will help researchers and designers with decision-making when building the single-user CR application.

REFERENCES

[1] 1999. XGobi vs the C2: Results of an experiment comparing data visualization in a 3-D immersive virtual reality environment with a 2-D workstation display. *Computational Statistics* 14, 1 (9 1999), 39–51. https://doi.org/10.1007/PL00022704

[2] 2020. ACM ISS International Workshop on Cross-Reality (XR) Interaction 2020. ACM, Lisbon, Portugal.

[3] Christoph Anthes, Rubén Jesús García-Hernández, Markus Wiedemann, and Dieter Kranzlmüller. 2016. State of the art of virtual reality technology. In *2016 IEEE Aerospace Conference*. 1–19. https://doi.org/10.1109/AERO.2016.7500674

[4] Rahul Arora, Rubaiat Habib Kazi, Tovi Grossman, George Fitzmaurice, and Karan Singh. 2018. *SymbiosisSketch: Combining 2D and 3D Sketching for Designing Detailed 3D Objects in Situ*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3173574.3173759

[5] Daniel Bachmann, Frank Weichert, and Gerhard Rinkenauer. 2018. Review of Three-Dimensional Human-Computer Interaction with Focus on the Leap Motion Controller. *Sensors* 18, 7 (2018). https://doi.org/10.3390/s18072194

[6] Natalia Bogdan, Tovi Grossman, and George Fitzmaurice. 2014. HybridSpace: Integrating 3D freehand input and stereo viewing into traditional desktop applications. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*. 51–58. https://doi.org/10.1109/3DUI.2014.6798842

[7] Doug A. Bowman, Chadwick A. Wingrave, J. M. Campbell, V. Q. Ly, and C. J. Rhoton. 2002. Novel Uses of Pinch Gloves™ for Virtual Environment Interaction Techniques. *Virtual Reality* 6 (2002), 122–129.

[8] Necati Cihan Camgöz, Ahmet Alp Kindiroglu, and Lale Akarun. 2015. Gesture Recognition Using Template Based Random Forest Classifiers. In *Computer Vision - ECCV 2014 Workshops*, Lourdes Agapito, Michael M. Bronstein, and Carsten Rother (Eds.). Springer International Publishing, Cham, 579–594.

[9] Sara Condino, Marina Carbone, Roberta Piazza, Mauro Ferrari, and Vincenzo Ferrari. 2020. Perceptual Limits of Optical See-Through Visors for Augmented Reality Guidance of Manual Tasks. *IEEE Transactions on Biomedical Engineering* 67, 2 (2020), 411–419. https://doi.org/10.1109/TBME.2019.2914517

[10] Austin Erickson, Kangsoo Kim, Gerd Bruder, and Gregory F. Welch. 2020. Exploring the Limitations of Environment Lighting on Optical See-Through Head-Mounted Displays. In *Symposium on Spatial User Interaction* (Virtual Event, Canada) *(SUI '20)*. Association for Computing Machinery, New York, NY, USA, Article 9, 8 pages. https://doi.org/10.1145/3385959.3418445

[11] Adrien Fonnet and Yannick Prié. 2021. Survey of Immersive Analytics. *IEEE Transactions on Visualization and Computer Graphics* 27, 3 (2021), 2101–2122. https://doi.org/10.1109/TVCG.2019.2929033

[12] Jerônimo Gustavo Grandi, Henrique Galvan Debarba, and Anderson Maciel. 2019. Characterizing Asymmetric Collaborative Interactions in Virtual and Augmented Realities. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 127–135. https://doi.org/10.1109/VR.2019.8798080

[13] Jan Gugenheimer, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. 2017. 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* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4021–4033. https://doi.org/10.1145/3025453.3025683

[14] DAVID HEANEY. 2019. HoloLens 2's Field of View Revealed. https://uploadvr.com/hololens-2-field-of-view/

[15] Urho Konttori. 2021. Merge real and virtual content – like never before. https://varjo.com/blog/video-pass-through-xr-changes-reality-as-you-know-it/

[16] Ernst Kruijff, J. Edward Swan, and Steven Feiner. 2010. Perceptual issues in augmented reality revisited. In *2010 IEEE International Symposium on Mixed and Augmented Reality*. 3–12. https://doi.org/10.1109/ISMAR.2010.5643530

[17] Baker N Zakzanis KK Lee JH Kim IY Kim SI Graham SJ Ku J, Mraz R. 2003. A data glove with tactile feedback for FMRI of virtual reality experiments. In *CyberPsychology and Behavior*.

[18] Piyush Kumar, Siddharth S. Rautaray, and Anupam Agrawal. 2012. Hand data glove: A new generation real-time mouse for Human-Computer Interaction. In *2012 1st International Conference on Recent Advances in Information Technology (RAIT)*. 750–755. https://doi.org/10.1109/RAIT.2012.6194548

[19] Ricardo Langner, Marc Satkowski, Wolfgang Büschel, and Raimund Dachselt. 2021. MARVIS: Combining Mobile Devices and Augmented Reality for Visual Data Analysis. In *Proceedings of the 2021 ACM Conference on Human Factors in Computing Systems* (Yokohama, Japan). ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3411764.3445593

[20] Kim Marriott, Jian Jhen Chen, Marcel Hlawatsch, Takayuki Itoh, Miguel A. Nacenta, Guido Reina, and Wolfgang Stuerzlinger. 2018. Immersive Analytics: Time to Reconsider the Value of 3D for Information Visualisation. In *Immersive Analytics*.

[21] Janine Mayer, Stefan Auer, Judith Friedl, and Christoph Anthes. 2021. Volumetric Data Interaction in AR and VR Using a Handheld Touch-Sensitive Device. In *ISS'21 Workshop Proceedings: "Transitional Interfaces in Mixed and Cross-Reality: A new frontier?"*, Hans-Christian Jetter, Jan-Henrik Schröder, Jan Gugenheimer, Mark Billinghurst, Christoph Anthes, Mohamed Khamis, and Tiare Feuchtner (Eds.). https://doi.org/10.18148/kops/352-2-1qsz0ws7eufba2

[22] Daniel Mendes, Fernando Fonseca, Bruno Araùjo, Alfredo Ferreira, and Joaquim Jorge. 2014. Mid-air interactions above stereoscopic interactive tables. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*. 3–10. https://doi.org/10.1109/3DUI.2014.6798833

[23] Paul Milgram, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1994. Augmented reality: A class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies* 2351 (January 1994). https://doi.org/10.1117/12.197321

[24] Mircosoft. 2019. Microsoft Hololens 2. https://www.microsoft.com/en-us/hololens/

[25] Kevin Pfeil, Sina Masnadi, Jacob Belga, Jose-Valentin T Sera-Josef, and Joseph LaViola. 2021. Distance Perception with a Video See-Through Head-Mounted Display. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 528, 9 pages. https://doi.org/10.1145/3411764.3445223

[26] Fabian Pointecker, Daniel Josef Schwajda, Dominik List, and Christoph Anthes. 2021. A Generic Architecture for Cross-Virtuality. 1–6. https://doi.org/10.18148/kops/352-2-1l3l2wncu3tgb5 null ; Conference date: 14-11-2021 Through 14-11-2021.

[27] Patrick Reipschlager, Tamara Flemisch, and Raimund Dachselt. 2021. Personal Augmented Reality for Information Visualization on Large Interactive Displays. *IEEE Transactions on Visualization and Computer Graphics* 27, 2 (2021), 1182–1192. https://doi.org/10.1109/TVCG.2020.3030460

[28] Andreas Riegler, Christoph Anthes, Hans-Christian Jetter, Christoph Heinzl, Clemens Holzmann, Herbert Jodlbauer, Manuel Brunner, Stefan Auer, Judith Friedl, Bernhard Fröhler, Christina Leitner, Fabian Pointecker, Daniel Schwajda, and Shailesh Tripathi. 2020. Cross-Virtuality Visualization, Interaction and Collaboration. In *Proceedings of the 1st ACM International Workshop on Cross-Reality Interaction* (Lisbon, Portugal). ACM.

[29] Martin J Schedlbauer. 2007. *A Survey of Manual Input Devices*. Technical Report. Citeseer.

[30] Daniel Schwajda, Fabian Pointecker, Leopold Böss, and Christoph Anthes. 2021. Transforming Graph-based Data Visualisations from Planar Displays into Augmented Reality 3D Space. In *ISS'21 Workshop Proceedings: "Transitional Interfaces in Mixed and Cross-Reality: A new frontier?"*, Hans-Christian Jetter, Jan-Henrik Schröder, Jan Gugenheimer, Mark Billinghurst, Christoph Anthes, Mohamed Khamis, and Tiare Feuchtner (Eds.). https://doi.org/10.18148/kops/352-2-1kugqssauin8a2

[31] Iuliana Sicaru, Ciprian Ciocianu, and Costin-Anton Boiangiu. 2017. A SURVEY ON AUGMENTED REALITY. (12 2017).

[32] Nanjia Wang, A. Aminbeidokhti, and F. Maurer. 2020. Individual and Collaborative Cross-reality Immersive Analytics - Initial Ideas. In *Proceedings of the 1st ACM International Workshop on Cross-Reality Interaction* (Lisbon, Portugal). ACM.

[33] Edward J. Wegman and Jürgen Symanzik. 2002. Immersive Projection Technology for Visual Data Mining. *Journal of Computational and Graphical Statistics* 11, 1 (2002), 163–188.

[34] D. Zhang, Y. Shen, S.K. Ong, and A.Y.C. Nee. 2010. An Affordable Augmented Reality Based Rehabilitation System for Hand Motions. In *2010 International Conference on Cyberworlds*. 346–353. https://doi.org/10.1109/CW.2010.31