Serious Cross Reality - Using CR to Enhance Analytics Workflow

Nanjia Wang*
University of Applied Sciences
Upper Austria
University of Calgary

Sze-Wing Chan †
University of Calgary
The University of Hong Kong

David Aigner‡
University of Applied Sciences
Upper Austria

Omar Addam §
University of Calgary
VizworX

Christoph Anthes¶
University of Applied Sciences Upper Austria

Frank Maurer‖
University of Calgary
VizworX

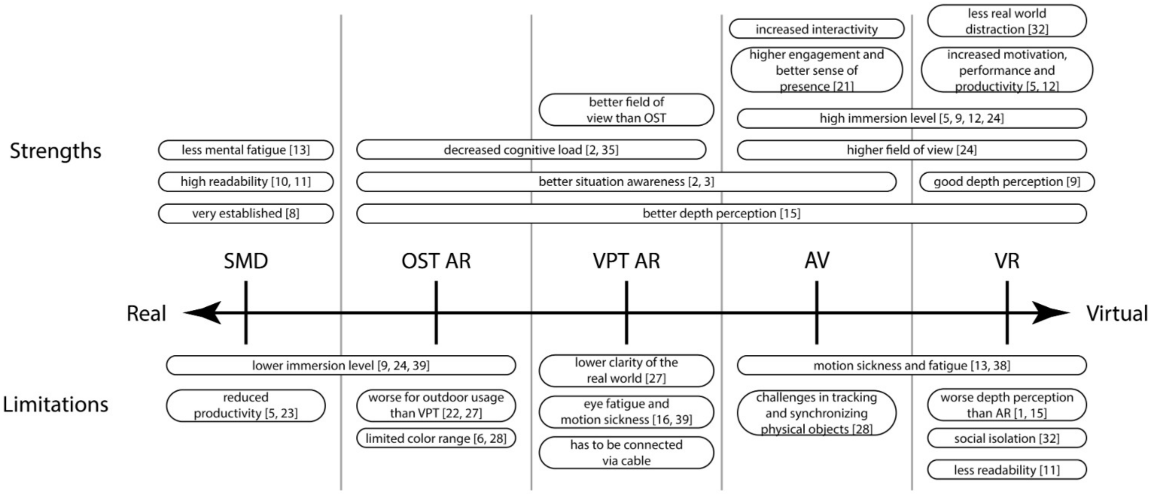

Figure 1: Strengths and limitations of technologies along the RVC, from left to right, there are standard monitor devices, optical see-through augmented reality, video pass-through augmented reality, augmented virtuality, and virtual reality.

ABSTRACT

In the recent years, an increasing number of researchers have started looking into the area of cross reality. This position paper argues the potential of cross reality in enhancing analytics workflow by bridging different points along the reality-virtuality continuum. First, the strengths and limitations of various points along the reality-virtuality continuum are identified. Participants' feedback from the three case studies is discussed to support our argument.

Index Terms: Human-centered computing—Mixed / augmented reality; Human-centered computing—HCI theory, concepts and models;

1 INTRODUCTION

Researchers have been exploiting the benefits of technologies at different points along the Reality-Virtuality Continuum (RVC) for years [27]. In order to enhance the understanding of complex data for decision-making, many studies investigated using immersive technologies to perform analytical reasoning [41]. With an increasing number of commercially available high-quality and affordable Virtual Reality (VR) or Augmented Reality (AR) devices, more researchers and developers started to look into replacing analytics work using conventional visualization and interaction interfaces such as desktops with immersive analytics using devices such as VR or AR Head-Mounted Displayts (HMDs). All technologies along the RVC have their strengths and limitations. As a result, systems at each point along RVC might be most suitable for certain types of tasks or visualizations. Nowadays, many researchers face challenges in analytics works with increasing complexity and involve multiple types of tasks simultaneously with 2D and 3D visualizations. A solution for solving these challenges is to move between different points (e.g., Standard Monitor Device (SMD), AR, Augmented Virtuality (AV), VR) along the RVC so that users can transition to the system that is most suitable for each type of task and visualization.

Cross Reality (CR) is a technology that interconnects systems at different points on the RVC. By definition, a CR application should support the transition between or concurrent usage of multiple systems along the RVC [45]. With the advancement of computation power, networking capabilities, and peripheral devices, developing such CR applications become realistic. Researchers have started to develop prototypes that support different scenarios of CR. Pointecker et al. implemented a prototype with four transition techniques allowing users to transition between AR and VR environments [31]. OneReality is another prototype that supports the transition of user and virtual objects progressively from the physical environment to a fully immersed virtual environment [36]. Schwajda et al. proposed a prototype that allows users to transition 2D graph data from an SMD to the AR space [37]. Some researchers are looking into concurrently interacting with multiple systems at different points along the RVC. CR prototypes that support concurrent usage scenarios usually utilize an AR HMD to enhance the user experience with SMDs [20, 21, 33]. While Mayer et al. proposed a prototype that

---

*e-mail: nanjia.wang1@ucalgary.ca
†email: win.chan1@ucalgary.ca
‡e-mail: david.aigner@fh-hagenberg.at
§e-mail: okaddam@ucalgary.ca
¶e-mail: christoph.anthes@fh- hagenberg.at
‖e-mail: frank.maurer@ucalgary.ca

uses a planar surface mobile device as a cutting plane that interacts with volumetric data in the AR environment [26].

2 STRENGTH AND LIMITATION ALONG THE RVC

For years researchers have been working on exploiting the benefits of technologies at different points along the RVC, such as SMD, AR, AV, and VR. Although technologies at each point on the RVC have advantages, the limitations indicate it is not ideal to use these technologies to replace others and serve as the sole tool for analytic works.

2.1 SMD

An SMD 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 [45].

SMD is currently the primary technology for commercial display and is how most people obtain information [9]. With years of development and usage, an established workflow exists for people to use SMDs. Meanwhile, because people are more familiar with using SMDs and the physical input interface, such as mouse, keyboard, and touchscreen, of SMDs allow passive haptic feedback and spontaneous and reliable interaction, and people have less mental fatigue with using SMDs compared to HMD [14]. The familiarity of SMDs also allows users to have higher readability, as most people are used to reading from SMDs since it requires less mental effort and time to get used to reading on SMDs [12]. Much research has been done on text setting for optimal readability on SMD since the 1980s, in which standards for different text parameters have already been established [11]. For example, the WCAG2.0 is a uniform standard of text and background color contrast, font, and font size initiated for website content on desktop and mobile devices [47].

However SMDs provide a low level of immersion due to a smaller field of view caused by limited screen size and the lack of depth perception [10]. Motion parallax and stereoscopic depth are two of the four principle sets for creating visual depth cues [10]. Monition parallax is the perception of an object being in a 3D space by moving a greater distance when the object is closer to the observer [5,39]. Stereoscopic depth is the distance obtained by presenting different images to the left and right eyes [46]. SMDs are not able to achieve both motion parallax and stereoscopic depth, causing a lack of depth perception. Meanwhile, the limited screen size of SMDs also reduces people's productivity [24]. As a user study conducted by Czerwinski et al. [6] shows participants finished the tasks 9% slower on a regular 15" flat display, compared to 42" wide curved display with a resolution of 3072 x 768, and 14 of 15 participants preferred the larger display.

2.2 AR

AR creates a space that enables the user to see the physical world overlaid or combined with interactive virtual objects that provide information regarding the physical world context. [3,18,43].

AR retains a spatial relationship between the virtual object and the real world that creates an illusion of both coexisting in the AR space, allowing users to be aware of their real-world environment and thus increasing situation awareness [2,4]. Situation awareness allows users to be aware of information that is required to perform a task, in which the information provided by the virtual object and the hints of the user surrounding offered by the physical environment awareness allow the user to perform real-world tasks better [2,4]. Meanwhile, context awareness, the awareness of information relevant to the physical environment, can be provided through virtual contents [2]. These virtual contents can increase users' safety and decrease their cognitive load by offering information that may not be seen in their environment, such as warnings of hazards [2,38]. Additionally, AR displays have more accurate depth perception and estimation. Compared to VR displays, the position and orientation tracker corrections and other important scene parameters in AR displays can be accurately calibrated according to real-world object that provides the true ground value [16].

Current AR HMDs are either optical see-through (OST) devices or video pass-through (VPT) devices, and both have hardware limitations [35]. OST devices have a see-through display medium with the virtual object overlay using transparent mirrors and lens [28,43]. Although OST devices allow a clear view of the real-world surroundings, they have a small field of view that causes lower immersion due to virtual objects clipping at the edge of the display [25,43]. For example, Microsoft's HoloLens 2, the most widely used OST device, has a field of view of 54°, while humans have over 180° horizontal binocular field of view [25]. Low contrast and brightness of OST device displays is another limitation causing it to be less suitable for outdoor usage [23,28]. In addition, as the surrounding environment's background color clashes or mixes with the color of the virtual contents, such as darker colors blends in and appear as semi-transparent and white objects fuse with a background of light color, resulting in OST devices having a limited color range [7,30]. VPT devices use VR displays with the virtual environment replaced by a live video of the real-world surroundings [17,43]. Although VPT devices do not have the limitations OST devices have and can provide a more realistic AR environment, they provide a lower clarity of the real world because of the constraints of VR display resolution [28]. State-of-the-art VPT devices such as Varjo XR3 or Apple Vision Pro have the ability to transition between AR and VR environments and have much broader FoV compared with OST devices. Furthermore, since the video feed of the surrounding is generated according to the user's eyes and head movement, most VR displays have fixed focus distance for eye tracking and latency of the video feed for head tracking, resulting in eye strain, fatigue, and motion sickness [17,43]. VPT devices such as Varjo XR3 utilize a calibrated mixed-reality camera system that captures high-definition video and renders it on 4K screens for both eyes. The lens is automatically adjusted based on the user's interpupillary distance, making it more comfortable and causing less fatigue. The clarity of video rendered on the screens makes it possible for users to read books or watch content on SMD while wearing the HMD. However, such devices require high computation power. Thus, the user needs to wear an HMD tethered to a computer which causes discomfort.

2.3 VR

VR is the technology that allows the participant to be immersed in a fully synthetic world [27].

VR applications provide a high immersion level and reduce external distractions to their users. The large field of view and the presence of depth cues increases the immersion of VR applications [10]. Modern VR displays usually have around 110° field of view, close to the human eye's field of view of over 180° [25]. Meanwhile, monition parallax and stereoscopic depth offered by VR HMDs enable users to have a good level of depth perception [10]. Additionally, high immersion and large surfaces offered by VR applications are proven to positively impact motivation, performance, and productivity [6,13].

Despite state-of-the-art VR HMDs have significant improvements in resolution, such as Varjo XR3, which equips with 4K screens. The readability level is not comparable to SMDs, as the user study conducted by Grout et al. [12] shows that people need more time to read text when using the Oculus Rift compared to a standard 23" display. The low readability may be caused by the lack of familiarity with reading in VR HMDs and insufficient research and standardization on reading settings for VR devices. As for reading text in a VR environment, additional text parameters, text distance, and angular size are needed, which currently do not have an established standard [19]. Although there are studies on the optimal research for reading settings on VR HMDs, they are targeted at specific devices, and the parameter value cannot be applied to other HMDs, making it harder to standardize for VR devices [19]. Motion sickness and mental fatigue are also associated with extended usage of VR HMDs. Dizziness and motion sickness are caused by the frequently moving images in the virtual space and the conflict between the users' self-perception and visual perception of motion [42]. Meanwhile, mental fatigue can be caused by unfamiliar interaction and haptic feedback due to the absence of a physical surface [14]. Additionally, visual and social isolation is an issue with VR applications, as the user is cut off from the physical world and the physical human interaction by the completely immersive virtual environment [34]. Although VR applications enable depth perception, it is less precise than the depth perception of AR applications. VR displays calibration accuracy will be lower than AR displays as scene setup parameters can not use real-world objects as reference [16]. Moreover, people's depth perception is distorted in an entirely virtual environment also because of the lack of real-world reference objects, proven by a user study conducted by Armbrüster et al. [1] where participants underestimated the distance between themselves and objects placed in a virtual environment.

AV is another point on the RVC between AR and VR that should not be neglected. AV is defined as a stage in which the user can see a virtual world which is enhanced by real-world objects [27]. AV prototyping can be traced back to 1997 when Simsarian et al. created a virtual world augmented by video textures taken of real world objects [40]. In early 2000s, Regenbrecht et al. proposed an application allowing users to collaborate on virtual 3D geometry on a physical table [32]. More studies were conducted in AR than in AV due to the technology limitation before VPT HMD, such as Varjo XR3 was commercialized [15]. AV has advantages such as improving the sense of presence and increasing interactivity using the embodiment of user and tangible objects. The study conducted by Lee et al. suggested that users were more engaged and felt more presence in the virtual world with AV technology [22]. Lufthansa Aviation Training also developed an AV flight simulator for commercial pilot training. The simulator combined a real cockpit with a physical control station to enhance the virtual environment. Thus it provides an immersive and realistic experience that enhances the effectiveness of the training. However, there are still challenges in developing AV applications, such as tracking and registering physical objects to match their position in the virtual environment and syncing the state of the physical object to the virtual environment in real-time [29].

3 CR USE CASES

Users' feedback from three case studies indicates that CR can benefit users working on serious analytic work. Three case studies aimed to enhance analytics workflow using immersive technology such as AR or VR HMDs.

3.1 Reservoir Engineering

A case study was conducted to explore the potential benefits of VR technologies to assist reservoir engineering workflows. A VR reservoir model analysis tool was developed to support common reservoir model analysis tasks in virtual environments. The study recruited 12 reservoir engineering experts as participants. All participants were asked to work on tasks such as model plane clipping and well path planning. The model plane clipping task required participants to use a plane clipper attached to their hands to cut away unwanted cells of the model in order to reveal useful insights. The well path planning task required participants to create an oil well passing a specific region within a reservoir model by adding and moving control points.

According to participant feedback, the plane cell clipper is one of reservoir engineers' most commonly used functionalities. Some participants noted that placing and rotating cell clippers in 3D space within a model on SMD using traditional input modalities such as a mouse and keyboard sometimes requires much effort. Placing or adjusting the clipping plane in a conventional tool on SMD requires the user to "rotate the model using a mouse and keyboard" and then "input a series of coordinates" to define the position and orientation of the clipping plan, which is very time-consuming. All participants who used this functionality with conventional software on an SMD voiced that doing such a task in our VR application was a better experience. Participants described their experience using plane clippers in VR as "easier," "faster," "more intuitive," and "more convenient" because they can "use my hand to move the cutter to whatever position I want" and "I can tile the angle of (the clipper) by rotating hands." Some participants also voiced that seeing the real-time visual effects of the clipping process while moving the clipping plane is useful. In addition, they can see the reservoir models more clearly compared with SMD software since they can walk much closer to examine the model. However, there was some criticism brought by participants. Some participants noted that some angles were hard to achieve by rotating the wrist. Participants also commonly voiced that placing the plane cutter at a precise position or orientation in VR using a hand or VR controller was hard. Similarly, 11 out of 12 participants consider drawing well paths within a 3D reservoir model in VR more convenient, intuitive, and easy in the well path planning tasks. However, a lack of accuracy and precision for finely placing wells remains an issue. Some participants suggested adding coordinate input functionality to both tasks to refine position and orientation.

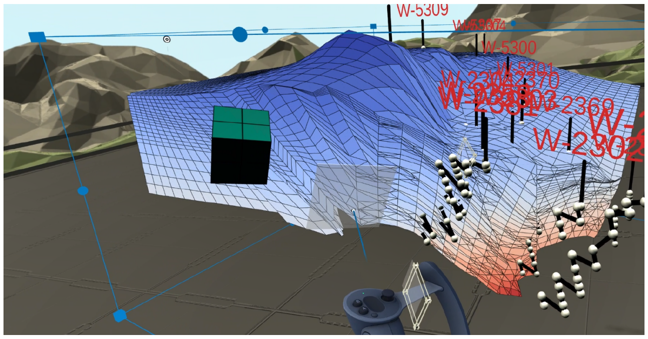

Figure 2: Using clipping plane mounted to hand to reveal insight of reservoir model

All participants thought a VR analysis tool could be a useful addition to the conventional SMD-based application. However, some participants noted that it is unnecessary to do a complete analysis process in VR for some simple cases. A CR interface can benefit engineers by allowing them to transition the reservoir model to an immersive space when needed. And it also allows engineers to roughly place clipping planes or wells using a hand or VR controller and use an SMD interface with a mouse and keyboard for precise adjustment.

3.2 Cardiac Surgery Planning

A pilot study was conducted to investigate the potential use of CR systems for cardiac surgery planning. A CR prototype was created for the study that supports transitioning the 3D heart model from a large SMD to the AR space and allows participants to transition from the AR to the VR environment. Four congenital heart disease (CHD) experts were recruited as participants in the study. Each participant was guided through multiple stages of the CR prototype, including interacting with 3D heart visualization on laptops and large multi-touch displays, transitioning 3D heart visualization from the large display to AR space, and transitioning the environment from AR to VR space. After the tutorial session, participants worked independently to analyze a heart model constructed using CT scan data with complex CHD, followed by a semi-structured interview to gather their feedback.

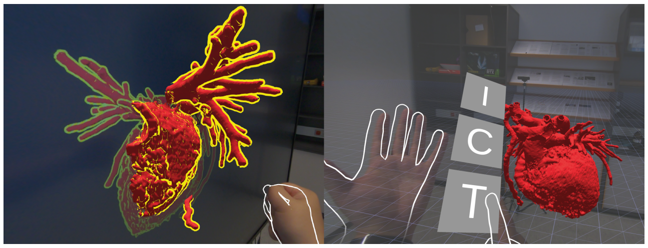

Figure 3: Transitioning 3D heart model from SMD to AR space using a combination of Grab and Drag gesture

Participants primarily mentioned the transition of the 3D heart visualization from the SMD to AR space was the most beneficial aspect of their day-to-day work. Participants noted that AR has many benefits supporting the preoperative planning on complex CHD cases. However, they all agreed that solely immersively application on HMD would not fully replace the conventional SMD-based medical image visualization tools since cardiologists ”have been using those CT and those MRI pictures for thirty years and are used to work on tasks using the established traditional tools and interfaces.” In addition, one participant mentioned that CT and MRI can provide enough information for simple CHD cases. Thus immersive analysis using AR or VR HMD is not necessary for every case. All participants emphasized the importance of CR to the surgery planning workflow by bridging the immersive analytics with SMD-based analytics so that users could take advantage brought by both technologies.

3.3 Engineering Design reviews

Constructing large-scale production facilities, such as chemical plants or refineries, incurs significant costs. A notable portion of these expenses, ranging from five to thirty percent, can be attributed to rework primarily caused by design errors that are only rectified during the construction phase. To mitigate these costs, design reviews are conducted at multiple stages of the design process, typically at 30%, 60%, and 90% completion.

Traditional design reviews often adopt a boardroom approach, where teams examine a 3D rendering of the design presented on a large 2D screen in a meeting room. Despite efforts to identify flaws during these reviews, errors still manage to slip through and manifest in the production phase more frequently than desired. However, rectifying mistakes during the design phase proves to be significantly more cost-effective than addressing them during construction. One key challenge that contributes to errors slipping through is the difficulty some participants face in understanding scale and spatial relationships in 2D drawings. Overcoming this challenge by allowing participants to walk through a design in a 1:1 scale has the potential to alleviate the problem.

Panoptica by EnsureworX[1] is an immersive collaborative environment designed to enhance the design review process. It empowers multiple users to simultaneously view, manipulate, and interact with a single 3D model in real-time. Panoptica enables collocated as well as distributed staff to engage synchronously with 3D models using natural human interactions, effectively enabling participants to walk through of 3D models during engineering design review meetings. This fosters increased engagement and overall improves the design review process.

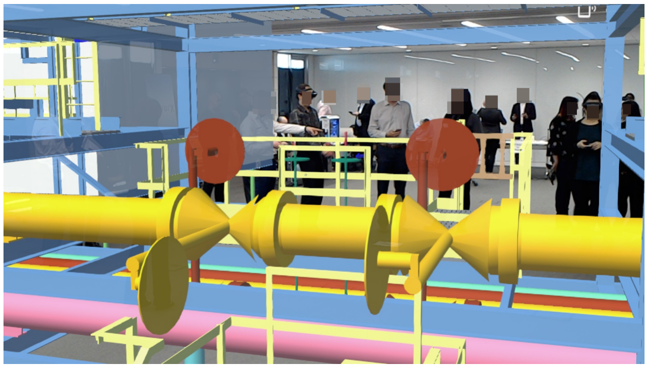

Figure 4: Engineers collaborate on designing large-scale production facilities in AR space

To ensure practicality and inclusivity, Panoptica adopts a cross-reality approach. Recognizing that not all participants in a design review have access to HMDs, the system accommodates collaboration through the use of smartphones, tablets, SMDs, AR, and VR devices. Additionally, since large-scale engineering models require substantial computational power that is not yet available on preferred platforms like HoloLens and HoloLens II, Panoptica is also accessible on VR HMDs. Furthermore, text input is essential for annotating 3D models and highlighting concerns. To enhance user-friendliness, Panoptica integrates with mobile devices to facilitate convenient text input, while HMDs enable associating comments with specific parts of the facility design.

4 FUTURE WORK AND CONCLUSION

CR has the potential to enhance analytics workflow in different fields since it can utilize the advantages of technologies along the RVC to overcome limitations of each other. However, researchers and designers will face many challenges due to its multi-user interface and multi-input modality nature [8, 44]. We propose the following future work as ideas to develop CR applications and to exploit benefits that can be brought to analytics work:

- Developing user experience design guidelines based on the empirical result from user studies. The guidelines should focus on core functionalities or scenarios of CR [45]. The design guidelines should aim to guide designers to develop CR applications that allow users seamless and effortless transition between different systems without being distracted from the task.

- Conducting case studies and comparing CR prototypes with existing monitor-based or HMD-based immersive analytics software on serious analytics tasks. The goal is to collect evidence to answer the research question of whether CR can be used for serious tasks.

- Developing CR prototypes that support co-located or distributed collaboration. With the potential popularization of using HMD for analytics work, the requirement of coll Theaboration across systems along the RVC will rise.

ACKNOWLEDGMENTS

This publication is a part of the X-PRO project. The project X-PRO is financed by research subsidies granted by the government of Upper Austria.

---

[1] https://vizworx.com/portfolio/EnsureworX

REFERENCES

[1] C. Armbrüster, M. Wolter, T. Kuhlen, W. Spijkers, and B. Fimm. Depth perception in virtual reality: Distance estimations in peri- and extrapersonal space. *CyberPsychology & Behavior*, 11(1):9–15, 2008. PMID: 18275307. doi: 10.1089/cpb.2007.9935

[2] S. Aromaa, A. Väätänen, I. Aaltonen, V. Goriachev, K. Helin, and J. Karjalainen. Awareness of the real-world environment when using augmented reality head-mounted display. *Applied Ergonomics*, 88:103145, 2020. doi: 10.1016/j.apergo.2020.103145

[3] R. T. Azuma. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, 6(4):355–385, 08 1997. doi: 10.1162/pres.1997.6.4.355

[4] A. H. Behzadan, S. Dong, and V. R. Kamat. Augmented reality visualization: A review of civil infrastructure system applications. *Advanced Engineering Informatics*, 29(2):252–267, 2015. Infrastructure Computer Vision. doi: 10.1016/j.aei.2015.03.005

[5] R. BRINKMANN. Chapter two - learning to see. In R. BRINKMANN, ed., *The Art and Science of Digital Compositing (Second Edition)*, The Morgan Kaufmann Series in Computer Graphics, pp. 15–51. Morgan Kaufmann, Boston, second edition ed., 2008. doi: 10.1016/B978-0-12-370638-6.00002-X

[6] M. Czerwinski, G. Smith, T. Regan, B. Meyers, G. Robertson, and G. Starkweather. Toward characterizing the productivity benefits of very large displays. In *(2003) Interact 2003*. IOS Press, January 2003.

[7] M. Fiorentino, S. Debernardis, A. E. Uva, and G. Monno. Augmented Reality Text Style Readability with See-Through Head-Mounted Displays in Industrial Context. *Presence: Teleoperators and Virtual Environments*, 22(2):171–190, 08 2013. doi: 10.1162/PRES_a_00146

[8] B. Fröhler, C. Anthes, F. Pointecker, J. Friedl, D. Schwajda, A. Riegler, S. Tripathi, C. Holzmann, M. Brunner, H. Jodlbauer, H.-C. Jetter, and C. Heinzl. A Survey on Cross-Virtuality Analytics. *Computer Graphics Forum*, 41(1):465–494, 2022.

[9] H.-Y. Gao, Q.-X. Yao, P. Liu, Z.-Q. Zheng, J.-C. Liu, H.-D. Zheng, C. Zeng, Y.-J. Yu, T. Sun, and Z.-X. Zeng. Latest development of display technologies. *Chinese Physics B*, 25(9):094203, aug 2016. doi: 10.1088/1674-1056/25/9/094203

[10] N. Gerig, J. Mayo, K. Baur, F. Wittmann, R. Riener, and P. Wolf. Missing depth cues in virtual reality limit performance and quality of three dimensional reaching movements. *PLOS ONE*, 13(1):1–18, 01 2018. doi: 10.1371/journal.pone.0189275

[11] J. D. Gould. Composing letters with computer-based text editors. *Proceedings of the Human Factors Society Annual Meeting*, 25(1):604–606, 1981. doi: 10.1177/1071181381025001159

[12] C. Grout, W. Rogers, M. Apperley, and S. Jones. Reading text in an immersive head-mounted display: An investigation into displaying desktop interfaces in a 3d virtual environment. In *Proceedings of the 15th New Zealand Conference on Human-Computer Interaction*, CHINZ 2015, p. 9–16. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2808047.2808055

[13] A. Helgert, A. Groeneveld, and S. C. Eimler. A qualitative analysis of interaction techniques in a virtual reality instruction environment: Experiences from a case study. In *2022 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, pp. 171–175, 2022. doi: 10.1109/AIVR56993.2022.00034

[14] M. Hirota, H. Kanda, T. Endo, T. Miyoshi, S. Miyagawa, Y. Hirohara, T. Yamaguchi, M. Saika, T. Morimoto, and T. Fujikado. Comparison of visual fatigue caused by head-mounted display for virtual reality and two-dimensional display using objective and subjective evaluation. *Ergonomics*, 62(6):759–766, 2019. PMID: 30773103. doi: 10.1080/00140139.2019.1582805

[15] M. C. Howard and M. M. Davis. A meta-analysis and systematic literature review of mixed reality rehabilitation programs: Investigating design characteristics of augmented reality and augmented virtuality. *Computers in Human Behavior*, 130:107197, 2022. doi: 10.1016/j.chb.2022.107197

[16] J. A. Jones, J. E. Swan, G. Singh, E. Kolstad, and S. R. Ellis. The effects of virtual reality, augmented reality, and motion parallax on egocentric depth perception. In *Proceedings of the 5th Symposium on Applied Perception in Graphics and Visualization*, APGV '08, p. 9–14. Association for Computing Machinery, New York, NY, USA, 2008. doi: 10.1145/1394281.1394283

[17] J. Kawai, H. Mitsuhara, and M. Shishibori. Tsunami evacuation drill system using motion hazard map and smart devices. In *2016 3rd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*, pp. 1–7, 2016. doi: 10.1109/ICT-DM.2016.7857221

[18] E. Klopfer and K. Squire. Environmental detectives—the development of an augmented reality platform for environmental simulations. *Educational Technology Research and Development*, 56(2):203–228, 2007. doi: 10.1007/s11423-007-9037-6

[19] T. Kojić, D. Ali, R. Greinacher, S. Möller, and J.-N. Voigt-Antons. User experience of reading in virtual reality — finding values for text distance, size and contrast. In *2020 Twelfth International Conference on Quality of Multimedia Experience (QoMEX)*, pp. 1–6, 2020. doi: 10.1109/QoMEX48832.2020.9123091

[20] R. Langner, M. Satkowski, W. Büschel, and R. Dachselt. Marvis: Combining mobile devices and augmented reality for visual data analysis. In *Proceedings of the 2021 ACM Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 5 2021. doi: 10.1145/3411764.3445593

[21] B. Lawton and F. Maurer. A case for enhancing uav ground control stations with cross reality. In *AVI'22 Workshop Proceedings: "ENHANCING CROSS-REALITY APPLICATIONS AND USER EXPERIENCES"*, 2022.

[22] G. A. Lee, J. Chen, M. Billinghurst, and R. Lindeman. Enhancing immersive cinematic experience with augmented virtuality. In *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*, pp. 115–116, 2016. doi: 10.1109/ISMAR-Adjunct.2016.0054

[23] Y.-H. LEE, T. ZHAN, and S.-T. WU. Prospects and challenges in augmented reality displays. *Virtual Reality Intelligent Hardware*, 1(1):10–20, 2019. doi: 10.3724/SP.J.2096-5796.2018.0009

[24] C. Ling, A. Stegman, C. Barhbaya, and R. Shehab. Are two better than one? a comparison between single- and dual-monitor work stations in productivity and user's windows management style. *International Journal of Human–Computer Interaction*, 33(3):190–198, 2017. doi: 10.1080/10447318.2016.1231392

[25] R. Lovreglio and M. Kinateder. Augmented reality for pedestrian evacuation research: Promises and limitations. *Safety Science*, 128:104750, 2020. doi: 10.1016/j.ssci.2020.104750

[26] J. Mayer, S. Auer, J. Friedl, and C. Anthes. Volumetric data interaction in ar and vr using a handheld touch-sensitive device. In H.-C. Jetter, J.-H. Schröder, J Gugenheimer, M. Billinghurst, C. Anthes, M. Khamis, and T. Feuchtner, eds., *ISS'21 Workshop Proceedings: "Transitional Interfaces in Mixed and Cross-Reality: A new frontier?"*, 2021. doi: 10.18148/kops/352-2-1qsz0ws7eufba2

[27] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino. Augmented reality: A class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies*, 2351, January 1994. doi: 10.1117/12.197321

[28] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino. Augmented reality: a class of displays on the reality-virtuality continuum. In H. Das, ed., *Telemanipulator and Telepresence Technologies*, vol. 2351, pp. 282 – 292. International Society for Optics and Photonics, SPIE, 1995. doi: 10.1117/12.197321

[29] M. Neges, S. Adwernat, and M. Abramovici. Augmented virtuality for maintenance training simulation under various stress conditions. *Procedia Manufacturing*, 19:171–178, 2018. Proceedings of the 6th International Conference in Through-life Engineering Services, University of Bremen, 7th and 8th November 2017. doi: 10.1016/j.promfg.2018.01.024

[30] J. Ping, Y. Liu, and D. Weng. Comparison in depth perception between virtual reality and augmented reality systems. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1124–1125, 2019. doi: 10.1109/VR.2019.8798174

[31] F. Pointecker, J. Friedl, D. Schwajda, H.-C. Jetter, and C. Anthes. Bridging the gap across realities: Visual transitions between virtual and augmented reality. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 827–836, 2022. doi: 10.

1109/ISMAR55827.2022.00101

[32] H. Regenbrecht, C. Ott, M. Wagner, T. Lum, P. Kohler, W. Wilke, and E. Mueller. An augmented virtuality approach to 3d videoconferencing. In *The Second IEEE and ACM International Symposium on Mixed and Augmented Reality, 2003. Proceedings.*, pp. 290–291, 2003. doi: 10.1109/ISMAR.2003.1240725

[33] P. Reipschlager, T. Flemisch, and R. Dachselt. Personal augmented reality for information visualization on large interactive displays. *IEEE Transactions on Visualization and Computer Graphics*, 27(2):1182–1192, 2021. doi: 10.1109/TVCG.2020.3030460

[34] A. Riegler, C. Anthes, H.-C. Jetter, C. Heinzl, C. Holzmann, H. Jodlbauer, M. Brunner, S. Auer, J. Friedl, B. Fröhler, C. Leitner, F. Pointecker, D. Schwajda, and S. Tripathi. Cross-virtuality visualization, interaction and collaboration. In *Proceedings of the 1st ACM International Workshop on Cross-Reality Interaction*. ACM, 2020.

[35] J. Rolland, R. Holloway, and H. Fuchs. Comparison of optical and video see-through, head-mounted displays. *Proceedings of SPIE - The International Society for Optical Engineering*, 01 1994. doi: 10.1117/12.197322

[36] J. S. Roo and M. Hachet. One reality: Augmenting how the physical world is experienced by combining multiple mixed reality modalities. UIST '17, p. 787–795. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3126594.3126638

[37] D. Schwajda, J. Friedl, F. Pointecker, H.-C. Jetter, and C. Anthes. Transforming graph data visualisations from 2d displays into augmented reality 3d space: A quantitative study. *Frontiers in Virtual Reality*, 4, 2023. doi: 10.3389/frvir.2023.1155628

[38] F. Schwarz and W. Fastenmeier. Visual advisory warnings about hidden dangers: Effects of specific symbols and spatial referencing on necessary and unnecessary warnings. *Applied Ergonomics*, 72:25–36, 2018. doi: 10.1016/j.apergo.2018.05.001

[39] W. R. Sherman and A. B. Craig. Chapter 4 - input: Interfacing the participant(s) with the virtual world. In W. R. Sherman and A. B. Craig, eds., *Understanding Virtual Reality (Second Edition)*, The Morgan Kaufmann Series in Computer Graphics, pp. 190–256. Morgan Kaufmann, Boston, second edition ed., 2018. doi: 10.1016/B978-0-12-800965-9.00004-0

[40] K. T. Simsarian and K.-P. Åkesson. Windows on the world: An example of augmented virtuality. 1997.

[41] R. Skarbez, N. F. Polys, J. T. Ogle, C. North, and D. A. Bowman. Immersive analytics: Theory and research agenda. *Frontiers in Robotics and AI*, 6, 2019. doi: 10.3389/frobt.2019.00082

[42] Y. Tai, Y. Yang, and X. Wang. Development of vr motion sickness test platform based on ue. In *2022 International Conference on Culture-Oriented Science and Technology (CoST)*, pp. 169–173, 2022. doi: 10.1109/CoST57098.2022.00043

[43] D. van Krevelen and R. Poelman. A survey of augmented reality technologies, applications and limitations. *International Journal of Virtual Reality*, 9(2):1–20, Jan. 2010. doi: 10.20870/IJVR.2010.9.2.2767

[44] N. Wang and F. Maurer. Challenges of single-user cross reality applications. In *AVI'22 Workshop Proceedings: "ENHANCING CROSS-REALITY APPLICATIONS AND USER EXPERIENCES"*, 2022.

[45] N. Wang and F. Maurer. A design space for single-user cross-reality applications. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces*, AVI 2022. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3531073.3531116

[46] C. Ware. Chapter seven - space perception. In C. Ware, ed., *Information Visualization (Fourth Edition)*, Interactive Technologies, pp. 245–296. Morgan Kaufmann, fourth edition ed., 2021. doi: 10.1016/B978-0-12-812875-6.00007-4

[47] R. Yates. Web site accessibility and usability: Towards more functional sites for all. *Campus-Wide Information Systems*, 22(4):180–188, 2005. doi: 10.1108/10650740510617494