Summary of methodology and guidelines

The successful integration of innovative three-dimensional (3D) display technologies, including headsets with near-eye displays, into various aspects of life such as education, work, and leisure, depends on multiple factors influencing how users perceive and interact with digital content. To advance toward a 3D display world tailored to individual needs and abilities, we implemented a comprehensive approach that considers both technological aspects and human factors within a Latvian Council of Science-funded project (No. lzp-2021/1-0399) titled "Development of guidelines for evaluating the visual effectiveness and ergonomics of innovative 3D displays," which ran from January 2021 to December 2024. Thus, we aimed to facilitate the responsible and successful integration of 3D display technologies into various applications. Our efforts concentrated on deepening the understanding of technological aspects and human factors influencing visual functions and user performance when using innovative 3D display technologies. This was achieved through a combination of subjective and objective assessment methods, and here we summarize the developed methodology and guidelines.

Individual variations in visual skills and abilities

Using headsets with near-eye displays requires a well-functioning visual system. Eye and vision problems, affecting visual skills to varying degrees, may hinder the ability to comfortably use 3D display technologies. Despite their frequency, vision problems have received limited attention in user studies, making it challenging to assess accessibility and promote inclusivity.

While full eye examinations are the most recommended option for a human-centred research approach – enabling diagnosis and a thorough consideration of baseline visual functions that can alter the impact of using 3D display technologies on visual system functionality (Sumarokova et al., 2024) – we propose a practical alternative. As a minimum, standard vision screenings should be conducted and reported for each participant in user studies. These screenings should include the assessment of visual acuity for each eye (at both distance and near), stereo acuity, and colour vision (Pladere et al., 2022).

By accounting for individual variations in visual skills and abilities, we emphasize the importance of not only further advancing traditional technical parameters of 3D display technology, such as image resolution, brightness, field of view, and consistent colour presentation, but also tailoring display and image parameters to meet users' visual system needs. Customizing display and image parameters can enhance user satisfaction, comfort, and overall performance when interacting with 3D digital content.

Visual system functionality following the use of 3D display technologies

Given the enclosed nature of headsets and the current lack of tools for real-time, high-accuracy assessments of vergence (coordinated eye movements) and ocular accommodation (focusing ability), a before-and-after study design can be employed to assess changes in visual functions following the use of 3D display technologies. This approach is suitable for a range of near-eye display technologies, including passive and active virtual reality, as well as video and optical see-through augmented reality systems (Abdullayeva et al., 2023; Livitcuka et al., 2023; Zizlane et al., 2023; Sumarokova et al., 2024).

Both standard clinical tests and objective measurements can be utilized to assess visual functions. Clinical tests for evaluating the near point of convergence, near point of accommodation, and accommodative facility are widely available and can be performed quickly before and after the use of 3D display technology. Objective methods, such as dynamic eccentric photorefraction, are less accessible but provide detailed insights into changes in visual system functionality. This includes detecting changes in additional parameters, such as accommodative microfluctuations and accommodation lag, after the use of 3D display technology (Abdullayeva et al., 2023; Sumarokova et al., 2024), which can provide valuable insights into the adaptability of the visual system to new 3D viewing conditions.

Dynamic eccentric photorefraction also offers the advantage of simultaneously recording vergence and accommodation responses. However, as this method does not have individual calibration for gaze measurements (resulting in a divergent offset between the measured and expected gaze positions), recalculations are necessary. We have proposed a method for calculating physiological vergence angles based on visual vergence data (Krauze et al., 2024).

Our studies, involving a large cohort of participants with and without binocular and accommodative disorders, revealed significant individual variations in both vergence and accommodation responses following the use of near-eye displays (Livitcuka et al., 2023; Zizlane et al., 2023; Sumarokova et al., 2024). These variations were observed in terms of both magnitude and direction of change, highlighting the need for further investigation into their underlying causes. This underscores the necessity of real-time, accurate assessments of visual functions to understand the adaptability of the visual system when using modern 3D display technologies.

3D image perception

Precise perception of digital content is essential for a satisfying experience with 3D displays and critical in some professional applications. For a comprehensive assessment of image perception, a combination of methods, such as electroencephalography (EEG), eye-tracking, and image depth judgements tests, can be applied. The event-related potential method enables detailed temporal analysis of neural oscillations, which may vary depending on viewing conditions, providing insights into whether differences occur during early or late stages of information processing.

Precise eye movement assessment and gaze tracking allow researchers to identify which part of an image the user is viewing at any given moment and how gaze distribution patterns change based on the type of digital content. Gaze distribution patterns during the search for information in 3D display images can reveal the user's ability to discern relative depth between different parts of the image (Krauze et al., 2023). However, these patterns do not confirm that the imprecise identification of depth components in 3D images is equivalent to viewing two-dimensional (2D) images.

Considering that the capability of the human visual system to perceive image depth varies across the visual field, the accurate perception of 3D images based on binocular disparity is facilitated when image items are displayed close together in a 2D layout (Krauze et al., 2023). Binocular disparity, the strongest depth cue at close viewing distances, should be one of key considerations when designing software for displaying images on 3D displays.

EEG studies have demonstrated the value of analysing event-related potentials and neural oscillations for objectively assessing the user experience for 3D display technologies. Notably, significant differences in event-related potentials and specifically the P3 component at the parietal (Pz) location when viewing 3D and 2D images are observed in both latency (timing) and amplitude (magnitude) (Naderi et al., 2023a; Naderi et al., 2023b). These findings indicate that EEG signal analysis can objectively differentiate between 3D and 2D visual experiences, particularly through changes in the P3 component. In addition, variations in cognitive load required to process information under different viewing conditions can be tracked using EEG signal analysis.

Thus, both EEG and eye-tracking methods offer the advantage of providing objective and detailed insights into the visual and cognitive processes that occur when using 3D display technologies. They also hold potential for identifying objective indicators of differences in user experience. However, it should be noted that both methods require customized software for calibration and marker integration, as conventional software may not be compatible with the unique optical structures of innovative 3D displays. Additionally, EEG is sensitive to multiple external and internal factors, and its data should be interpreted with caution. It is recommended to be used as a complement to other methods rather than as a stand-alone approach.

Future directions and prospects

Looking ahead, the future of 3D display technologies may hold exciting possibilities, including the development of real-time tools for accurately monitoring different visual functions (including ocular accommodation and vergence) and adapting to user-specific visual system needs. Continued interdisciplinary research is crucial to overcoming current challenges and expanding applications. In the future, prioritizing user-centric design and accessibility can enable broader adoption of 3D display technologies.

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