Original Article

Comparative Analysis of Augmented Reality Devices for Surgical Applications

Alexis Bader[1,2,3], Yao Li[2,3], Sergey Drobinsky[4], Matías de la Fuente[4], Jan Egger[5], Behrus Puladi[2,3,✉]

1 Department of Systems Engineering, University of Waterloo, Canada
2 Department of Oral and Maxillofacial Surgery, University Hospital RWTH Aachen, Aachen, Germany
3 Institute of Medical Informatics, University Hospital RWTH Aachen, Aachen, Germany
4 Chair of Medical Engineering, RWTH Aachen University, Aachen, Germany
5 Institute for Artificial Intelligence in Medicine, Essen University Hospital, Essen, Germany

[✉]**Corresponding author:**
Dr. med. Dr. med. dent. Behrus Puladi
E-mail: bpuladi@ukaachen.de
Tel.: +49-241-80-38389
Fax: +49-241-80-82430
Department of Oral and Maxillofacial Surgery & Institute of Medical Informatics,
University Hospital RWTH Aachen,
Pauwelsstraße 30, 52074 Aachen, Germany

Key words: Augmented Reality (AR), Head Mounted Display (HMD), Depth Perception, Resolution, Contrast Detection

Abstract:
Augmented Reality (AR) Head Mounted Displays (HMDs) hold promise in revolutionizing surgical procedures by providing enhanced visualization and information overlay capabilities. This study evaluates and compares Optical See-Through (OST) and Video See-Through (VST) AR devices across key performance metrics crucial for surgical applications: depth perception, passthrough quality, and resolution. Four current state-of-the-art HMDs, including the Microsoft HoloLens 2, Apple Vision Pro, Meta Quest 3, and Varjo XR3, were tested using standardized methodologies in Unity software. Resolution testing indicated comparable performance across all devices, with the Varjo XR3 achieving only a slightly higher ability to render finely detailed projections. However, the depth perception and contrast detection tests revealed significant variability among devices, with the Apple Vision Pro demonstrating superior accuracy compared to the Varjo XR3, Meta Quest 3, and Microsoft HoloLens 2. Based on these findings, the Apple Vision Pro is concluded to be best suited for surgical applications, excelling in depth perception and contrast detection while maintaining high resolution. Further research expanding device comparisons and participant numbers will enhance understanding and applicability in surgical environments.

Introduction

Motivation

As the field of Augmented Reality (AR) gains attention, a diverse array of AR Head Mounted Displays (HMD) is emerging, each with capabilities suited to a wide range of applications. Particularly in healthcare, there exists a great potential for these tools to enhance surgical procedures, providing surgeons with a convenient display of relevant information in effort to improve patient outcomes (Taghian et al., 2023).

AR devices can be broadly categorized into Optical See-Through (OST) and Video See-Through (VST) systems (Debernardis et al., 2014). OST devices use transparent displays to project images directly into the user's line of sight, allowing for a natural view of the physical environment with superimposed digital information. In contrast, VST devices utilize cameras to capture the real world and display it on a screen, merging it with virtual elements (Debernardis et al., 2014).

At the current state of AR hardware capabilities, achieving a perfect display in all regards is not yet possible (Zhan et al., 2020). AR technology introduces various inaccuracies in both passthrough quality and the performance of virtual projections (Xia et al., 2022). However, different AR devices specialize in distinct areas, allowing some to outperform others in specific categories (Qian et al., 2017). For medical applications, particularly in surgery, it is crucial that an AR device enhances a surgeon's practice without impeding their natural capabilities. Therefore, several key factors must be upheld by the device to ensure it is beneficial in a surgical setting.

One of the most important aspects of an augmented reality device is depth perception, which is crucial in many surgical applications (El Jamiy & Marsh, 2019). For example, in reviews of AR applications in neurosurgery and orthopaedic surgery, the most common application of AR technology serves as a navigation system for screw placement, a task identified as critically dependent on accurate depth perception (Azad et al., 2024; Casari et al., 2021). It is important the surgeon maintains an accurate perception of the placement of virtual objects, especially relevant with concern to close-range accuracy (Martin-Gomez et al., 2022). For both OST and VST devices, measuring the accuracy of interpreting virtual objects in the projected space is crucial to determine their reliability in surgical contexts.

Furthermore, a significant factor of AR technology is the contrast and color sensitivity of the physical world (Livingston et al., 2013). It is crucial that the passthrough of the physical environment, particularly in low-contrast scenarios common in surgical settings, is clear enough to detect intricate details. Surgeons must be able to discern small differences in contrast to identify bodily structures or interpret diagnostic scans, which is essential for effective decision-making in the operating room (OR) (Qian et al., 2017). Therefore, evaluating the variations in environment visibility across different AR HMDs is essential for selecting the most suitable devices for surgical use.

Lastly, a crucial attribute of a HMD used in surgery is its resolution, which must be capable of accurately rendering small structures and intricate images without error. Many hardware dependent factors impact the perceived display quality of virtual projections, including field of view (FOV), pixel density, and brightness (Zhan et al., 2020). These features can affect the visibility of small projections, which may be further impacted by other factors including the contrast and color of the background environment (Livingston et al., 2013). In a surgical setting, where detailed imagery is essential for visualizing intricate vasculature and nervous structures, any deficiencies in the device's ability to render thin projections from different orientations could be problematic (Ezer et al., 2021). Therefore, it is imperative to evaluate whether an HMD can consistently render detailed images accurately, regardless of orientation, to ensure it meets the demands of surgical applications.

State of the art

Since depth estimation is one of the most important qualities in simulating and interacting in a natural way in virtual and augmented realities, there have been several studies which investigate this topic. (Fischer et al., 2020) conducted a study measuring the positioning of a virtual object with reference to a 3D printed model. It was found that the position was statistically similar in the horizontal and vertical axis's but exhibited a statistically significant misalignment in the perception of depth for all types of renderings tested. This result is consistent across many studies, and it is accepted that virtual projections in mixed reality systems do not display the all the necessary cues to accurately perceive depth in OST or VST (Martin-Gomez et al., 2022).

While there exists a higher number of studies which compare Virtual Reality (VR) and AR systems for attributes such as depth perception (Kyaw et al., 2023; Westermeier et al., 2024; Wu & Kim, 2022), purely AR systems have been less studied (El Jamiy & Marsh, 2019). Studies comparing OST and VST AR systems have been conducted, however, as pointed out by (Adams et al., 2022) results of these studies, especially in reference to evaluations of depth, are inconclusive. Specifically, while a higher number of studies conclude an underestimation of virtual objects in OST and VST scenarios, numerous studies also contrastingly conclude that there is a consistent overestimation of virtual objects (Adams et al., 2022).

Furthermore, various studies on the use of AR in medicine have identified visualization as the area most in need of improvement (Villagran-Vizcarra et al., 2023). The display capabilities of AR devices remain a significant bottleneck in the real-life implementation of these systems in medical applications (Casari et al., 2021). Therefore, this aspect is crucial in the review of HMD AR devices. For both optical see-through (OST) and video see-through (VST) devices, virtual projections must be displayed with sufficient resolution to provide detailed information to the user.

Contrast perception has been previously studied to assess the suitability of AR devices for surgical use, with findings highlighting this as a critical area for improvement (Shenai et al., 2011). This is particularly relevant to VST devices, which can introduce inaccuracies in the environment through both the camera and display. For example, in a study of a remote surgery system, color contrast was identified as a technical issue needing further development, thus, the ability of HMD AR devices to handle contrast perception is particularly valuable for evaluating their feasibility in surgical applications (Shenai et al., 2011).

The knowledge gap existing

There are very few studies comparing various state-of-the-art Optical See-Through (OST) and Video See-Through (VST) devices to evaluate depth and other performance metrics within the same category of see-through devices (Qian et al., 2017). This gap in current knowledge is significant, as it would be valuable to determine if there are substantial performance differences between various VST and OST devices, especially given their vastly different price points. Such insights could guide purchasing decisions for AR surgical aids, particularly those focusing on depth estimates, low contrast environments, or high-resolution rendering.

Additionally, to our knowledge no studies currently compare the contrast perception of the pass-through capabilities of VST and OST devices specifically with the color schemes present in surgical settings. While there are studies that test contrast perception in greyscale for OST devices (Qian et al., 2017), these are less applicable to surgical applications. Each OST and VST device have significantly different display color profiles, making this aspect of the investigation not only more interesting but also far more useful for surgical applications. Understanding how each device handles the intricate and specific color contrasts found in operating rooms is critical for optimizing their use in surgical procedures.

Furthermore, there have been no studies conducted using the Apple Vision Pro for depth, contrast or resolution evaluation. Thus, this study aims to determine a benchmark of suitability for a surgical application of this device against more heavily researched devices. The Apple Vision Pro, being the newest and a promising device, warrants particular attention in this evaluation.

Ultimately, understanding the differences of each device will inform the selection of the most appropriate AR HMDs for surgical applications. This study aims to systematically evaluate and compare the key attributes of various OPT and DST AR HMDs by answering the following questions:

1.) Are there any differences in the depth perception of current HMD devices?
2.) Are there any differences in the see-through function of current HMD devices?
3.) Are there any differences in the resolution of finely detailed virtual projections of current HMD devices?

Material and Methods

Hardware

Four MR HMDs were compared in this study. Three VST and one OST devices was used with specifications listed in Table 1.

Table 1. Hardware specifications of each headset

Device	OST/VST	Resolution (Pixels)	Memory (RAM)	Camera	Base Model Price at launch (USD)
Microsoft HoloLens 2	OST	2048 x 1365	4-GB	Dual 8-MP	$3500
Apple Vision Pro	VST	3660 x 3200	16 GB	Dual 6.5-MP	$3499
Meta Quest 3	VST	2,064 x 2,208	8 GB	Dual 4-MP	$499

Varjo XR3	VST	Focus area: 1920 x 1920 Peripheral: 2880 x 2720	Minimum 32 GB RAM computer required	Dual 12-MP	$5995

Software

Unity version 2022.3.30 was used to create a base program using the Mixed Reality Template for all devices.

Depth Perception Test

In applications where a virtual image is overlayed on the surgical scene, (Martin-Gomez et al., 2022) uses a distance of 52-78 cm from the surgeon for virtual projections. Thus, the depth perception of virtual projections was tested in a close range view (<1 m from the Virtual Unity camera), as this best simulates the use case of the AR in a surgical context. Two 3D virtual objects 10 cm in width appeared in front of the participant. The subjects remained stationary and were confined to view the objects from the front view of the objects. The object on the left acted as a target object, which was spawned randomly between 30 cm and 100 cm away from the participant in each iteration. The blue moveable object, as seen in Figure 1, was spawned consistently 40 cm away from the participants. With a keyboard, the participants adjusted the moveable object forward or backwards to align the two objects. This protocol was repeated for various shaped objects, including a cube, sphere and cylinder. The Z-axis position of each object was recorded from Unity and saved into a csv file.

(a) (b) (c)

Figure 1. Depth Alignment test with cubes (a), spheres (b), and cylinders (c)

Resolution Test

Three groups of adjacent lines, orientated horizontally, vertically, and at a 45-degree angle were displayed 100 cm in front of the participant at an initial thickness of 1 cm as seen in Figure 2. Using a keyboard, the participant adjusted the thickness to the minimum thickness at which the lines were still visible without visual defects. Visual defects were defined as breaks in the line or significant instability of the projection. This protocol was repeated for each line group, and the thickness of each line was recorded into a csv file.

(a) (b) (c)

Figure 2. Resolution test with horizontal lines (a), diagonal lines (b), and vertical lines (c)

Contrast Test

Using an image from a neck surgery from Section 4 of the Atlas of Surgical Techniques in Trauma from Cambridge University Press (https://www.cambridge.org/core/books/abs/atlas-of-surgical-techniques-in-trauma/neck/1EA13898BFCDB48D0C71148EFAE963EC), a color palette was created to reflect common colors involved in standard maxillofacial surgical procedures as seen in Figure 3 (a). Twenty images of four random letters with color combinations from this palette were printed and shown to the participant while wearing the HMD device as seen in Figure 3 (b) and (c). In a protocol adapted from Qian et al., the participant was asked to read the letters seen on the paper and was scored on the accuracy of their verbal reporting (Qian et al., 2017). If there was an error in any of the four letters on the image, the trial was recorded as a failure, as the visibility would not be suited for use during a surgical procedure.

(a) (b) (c)

Figure 3. The color palette was extracted from the surgical image (a) and used to create various images of random letters with these colors (b). The images were printed and viewed through the HMD devices (c).

Procedure

The investigation included each of the three tests (depth, resolution and contrast), for each of the four HMD devices (AVP, Meta Quest, HoloLens, and Varjo), for two participants. For devices which require eye calibration (Apple Vision Pro, Varjo XR3, HoloLens 2), the calibration was completed for each participant. For the depth test, each 3-D object alignment task was repeated five times, resulting in a total of fifteen alignment trials per participant. Similarly, for the resolution test, each line orientation minimization was repeated five times, leading to a total of fifteen tests per participant for this section. For the contrast test, participants were shown five images of random letter and colour combinations, with each image containing four letters counted as one trial. This procedure was repeated for each of the four devices in a random order for each participant to avoid ordering effects.

Figure 4. The setup of a participant for the test with Meta Quest 3 and keyboard.

Results

Depth Perception Test

The results of the depth perception portion of the investigation are shown in Figure 5. The illustration depicts the average absolute depth error for each moveable object and is separated for each device tested. The AVP had the lowest mean absolute error of 0.572 cm, followed by the Meta Quest 3 (1.58 cm), the HoloLens 2 (1.66 cm), and the Varjo XR3 (2.88 cm). A single factor ANOVA analysis (α=0.05) was conducted for the results to determine if there exists a statistical difference between the devices for average absolute depth error. It was found that there exists a significant difference between the means of each device (F= 12.04, p=0.0024), thus, the null hypothesis is rejected. A Fisher LSD test further reveals that there is a significant difference between all group means except for the Meta Quest 3 and the HoloLens devices.

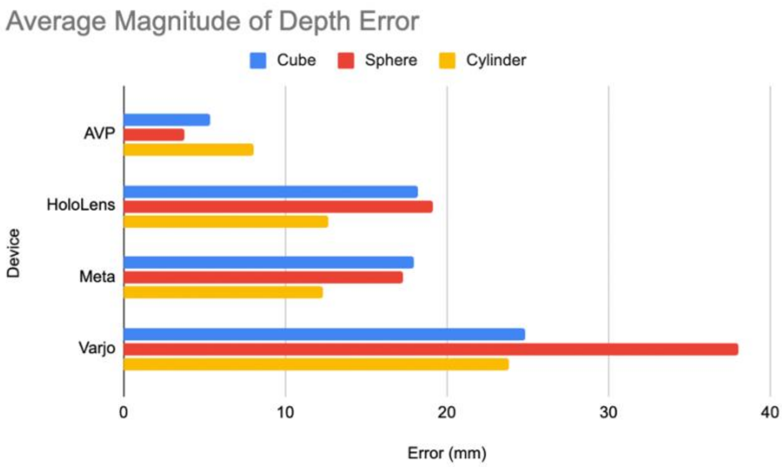

Figure 5. Magnitude of relative depth error of each moveable and target object depth for each device.

Resolution Test

The results from the resolution test are shown in Figure 6. The illustration depicts the minimum visible line thickness for each orientation of line grouping, separated for each device tested. The Varjo XR3 has the lowest mean minimum thickness required of 0.052 cm, followed by the HoloLens 2 (0.0652 cm), the Apple Vision Pro (0.0671 cm), and the Meta Quest 3 (0.105 cm). A single factor ANOVA analysis (α=0.05) was conducted for the results to determine if there exists a statistical difference between the devices for the minimum line thickness able to be displayed. It was found that there is not a significant difference between means of each device (F=3.179, p=0.0847), thus, the null hypothesis is accepted.

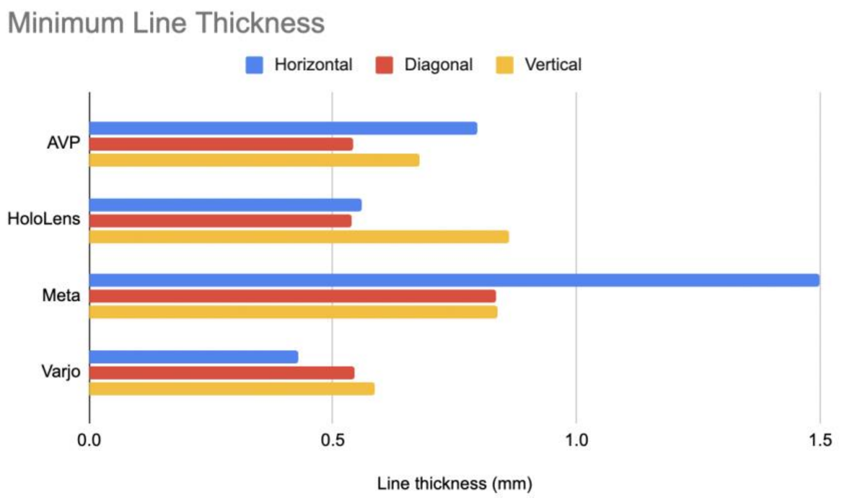

Figure 6. Minimum visible line thickness for each line orientation for each device.

The results from the contrast test are shown in Figure 7. The illustration depicts the percent correctness of letter reporting and is separated for each device tested. The device with the highest percentage of correct trails was the AVP at 100% accuracy, followed by the Varjo at 90%, HoloLens at 80%, and Meta Quest at 50%.

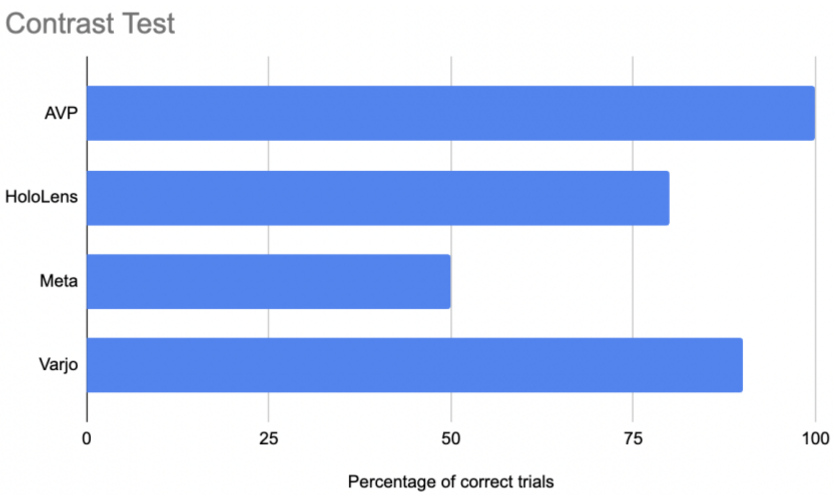

Figure 7. Percent correctness of letter reporting for each device.

Discussion

The results of the depth perception test reveal notable differences among the devices in their ability to perceive depth of visual projections on the display. This factor is crucial in selecting a device for surgical applications where accurate depth perception is essential. The Apple Vision Pro demonstrates superior depth perception capabilities, while the Varjo XR3 shows the lowest ability in this regard. The Meta Quest and HoloLens perform similarly, falling between the Apple Vision Pro and Varjo XR3. Given that the HoloLens performs in the middle range among the devices, it suggests that there is no superiority between OST and VST devices for depth perception and this is more dependent on other hardware factors. Therefore, it cannot be definitively concluded that one type of device is inherently better than the other solely based on depth perception performance. These results are comparable with the results of similar depth perception studies. For instance, in a study comparing the absolute depth of virtual objects with the HoloLens 2 and the Varjo XR3, it was observed that participants underestimated distances 24% with the HoloLens and 29% with the Varjo (Bodenheimer et al., 2023). The superiority of the HoloLens over Varjo XR3 is once again confirmed by (Adams et al., 2022), and consistent with the results of this investigation. However, in a study evaluating the alignment of a physical object with a virtual projection on the HoloLens 2 and HTC Vive Pro, the Vive device outperformed the HoloLens (Martin-Gomez et al., 2022). Although the HTC was not evaluated in this investigation, other VST devices were evaluated and similarly outperformed the HoloLens in terms of accuracy of depth perception. Thus, both the results from this investigation and others support the fact that the HoloLens 2 is better than the Varjo XR3 in terms of depth perception abilities, but not as capable as other VST devices in this area.

Results from the resolution test indicate that all devices have a comparable ability to display complex projections in any orientation. Since all devices exhibited similar performance, this suggests that resolution is not the most critical factor in determining the best device for surgical applications, as they are on a relatively similar level. This result is interesting when examining the hardware specifications of each device, as they vary significantly in their pixel count on the display. Specifically, the Apple Vision Pro has a resolution of 3660 x 3200 while the Meta Quest 3 only has a count of 2,064 x 2,208, yet they perform similarly in this test. This could be explained by the aforementioned factors by (Livingston et al., 2013) which may affect the ability to detect small projections, such as the color profile and contrast of the line with the background. Although the environment lighting, color of the lines, as well as the background remained consistent throughout the investigation, the individual cameras and display of each device may have a larger effect on the ability to perceive small details in projections rather than the resolution of the screen itself.

The results of the contrast detection test reveal significant differences among the devices in their ability to detect color in varying levels of contrast, which is a critical consideration for selecting devices in surgical applications. Despite the HoloLens being an OST modality, it did not perform the best in contrast detection. This suggests that VST devices may offer advantages in enhancing the detection of subtle color differences through their color display capabilities. Therefore, similarly, it cannot be definitively concluded whether VST or OST devices are superior overall in this regard. However, for applications requiring precise detection of minute color differences, the Apple Vision Pro emerges as the most suitable option, while the Meta Quest 3 is the least.

Conclusion

With a wide range of available AR HMDs, each offering unique advantages and disadvantages, it is essential to identify which is best suited for specific applications. For surgical use, the key factors for optimal suitability are accurate depth perception, contrast detection, and high resolution. Among the four AR HMD devices evaluated in this study, the Apple Vision Pro proved to be the most suitable for surgical applications. It significantly outperforms the other devices in simulating accurate depth cues, allowing users to better perceive the depth of objects in the virtual space. Although the AVP does not show a significant difference in resolution compared to other devices, it achieves a perfect score on the contrast detection test. This ensures that surgeons have near-perfect visibility of their surgical field while also benefiting from high-resolution virtual projections. Additionally, as a mid-range device priced at $3500 USD, the AVP is relatively accessible for use in research and development settings. Future research will expand upon this study protocol by increasing the number of participants and including a broader range of OST AR devices. This approach aims to enhance the generalizability of findings and enable more robust conclusions regarding both VST and OST devices in surgical applications.

References

Adams, H., Stefanucci, J., Creem-Regehr, S., & Bodenheimer, B. (2022). Depth Perception in Augmented Reality: The Effects of Display, Shadow, and Position. *Proceedings - 2022 IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2022*. https://doi.org/10.1109/VR51125.2022.00101

Azad, T. D., Warman, A., Tracz, J. A., Hughes, L. P., Judy, B. F., & Witham, T. F. (2024). Augmented reality in spine surgery – past, present, and future. In *Spine Journal* (Vol. 24, Issue 1). https://doi.org/10.1016/j.spinee.2023.08.015

Bodenheimer, B., Adams, H., Whitaker, M., Stefanucci, J., & Creem-Regehr, S. (2023). Perceiving Absolute Distance in Augmented Reality Displays with Realistic and Non-realistic Shadows. *Proceedings - SAP 2023: ACM Symposium on Applied Perception*. https://doi.org/10.1145/3605495.3605800

Casari, F. A., Navab, N., Hruby, L. A., Kriechling, P., Nakamura, R., Tori, R., de Lourdes dos Santos Nunes, F., Queiroz, M. C., Fürnstahl, P., & Farshad, M. (2021). Augmented Reality in Orthopedic Surgery Is Emerging from Proof of Concept Towards Clinical Studies: a Literature Review Explaining the Technology and Current State of the Art. In *Current Reviews in Musculoskeletal Medicine* (Vol. 14, Issue 2). https://doi.org/10.1007/s12178-021-09699-3

Debernardis, S., Fiorentino, M., Gattullo, M., Monno, G., & Uva, A. E. (2014). Text readability in head-worn displays: Color and style optimization in video versus optical see-through devices. *IEEE Transactions on Visualization and Computer Graphics*, *20*(1). https://doi.org/10.1109/TVCG.2013.86

El Jamiy, F., & Marsh, R. (2019). Survey on depth perception in head mounted displays: Distance estimation in virtual reality, augmented reality, and mixed reality. In *IET Image Processing* (Vol. 13, Issue 5). https://doi.org/10.1049/iet-ipr.2018.5920

Ezer, M., Aydoğan, T. B., & Huri, E. (2021). Urologic surgery in digital era: Foresights and futuristic approach. *Balkan Medical Journal*, *38*(6). https://doi.org/10.5152/balkanmedj.2021.21957

Fischer, M., Leuze, C., Perkins, S., Rosenberg, J., Daniel, B., & Martin-Gomez, A. (2020). Evaluation of Different Visualization Techniques for Perception-Based Alignment in Medical AR. *Adjunct Proceedings of the 2020 IEEE International Symposium on Mixed and Augmented Reality, ISMAR-Adjunct 2020*. https://doi.org/10.1109/ISMAR-Adjunct51615.2020.00027

Kyaw, N., Gu, M., Croft, E., & Cosgun, A. (2023). Comparing Usability of Augmented Reality and Virtual Reality for Creating Virtual Bounding Boxes of Real Objects. *Applied Sciences (Switzerland)*, *13*(21). https://doi.org/10.3390/app132111693

Livingston, M. A., Gabbard, J. L., Swan, J. E., Sibley, C. M., & Barrow, J. H. (2013). Basic Perception in Head-Worn Augmented Reality Displays. In *Human Factors in Augmented Reality Environments*. https://doi.org/10.1007/978-1-4614-4205-9_3

Martin-Gomez, A., Weiss, J., Keller, A., Eck, U., Roth, D., & Navab, N. (2022). The Impact of Focus and Context Visualization Techniques on Depth Perception in Optical See-Through Head-Mounted Displays. *IEEE Transactions on Visualization and Computer Graphics*, *28*(12). https://doi.org/10.1109/TVCG.2021.3079849

Qian, L., Barthel, A., Johnson, A., Osgood, G., Kazanzides, P., Navab, N., & Fuerst, B. (2017). Comparison of optical see-through head-mounted displays for surgical interventions with object-anchored 2D-display. *International Journal of Computer Assisted Radiology and Surgery*, *12*(6). https://doi.org/10.1007/s11548-017-1564-y

Shenai, M. B., Dillavou, M., Shum, C., Ross, D., Tubbs, R. S., Shih, A., & Guthrie, B. L. (2011). Virtual interactive presence and augmented reality (VIPAR) for remote surgical assistance. *Neurosurgery*, *68*(SUPPL. 1). https://doi.org/10.1227/NEU.0b013e3182077efd

Taghian, A., Abo-Zahhad, M., Sayed, M. S., & Abd El-Malek, A. H. (2023). Virtual and augmented reality in biomedical engineering. In *BioMedical Engineering Online* (Vol. 22, Issue 1). https://doi.org/10.1186/s12938-023-01138-3

Villagran-Vizcarra, D. C., Luviano-Cruz, D., Pérez-Domínguez, L. A., Méndez-González, L. C., & Garcia-Luna, F. (2023). Applications Analyses, Challenges and Development of Augmented Reality in Education, Industry, Marketing, Medicine, and Entertainment. In *Applied Sciences (Switzerland)* (Vol. 13, Issue 5). https://doi.org/10.3390/app13052766

Westermeier, F., Brubach, L., Wienrich, C., & Latoschik, M. E. (2024). Assessing Depth Perception in VR and Video See-Through AR: A Comparison on Distance Judgment, Performance, and Preference. *IEEE Transactions on Visualization and Computer Graphics*, *30*(5). https://doi.org/10.1109/TVCG.2024.3372061

Wu, Y. F., & Kim, E. Y. (2022). Users' Perceptions of Technological Features in Augmented Reality (AR) and Virtual Reality (VR) in Fashion Retailing: A Qualitative Content Analysis. *Mobile Information Systems*, *2022*. https://doi.org/10.1155/2022/3080280

Xia, X., Guan, F. Y., Cai, Y., & Magnenat Thalmann, N. (2022). Challenges and Advancements for AR Optical See-Through Near-Eye Displays: A Review. In *Frontiers in Virtual Reality* (Vol. 3). https://doi.org/10.3389/frvir.2022.838237

Zhan, T., Yin, K., Xiong, J., He, Z., & Wu, S. T. (2020). Augmented Reality and Virtual Reality Displays: Perspectives and Challenges. In *iScience* (Vol. 23, Issue 8). https://doi.org/10.1016/j.isci.2020.101397