The Criticality of Human-Computer Interaction/Human-Machine Interaction for Healthcare

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ABSTRACT

As advanced technology continues to permeate the Department of Defense and healthcare simulation enterprises, virtual reality systems coupling head mounted display systems with advanced commercial rendering have transitioned from entertainment applications to powerful tools for serious applications in modeling, simulation, and training. Caution is warranted prior to adoption of the technology, as human-computer interactions and human-machine interactions are arguably more critical in the design and development of these systems given the users' full immersion in these digital environments. Inadequate testing and validation can potentially lead to negative training, so care must be taken to ensure accurate representation of both the environment and the users' interaction with it. The software and hardware systems need to be developed and tested using best practice methods for human-machine interaction and human-computer interaction. The authors will discuss the research and application of human-machine interaction and human-computer interaction to ensure that a virtual reality system intended to be used as Software as a Medical Device is sufficient for its intended use. Despite the growing use of 3-Dimensional (3D) displays and visualization, current standards for healthcare displays are based on traditional 2-Dimensional (2D) monitors. The authors discuss their derived methods and testing to ensure distortion compliance with the American College of Radiology Technical Standard for Electronic Practice of Medical Imaging for a virtual reality system. This paper describes head mounted display hardware testing to characterize distortion to ensure that system preserves and presents accurate, clear 3D representations. The authors conclude with a summary of the impacts of the test results and methods for the healthcare community and wider simulation and training communities.

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INTRODUCTION

Human-Computer Interaction (HCI) is the study of the interaction between humans (i.e., users) and computers (i.e., technology) with a focus on the design of the interactive technology. Examples of HCI include Natural Language Processing applications, such as Amazon's Alexa or Apple's Siri, augmented reality, and Virtual Reality (VR) technologies, that allow for immersive interaction between the user and the digital world. Human-Machine Interaction (HMI) is the hardware or software through which a user interacts with a system. Examples of modern HMIs include touch display panels, mobile devices, and VR. The integration of advanced technologies, such as VR, into a multitude of industries with non-traditional users has resulted in a greater criticality for the optimization of HCI and HMI.

Despite VR being first introduced in the 1960s, the popularity of VR has started to grow within the last decade as the technology, affordability, and accessibility have improved for the common consumer. VR systems use Head Mounted Displays (HMDs) that have also become more popular and available. Despite VR being initially marketed towards the entertainment and gaming industries, the technological applications of VR have advanced such that they can be applied to a variety of industries including education, training, simulation, and healthcare. With these additional, non-traditional applications, there is a lack of general understanding of the strengths and limitations of VR (Hamad, 2022). One of the key technical limitations includes the lack of technical standardization that can limit the effectiveness of VR in certain applications.

VR systems that use HMD systems have been slower to adopt for non-entertainment applications in modeling, simulation, and training. Pettey is quoted as saying, "The biggest barrier to wide adoption of immersive technologies is the lack of good user experience design" (2018). In the healthcare and defense industries, HCI/HMI are more critical in the design and development phase given the users' full immersion into these digital environments. Analyzing the quality and performance of the hardware interfacing with the user is crucial to evaluate the concerns from reluctant industries to better understand the interactions between the user and the technology in applications such as VR. HCI/HMI play an important role in the adoption of VR in the training and simulation communities, so the evaluation and characterization of a VR HMD provides informative results to address the concerns.

PRIOR RESEARCH

Applications of Virtual Reality

As a technology, VR has made significant leaps in its evolution, but even more substantial testing and research must occur before VR can be fully utilized in several purposes. The current software and hardware that comprise VR systems have been evaluated to better understand the limitations for its appropriate use. A literary review was performed to assess how different types of VR applications can be utilized along with advantages and disadvantages of each. Applications such as driving simulations, education, public health, and medical training each have the potential to be greatly benefited by the incorporation of VR. As more VR application scenarios are being developed by subject matter experts from different fields, VR can become the next big technological turning point (Hamad & Jia, 2022).

Integrated (Biometric) Sensors

The success or failure in the development of new VR applications is more dependent on the user's experience rather than on the technology itself. The user's quality of experience is driven by three types of influential factors: technological, contextual, and human. Measuring the behavior and experience of VR use is critical to examining the usability of the application and understanding potential HCI/HMI adjustments. A study was performed through the instrumentation of an HMD with several sensors to assess human influential factors in real-time (Moinnereau et al., 2022). The study showed that some participants experienced physical and mental fatigue after extended play but were able to successfully deploy and use the system without significant difficulties due to the advancement of the hardware and technology. Continual assessment of the usage of VR helps developers understand the criticality of HCI/HMI, generalize the technical specifications that result in a successful user experience, and apply lessons learned to further advance the industry towards greater adoption.

To further evaluate the lower adoption rate for VR in applications outside of entertainment and gaming, a different, related study was conducted to understand players' intention to use VR for gaming. The study described that online questionnaires were distributed and collected for inexperienced and experienced players to identify the positive and negative influences of the benefit factors such as flow, spatial presence, and relaxation. The study results showed that to attract the inexperienced users, the effects of visual fatigue must be minimized. The study suggests that for VR to continue to be adopted, hardware/firmware of VR devices should be continuously upgraded to allow higher resolution to reduce visual fatigue (Lee et al., 2020). Visualization is a key factor to HCI/HMI, so its optimization is crucial to the further adoption of VR in non-traditional applications.

User Satisfaction

The use of VR provides a unique experience that impacts the satisfaction of users differently than traditional displays such as computer or television monitors. Through the immersive digital environment of VR, the experience can enhance overall satisfaction, enjoyment, and engrossment in comparison to the use of a traditional monitor. For the video game industry, researchers have been interested in examining how VR HMDs affect the experience of its players with study participants reporting higher scores of immersions and flow in comparison to traditional monitors (Shelstad et al., 2017). One study was conducted to directly compare the user satisfaction of using a VR HMD versus traditional computer monitors. The study showed that among other categories, visual aesthetic was rated higher for VR HMD use in comparison to traditional monitors. Visual aesthetics is generally how pleasing a display is to the user. 3D visualization adds depth and perception that 2D visualization cannot. This additional nuance that VR HMDs provide through 3D visualization gives the user an enhanced visual aesthetic that improves user satisfaction. The comparison of VR HMDs to traditional monitors is important to understand and express the similarities and differences that could result in wider adoption and better user satisfaction.

Testing, Distortion

Commercial VR HMDs currently rely on optics to create a realistic virtual world. The spatial mapping between the display and virtual world is critically important to geometric reproduction. In practice, the mapping is not perfect because the transmitted light field from a VR display is different from the naturally occurring light field from a real environment. This results in visual distortion of the image. A study was performed to explore the perceptual effects of dynamically changing distortion by manipulation of the visual distortion of the users to determine the level of disorientation and dizziness. Results from the study indicated that the level of disorientation and dizziness is significantly affected by the intensity of the visual distortion (Chan et al., 2022). Distortion is a key contributor to HCI/HMI; therefore, adequate evaluation of distortion in VR HMDs can help communicate optimization techniques to prevent issues.

In modern VR HMDs, the near-eye optics that are typically used to focus and place images at a fixed optical distance from the viewer also introduce undesired distortions in the visual field. Despite the application of distortion mitigation techniques, unavoidable factors such as approximations in the modeling of optical properties, manufacturing tolerances, and observer anatomical variability, prevent residuals distortions from being eliminated. A study was performed to evaluate the impact of radial distortion on perceived surface attitude. The study showed that slant discrimination is degraded by radial distortions at or above 5%, while a level of 1% distortion is insufficient to produce significant changes to slant perception. The study concludes that it is very important to adequately model and correct lens distortion to improve the VR user experience. In applications that require high accuracy and precision, it is especially important to adequately correct lens distortion (Tong et al., 2019). Understanding the significance of lens distortion within VR HMDs is critical to drive the need to evaluate VR HMDs to provide results and information to the user to maximize the user experience and provide for a wider adoption.

OUR RESEARCH

Previous studies have been conducted to evaluate the VR user experience to highlight the importance of HCI/HMI. One of the applications that has the potential to be greatly benefited by the incorporation of VR is public health, but caution from HCI/HMI concerns has slowed its adoption. One application of VR in public health is with a Software as a Medical Device system as a pathway for more advanced medical image viewing. The Food and Drug Administration (FDA) refers developers to the reference document Display Devices of Diagnostic Radiology, issued in 2017, for guidance on evaluation of HCI/HMI for medical image viewing. This guidance provides recommendations on image quality testing for conventional diagnostic displays/monitors. However, the existing guidance and standards were derived for 2D medical image viewing with desktop monitors. The standards and protocols for viewing medical imagery using desktop monitors have evolved for modern technology, but those same standards are open to interpretation for applications using VR and 3D visualizations. Our research aims to provide insight to industries, such as healthcare, defense, and simulation, to characterize VR HMDs using adjacent industry standards to evaluate their quality and performance for critical applications.

Distortion is a key metric that has a significant effect on HCI/HMI. Its application for conventional monitors and display systems is well understood and documented by optical design and manufacturing companies such as Shanghai-Optics and Edmund Optics (Shanghai-Optics, n.d.; Hollows & James, n.d.). Quantitative evaluation of distortion in HMD systems in the medical domain is the focus area for our research.

- Distortion is an optical aberration that describes how the magnification within an image change across the field of view at a fixed working distance. Distortion is specified as a percentage of the field height with the two main types of distortion being keystone distortion and pincushion/barrel distortion.

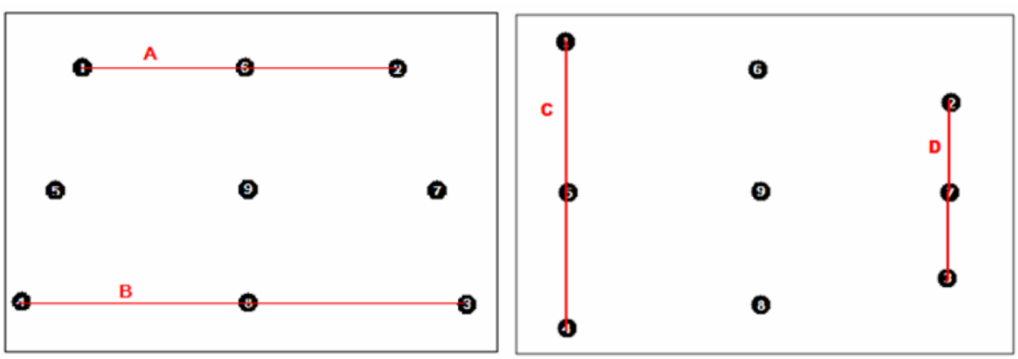

Figure 1. A Depiction of Keystone Distortion, Vertical (Left Image) and Horizontal (Right Image)

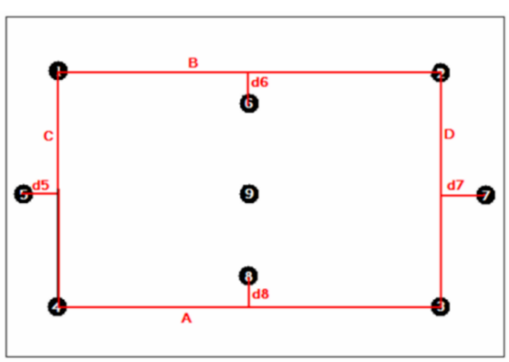

Figure 2. A Depiction of Pincushion/Barrel Distortion

Technical Standards Research and Integration

When evaluating VR HMDs as 3D diagnostic Radiology displays, there is not a universally accepted standard for their use as displays for 3D medical imagery and modeling viewing. With VR still permeating several industries, its adoption and integration into many fields and standards are still in process. To drive progress towards adoption, our evaluation of HMDs as medical image viewers was developed from the American College of Radiology, American Association of Physicists in Medicine, and the Society for Imaging Informatics in Medicine (ACR–AAPM–SIIM) Technical Standard for Electronic Practice of Medical Imaging (PMC3553359). Among the important characteristics of traditional medical image viewing monitors, distortion has the potential to influence a significant role in the HCI/HMI of a VR system. To determine the acceptable distortion percentages of an HMD for use as a 3D model diagnostic display, we analyzed the recommended viewing angles for an individual viewing a medical image. According to the ergonomic factors listed by the American College of Radiology (ACR) technical standard, monitors should be placed approximately 2/3 m (26.25 in.) from the viewer. The display diagonal size of the monitor is recommended to be 80% of the viewing distance, or 53 cm., which corresponds to a standard 21.5 in. monitor (10.51 in. width by 18.74 in. height). The ACR standard horizontal and vertical viewing angles of an individual using a conventional monitor were calculated to be 19.6° horizontal and 11.3° vertical as is shown in Figure 3 (Norweck et al., 2012).

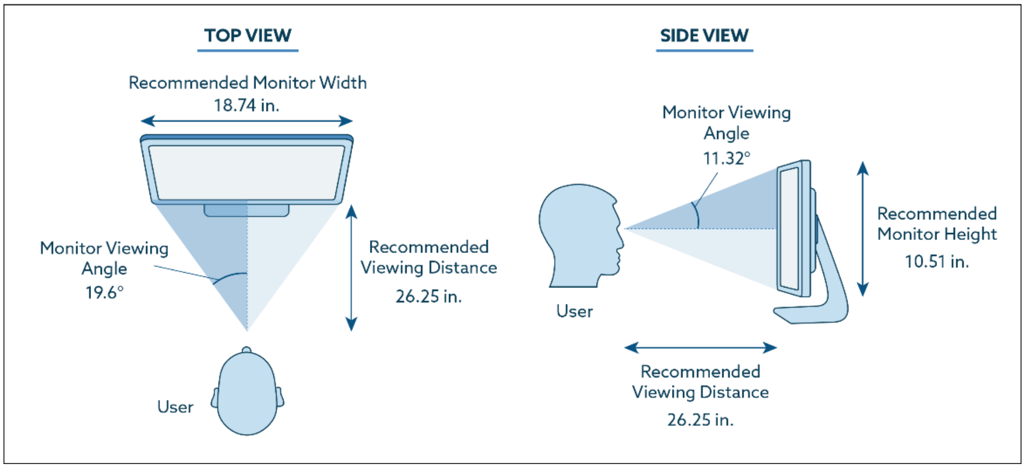

Figure 3. Top and Side View Monitor Viewing Diagrams

LaValle (2020) discusses that the eyes and head rotate together to fixate on a target while immersed in VR. The immediate field of view (FOV) of the VR user is approximately ±35° horizontal, 20° upward, and 25° downward. The immediate field of view was applied as the viewing angle (horizontal and vertical) for a traditional monitor to determine acceptable distortion percentages of an HMD for medical image viewing. The equivalent monitor width and height were calculated to be 36.76 in. and 9.55 in. respectively and were used to calculate the equivalent distortion percentages. Figures 4 and 5 show the equivalent monitor width and height we derived using the immediate field of view for VR users and recommended ergonomic factors listed in the electronic medical imaging technical standard.

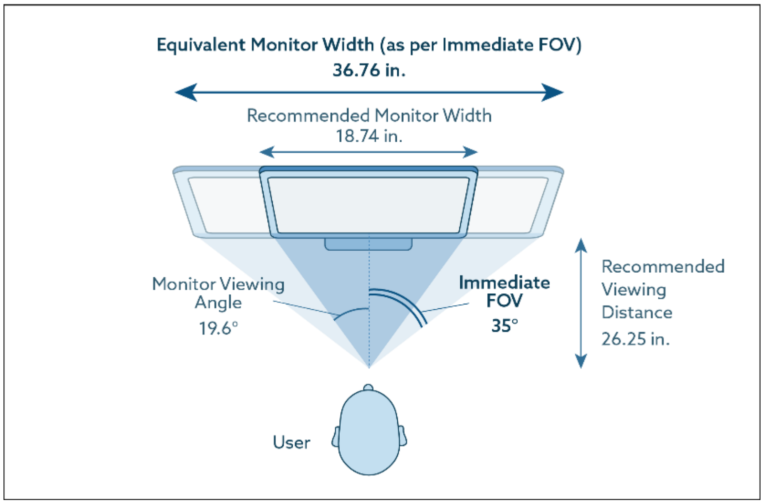

Figure 4. Equivalent Monitor Width Viewing Diagram

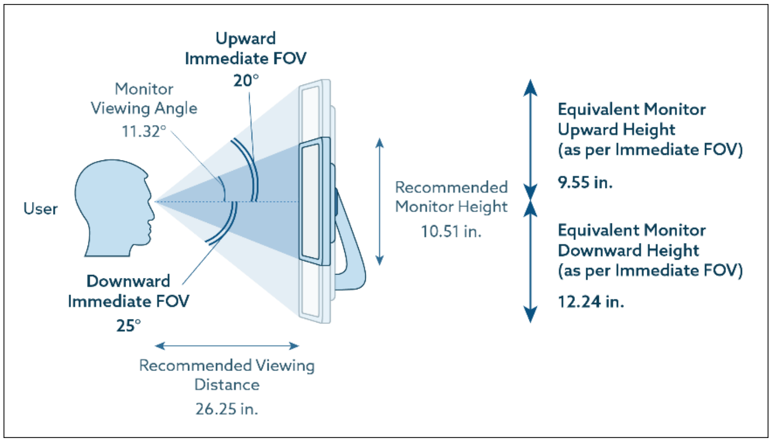

Figure 5. Equivalent Monitor Height Viewing Diagram

When describing lens distortion, optical design and manufacturing companies Shanghai-Optics and Edmund Optics both share that a distortion percentage of ±3% is commonly acceptable in a vision system (Shanghai-Optics, n.d.; Hollows & James, n.d.). Using the commonly accepted ±3% distortion percentage along with the ACR recommended ergonomic viewing angles, the acceptable distortion percentages of an HMD were also normalized with the monitor width and height based on the immediate field of view of the user. The equivalent maximum pincushion/barrel left and right distortions were calculated to be ±5.88% while the equivalent maximum pincushion/barrel top and bottom distortion are ±5.45% and ±6.99% respectively. The equivalent maximum Keystone Horizontal percentage was calculated to be ±5.88% while the equivalent maximum Keystone Vertical percentage was calculated to be ±6.22%. Table 1 shows our calculations of acceptable distortion percentages of an HMD for medical image viewing. If each distortion measurement/calculation is within the acceptable distortion level, the tested HMD was considered acceptable.

Table 1. Distortion Testing Acceptance Criteria

Measurement/Calculation	Acceptable Distortion Percentage
Maximum Pincushion/Barrel Distortion Left	Maximum Distortion Left < ±5.88%
Maximum Pincushion/Barrel Distortion Right	Maximum Distortion Left < ±5.88%
Maximum Pincushion/Barrel Distortion Top	Maximum Distortion Top < ±5.45%
Maximum Pincushion/Barrel Distortion Bottom	Maximum Distortion Bottom < ±6.99%
Maximum Keystone Horizontal	Maximum Keystone Horizontal < ±5.88%
Maximum Keystone Vertical	Maximum Keystone Horizontal < ±6.22%

HCI/HMI Best Practices

As technology continues to advance and evolve, the need for efficient and seamless interaction between humans and machines is increasingly important. HCI/HMI plays a critical role in enabling this interaction, allowing users to communicate with machines effectively and intuitively. An effective HCI/HMI system should be user-friendly, intuitive, and capable of facilitating efficient communication between the human user and the machine. To achieve this, several key components must be considered when designing an HCI/HMI system. These components include:

1. User Interface
2. Input Devices
3. Feedback Mechanisms
4. Software Tools

The recommended practices for designing an optimum HCI/HMI system require careful consideration of several factors, including the needs of the user, the requirements of the machine, and the overall goals of the system (Burk, 2023). The following best practices are recommended to help guide the design process:

1. Focus on the User
2. Simplicity is Key
3. Consistency
4. Provide Clear Feedback
5. Prioritize Safety

When preparing to analyze a designed HCI/HMI system based on intended uses, research and experiences were compiled to develop the below recommended best practices.

1. Review the use case(s) for the system.
2. Define the appropriate system characteristics to study based on the intended uses.
3. Determine the appropriate acceptance criteria and metrics for the selected system characteristics based on the intended uses.
4. As necessary, adjust the existing test methods for evaluating the system characteristics.
5. Consider applying well-received methods and characteristics from similar devices.
6. Perform the evaluation, objectively evaluate the results, and make the necessary adjustments to improve the HCI/HMI of the system.

Each of these best practices were used in the development of our system approach and should be used in the development of all HCI/HMI systems. Developing an optimized HCI/HMI system requires continued and intentional consideration throughout each phase. Each practice is an important factor in reducing HCI/HMI issues and is critical to the design and development of any system.

Approach

The Distortion characterization testing was performed using one VIVE Pro 2 HMD, fixtured using a vertically mounted ProMetric® I29 Ultra High-Resolution Imaging Colorimeter with a Xenobiotic Responsive Element Lens as depicted in Figure 6. An XYZ Translation Stage along with a vertical bar was applied to attach and stabilize the VR headset for testing. The hardware configuration we used includes:

- ProMetric I29 Ultra High-Resolution Imaging Colorimeter
- XRE Lens (Y series, folded)
- XYZ Translation Stage

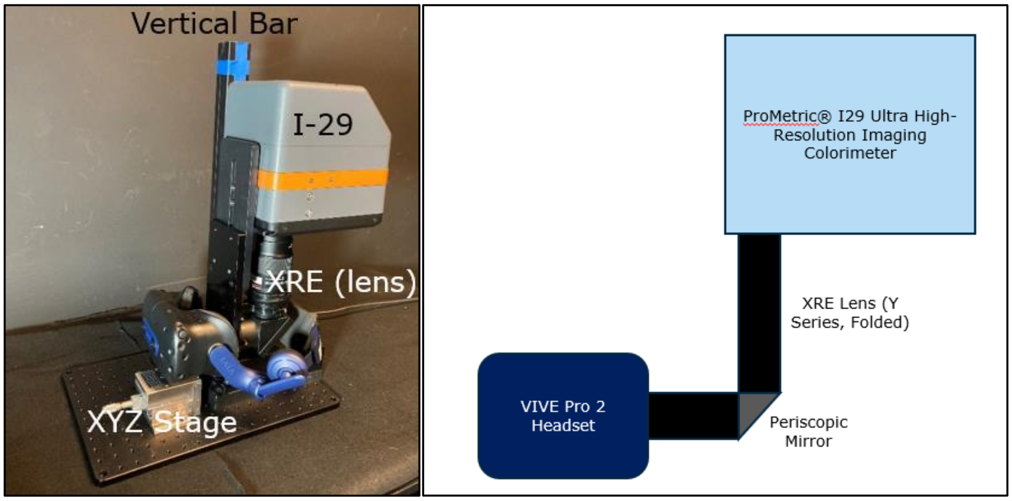

Figure 6. Image Display Test Fixture Setup (Left) and Diagram (Right)

A software application called Virtual Desktop, along with the use of SteamVR™, was used to display the measurement images needed for distortion testing within the VR HMD. The Virtual Desktop application created the images to be displayed on the HMD. The Radiant Vision Systems TrueTest™ Augmented Reality Virtual Reality (TT-ARVRTM™) Display Test Module software was used with the ProMetric I29 Ultra High-Resolution Imaging Colorimeter to measure and calculate the distortion values. The software we used includes:

- Virtual Desktop
- TT-ARVRTM Display Test Module
- SteamVR

Test Methods

To test the VR HMD for distortion, a 2D measurement image with nine specific fixed points was applied with a vertical and horizontal 70° field of view. A distortion 9-point test was applied to measure several geometric distortion parameters to determine if the measurement image (9 dots on a 3x3 grid) is off-center, rotated, keystoned, or pin-cushioned/barrel distorted. The TT-ARVRTM Display Test Module finds the center location of the nine dots and performs various geometric measurements between the positions of the dots.

The field of view of the HMD under test is fixed at approximately 120° horizontal and 99° vertical. To better visualize the in-HMD distortion testing method, a depiction of the user's immediate field of view (70° horizontal and 45° vertical) with the 70° field of view measurement image (along with the nine measurement points) that was applied within field of view of the HMD is shown in Figure 7. With the immediate field of view for a VR user totaling 70° horizontal and 45° vertical, the distortion testing field of view of 70° (vertical and horizontal) was determined to be appropriate.

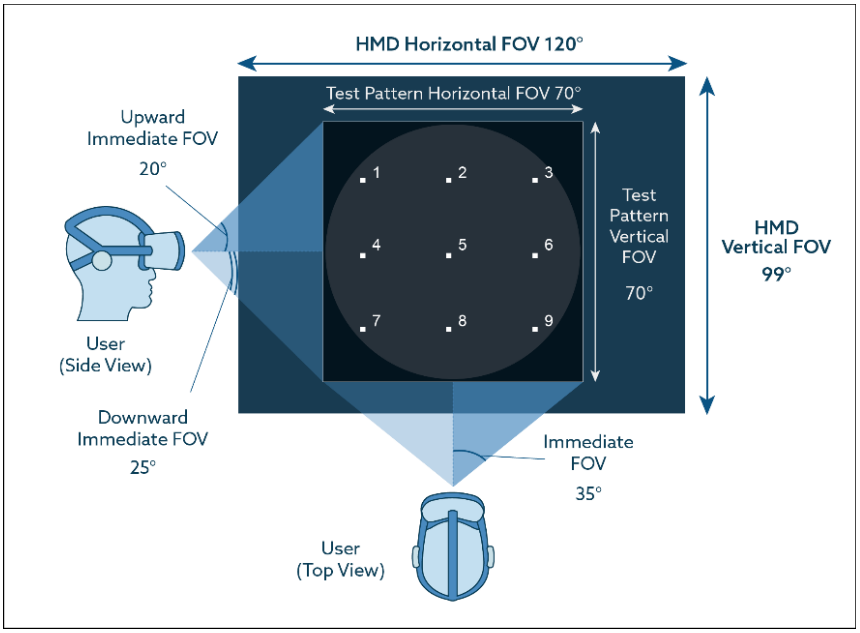

Figure 7. Distortion Testing in-HMD Depiction

The method used to test the HMD was derived using the HCI/HMI best practices along with the ACR technical standards and the International Electrotechnical Commission (IEC) international standard IEC 63145-20-20. The IEC 63145-20-20 international standard provides the fundamental measurement methods for the optical properties and image quality of eyewear displays as related to distortion (International Electrotechnical Commission, 2019). Without a universally accepted method to test an HMD as a medical image viewer, our method of calculating a VR HMD equivalent monitor height and width using the recommended monitor viewing angles with the identified immediate field of view, provided a method to modifying legacy methods/metrics to accommodate the VR HMD system. Our method of calculating acceptable image/display quality parameters may also be applied across multiple industries that do not have a universally accepted image/display quality standard for HMDs. Developing methods to verify image/display quality will allow inadequate HMDs to be identified. It will also allow acceptable performing HMDs to showcase image quality metrics that can allow their adoption across a broader set of industries.

Results

Table 2 shows the distortion measurements and calculations for the HMD while Figure 8 shows the 2D 9-point distortion measuring points within the measurement image as seen by the HMD.

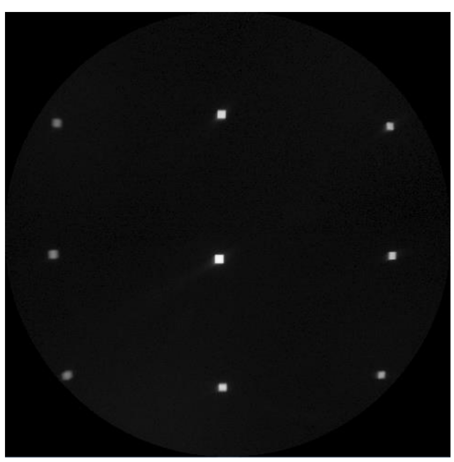

Figure 8. 9-Point Distortion Measuring Points within the Measurement Image

Table 2. Clarus Viewer HMD Distortion Testing Results

Measurement/Calculation	Measured/ Calculated Value	Acceptable Distortion Percentage	Result
Maximum Pincushion/Barrel Distortion Left	2.7789%	Maximum Distortion Left < ±5.88%	Passed
Maximum Pincushion/Barrel Distortion Right	2.0809%	Maximum Distortion Left < ±5.88%	Passed
Maximum Pincushion/Barrel Distortion Top	4.0942%	Maximum Distortion Top < ±5.45%	Passed
Maximum Pincushion/Barrel Distortion Bottom	4.8818%	Maximum Distortion Bottom < ±6.99%	Passed
Maximum Keystone Horizontal	-1.5019%	Maximum Keystone Horizontal < ±5.88%	Passed
Maximum Keystone Vertical	-5.805%	Maximum Keystone Horizontal < ±6.22%	Passed

The HMD under test contained some image distortion as shown in Figure 8. The distortion measurements were less than the maximum allowable values provided in Table 2. Consequently, the system passed the requirements needed to be considered appropriate for use as an HMD for medical image viewing.

CONCLUSIONS AND FUTURE WORK

Accurate representation of both the 3D VR environment and the user's interaction with that environment is critical in the design and development of systems. Inadequate user experience with these systems can lead to negative training and improper use. Therefore, when evaluating VR HMDs for use as a 3D medical image viewer for diagnostics, distortion was a key test parameter for characterization. Chan et al. (2022) noted that disorientation and dizziness are significantly affected by the intensity of distortion. We conducted distortion characterization of the 2D image display of our system's HMD to objectively evaluate the performance of the HMD in comparison to the American College of Radiology medical display standards. We used the results to determine if the image quality, measurement accuracy, and visibility of virtual content was sufficient based on the intended use of the VR system's application as a medical image viewer. After deriving the appropriate acceptable distortion percentages and evaluating the test results, our system's HMD was determined to be sufficient. Distortion was noted within the HMD under test, but when comparing the results to the acceptable distortion percentages derived from the ACR technical standards, the noted distortion percentages were acceptable. Distortion is a key contributor to HCI/HMI, so adequate evaluation of distortion in VR HMDs can help communicate inadequacies to allow for improvement and to prevent misuse within critical industries.

The study that we conducted contained limitations that could be expanded in future work. Our work included the testing and characterization of one VR HMD. Continued efforts should include the testing of multiple VR HMD systems to confirm consistency and identify differences. The study of other VR HMD types would also be beneficial for future work to test HCI/HMI to collect data on the usage of other HMDs on a multitude of industries. HCI/HMI is also critical in the implementation of other extended reality (XR) technologies for healthcare. The study of other XR HMDs and technologies such as augmented reality (AR) would be beneficial to continue exploring innovations in healthcare.

To further analyze the adequacy of HMDs in other industries that do not have a universally accepted image/display quality standard, other image display quality parameters can utilize the test method that we derived for distortion. Image display quality parameters such as luminance, contrast, and resolution are all key contributors to HCI/HMI and can significantly affect the user's experience. For other industries such as defense, training and simulation, our testing and methodology shows how an HMD can be validated for use without the universal adoption of HMD specific standards or guidance. Tailoring the traditional and accepted standards allows for traceable data to be developed to evaluate HMDs' quality for usage within a multitude of industries. HCI/HMI is critical to the adoption and enhancement of all technologies, so continued testing and test method derivation is essential to the advancement of technology.

REFERENCES

Burk, M. (2023, April 18). *Demystifying HMI: A comprehensive guide to human-machine interface technology*. ALMAX. **https://almaxeis.com/demystifying-hmi-a-comprehensive-guide-to-human-machine-interface-technology/**

Chan, T. T., Wang, Y., So, R. H., & Jia, J. (2022). Predicting subjective discomfort associated with lens distortion in VR headsets during vestibulo-ocular response to VR scenes. *IEEE Transactions on Visualization and Computer Graphics*, 1–1. **https://www.researchgate.net/publication/360060264_Predicting_Subjective_Discomfort_Associated_with_Lens_Distortion_in_VR_Headsets_During_Vestibulo-Ocular_Response_to_VR_Scenes**

Hamad, A., & Jia, B. (2022). How virtual reality technology has changed our lives: An overview of the current and potential applications and limitations. *International Journal of Environmental Research and Public Health*, *19*(18), 11278. **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9517547/**

Hollows, G., & James, N. (n.d.). *Distortion*. Edmund Optics. Retrieved May 3, 2023, from **https://www.edmundoptics.com/knowledge-center/application-notes/imaging/distortion/**

International Electrotechnical Commission. (2019). *Eyewear display: Part 20-20: Fundamental measurement methods - image quality* (IEC 63145-20-20:2019). Retrieved from **https://webstore.iec.ch/publication/61596**

Pettey, C. (2018). *3 Reasons why VR and AR are slow to take off*. Gartner. Retrieved May 3, 2023, from **https://www.gartner.com/smarterwithgartner/3-reasons-why-vr-and-ar-are-slow-to-take-off#:~:text=3D%20design%20interface-**

LaValle, S. M. (2020). *Virtual reality* (1st ed.) Cambridge University Press.

Lee, C. C., Hsiao, K. L., & Chen, C. C. (2020). Exploring the benefit and sacrifice factors of virtual reality gameplay. *Frontiers in Psychology, 11*. **https://www.frontiersin.org/articles/10.3389/fpsyg.2020.00251/full**

Moinnereau, M. A., Oliveira, A. A., & Falk, T. H. (2022). Instrumenting a virtual reality headset for at-home gamer experience monitoring and behavioral assessment. *Frontier in Virtual Reality, 3*. **https://doaj.org/article/0df3422b6f724f9e87bd07ab946064fd**

Norweck, J. T., Seibert, J. A., Andriole, K. P., Clunie, D. A., Curran, B. H., Flynn, M. J., Krupinski, E., Lieto, R. P., Peck, D. J., Mian, T. A., & Wyatt, M. (2012). ACR–AAPM–SIIM technical standard for electronic practice of medical imaging. *Journal of Digital Imaging*, *26*(1), 38–52. **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3553359/**

Shanghai-Optics. *Understanding Lens Distortion*. (n.d.). Shanghai-Optics. Retrieved May 3, 2023, from **https://www.shanghai-optics.com/about-us/resources/understanding-lens-distortion/**

Shelstad, W. J., Smith, D.C., & Chaparro, B. S. (2017). Gaming on the rift: how virtual reality affects game user satisfaction. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *61*(1), 2072–2076. **https://www.researchgate.net/publication/320544794_Gaming_on_the_Rift_How_Virtual_Reality_Affects_Game_User_Satisfaction**

Tong, J., Allison, R. S., & Wilcox, L. M. (2019). The impact of radial distortions in VR headsets on perceived surface slant. *Journal of Imaging Science and Technology*, *63*(6). **https://percept.eecs.yorku.ca/papers/Tong%20JIST%202019.pdf**