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OPEN ACCESS

DOI: 10.15199/48.2025.04.32

Virtualization of vision diagnosis, therapy and training – concept of an optometric system

Wirtualizacja diagnostyki, terapii i treningu widzenia – koncepcja systemu optometrycznego

***Abstract**. Virtual reality technologies are gaining increasing prominence in medical diagnostics and therapeutic applications. This study introduces the conceptual framework and current development status of a system specifically designed for vision diagnostics and therapy employing wireless virtual reality (VR) goggles. The virtualization of diagnostic tests enables enhanced automation in data analysis while facilitating rapid dissemination of laboratory findings to optometrists. Preliminary tests provide proof of the effectiveness of the proposed vision therapy solutions.*

***Streszczenie.** Rozwiązania sięgające po wirtualną rzeczywistość stają się coraz popularniejsze w diagnostyce i terapii medycznej. W artykule przedstawiono koncepcję i aktualny stan prac nad systemem dedykowanym do diagnostyki i terapii wzroku z użyciem bezprzewodowych gogli VR. Wirtualizacja testów oferuje nie tylko zwiększenie stopnia automatyzacji analizy danych, ale także szybsze udostępnianie optometrystom rezultatów prac laboratoryjnych. Wstępne testy potwierdzają skuteczność zaproponowanych rozwiązań dot. terapii wzroku.*

Keywords: vision therapy, virtual reality, wireless goggle VR
Słowa kluczowe: terapia widzenia, rzeczywistość wirtualna, bezprzewodowe gogle VR

Introduction

Vision serves as a fundamental sensory system for humans, facilitating effective interaction with the surrounding environment. A wide array of visual skills is indispensable for achieving success across virtually all aspects of daily life, ranging from reading and writing to specialized activities in professional or athletic domains. Among the critical visual competencies are ocular motor control (binocular coordination, encompassing both rapid and smooth eye movements across the visual field as well as convergence), accommodation flexibility and endurance (shifting focus between near and distant objects or maintaining focus on a single object), colour and depth perception, visuomotor coordination, visual memory, visual reasoning, visual perception (spatial awareness and understanding of events within the visual field), and sensory integration (the ability to combine visual input with other sensory modalities to perform complex tasks). These competencies underscore the critical role of vision in supporting not only cognitive functions and decision-making processes but also a broad spectrum of motor abilities, ranging from fundamental to highly complex tasks [1]. Furthermore, the condition of the visual system is not only indicative of specific professional aptitudes but may also contribute to occupational or even social exclusion in cases of dysfunction [2]. In this context, the availability of advanced procedures designed to address visual impairments and enhance existing visual capabilities represents a significant development. Notably, the process of cultivating visual skills begins at the earliest stages of individual development and, importantly, can continue across the entire human lifespan.

Contemporary approaches to vision diagnostics and therapy are predominantly based on conventional, clinic-based solutions that rely on specialized and often costly equipment (Fig. 1). These include devices such as phoropters, optotype charts, trial lens sets, and binocular vision testing tools. Diagnostic procedures typically encompass assessments of visual acuity, binocular vision function including simultaneous perception, fusion, and stereopsis as well as evaluations of ocular motility and accommodation.

In recent years, virtual reality (VR) technologies have been introduced into the field of vision therapy [3]. Notable examples include applications such as RemmedVision, designed for home-based vision therapy, and programs like OpticsTrainer and Vivid Vision, which focus on developing visual skills. However, these solutions remain relatively few and are predominantly reliant on wired systems, such as HTC Vive or Oculus Rift, which necessitate the use of external computing devices (desktop or laptop).

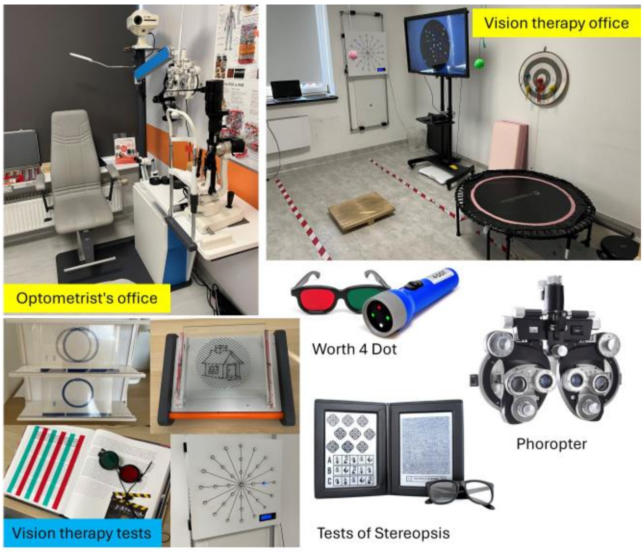

Fig. 1. Vision diagnostics and therapy office with equipment - Retina Eye Clinic and Hospital / Good Optometrist – Warsaw.

The limited availability of optometrists, particularly in smaller towns, and the even scarcer access to therapy offered by well-equipped specialized centers, underscores the need for alternative solutions. Such solutions must not only assist in identifying individuals who require vision therapy but also streamline the therapeutic process for diverse age groups and professional demographics. Emerging technologies, including virtual environments, present a promising avenue for significant cost reductions, enabled by the use of a single essential device: VR goggles. Although current head mounted display (HMD) devices face hardware constraints, such as limitations in image resolution and the vergence-accommodation conflict, the advanced capabilities of modern virtual technologies, derived from their integrated hardware and software systems, allow for the implementation of various tools for vision diagnostics, therapy, and skill enhancement within virtual environments.

This article presents a proposed approach to the virtualization of vision diagnostics and therapy, utilizing the popular Meta Quest 2 HMD as a foundational element of the proposed optometric diagnostic-therapeutic-training system. Although the chosen goggles do not have eye-tracking functions, their selection was dictated by affordability, portability as well as, the ability to easily and effectively translate solutions developed in the lab into formats suitable for testing and use in optometric practice. The article also presents potential applications of the developed system in specialized training sessions aimed at increasing visual competence, which is often unique, while tailored to the requirements of specific professional groups. We used one of the realistic virtual environments created by our team, dedicated to military simulations, which includes an advanced terrain model and allows positioning of various objects. This solution was customized to the training needs of the system described in the article. Due to the complexity of field scenes, their implementation would not be possible in wireless VR goggles. Therefore, the proposed system can work with a dedicated VR server that generates images and video sequences for selected tests, enabling work in complex virtual environments.

Paradigms of vision therapy

Optometric vision therapy is primarily aimed at addressing dysfunctions within the visual system, with a particular focus on binocular vision disorders such as accommodation and vergence. This approach utilizes specific, sequential paradigms of sensory-motor-perceptual stimulation to enhance visual skills [4]. The core paradigms underlying vision therapy are as follows:

a) Task and Goal Specificity: Exercises are meticulously designed to target particular deficits or dysfunctions within the visual system, including accommodation, ocular tracking, binocular vision, and visual perception.

b) Sequential Training Structure: Therapy is implemented in a progressive manner, starting with basic exercises to establish foundational skills and advancing to more complex, integrative tasks.

c) Sensory Stimulation: The use of visual patterns, colours, and motion stimuli activates specific neural pathways involved in visual processing, thereby training the visual system in a targeted and effective manner.

d) Motor Integration: Therapy incorporates tasks requiring precise control of ocular movements (e.g., smooth pursuits and saccades) as well as visuomotor coordination exercises, integrating visual inputs with motor outputs to improve overall neural coordination.

e) Perceptual Engagement: Beyond the physiological function of the eyes, therapy emphasizes the brain’s ability to process and respond to visual stimuli, enhancing skills such as spatial awareness, depth perception, and pattern recognition.

Training protocols developed based on these paradigms address various aspects of visual function, including:

Binocular Vision Training: Incorporating tools such as stereograms and prisms to alleviate visual fatigue and enhance depth perception.

Dynamic Visual Acuity and Tracking: Exercises involving the tracking of moving objects to improve visual skills essential for real-world activities, such as driving or athletic performance.

Multisensory Integration Tasks: Combining visual exercises with auditory or proprioceptive challenges to enhance the brain’s ability to process complex multisensory information more efficiently.

This structured and systematic approach ensures a comprehensive improvement in both visual and related cognitive-motor functions [5].

Scientific research on vision training employing the aforementioned elements demonstrates that such interventions positively influence various aspects of daily human functioning. In children, this is reflected in improved academic performance [6]; in adults, it facilitates the completion of occupational tasks requiring prolonged visual concentration; and in athletes, it enhances reaction times and spatial judgment [7].

Verification of implementation capabilities

Conventional diagnostic and therapeutic approaches in vision therapy predominantly rely on presenting visual stimuli through physical objects. Similarly, interactions with objects during vision therapy are typically physical in nature. These methods require diverse equipment in clinical settings and adequate spatial arrangements to facilitate evaluations at various distances, commonly ranging from near (0.4 m) to far (6 m).

Virtual reality technologies offer a promising solution to these challenges. The integration of VR-based systems for vision diagnostics and therapy capitalizes on the ability to digitally generate realistic three-dimensional objects through the synthesis of appropriate images for the left and right eyes, displayed via head-mounted displays (HMDs). Physical interactions with objects, which are sometimes an integral part of vision therapy, can be substituted with virtual haptic solutions in a VR environment. A simple implementation involves using the controller's vibration to provide haptic feedback, which signals potential contact between the user and a virtual object. Certain tests, particularly those tailored for professional applications, may require the synthesis of highly realistic visualizations. While this poses no significant challenge for high-performance desktop computing systems, wireless VR headsets may necessitate the use of an external processing unit to generate the required training content.

Recent efforts have primarily focused on the synthesis of images with parameters optimized for the left and right eyes, utilizing software tools available through the Unity 3D platform [9,10]. These tools facilitate not only the simulation of visual system functions but also the emulation of optometric equipment, enabling the efficient implementation of diagnostic and therapeutic solutions. However, despite the significant advantages provided by software tools, limitations persist with the hardware components responsible for rendering the visual content. These challenges include achieving the required resolution of displayed images and enabling the modification of the perceived distance at which virtual images are presented.

A critical limitation, particularly in the context of optometric visual acuity measurement, is the absence VR googles capable of achieving angular resolutions of synthesized images that surpass the resolving power of the human eye (approximately 1 arcminute). Arc minute determinate the size of the smallest details which healthy human’s eyes can detect, while the peripheral horizontal field of view (the area of space that can be seen without moving the eyes or head) can reach 220° degrees. Analyzing the pixel resolution and the angular field of view provided by various commercially available HMD models reveals that angular resolutions are typically on the order of several degrees, resulting in noticeable pixelation of the displayed image. Test measurements conducted with the Meta Quest 2 HMD, selected as a representative device, demonstrated an actual angular resolution of approximately 3 arcminutes (Fig. 2). The findings of this study draw attention to a more significant limitation inherent in commercially available HMDs: the inability to accommodate changes in ocular focus. This constraint, characterized by a fixed distance at which the virtual image is formed, corresponds to the well-documented vergence-accommodation conflict (Fig. 3) [11].

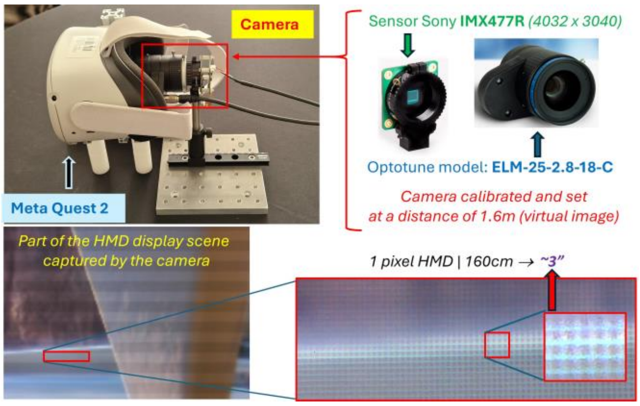

Fig. 2. Measurement stand and result of HMD angular resolution evaluation

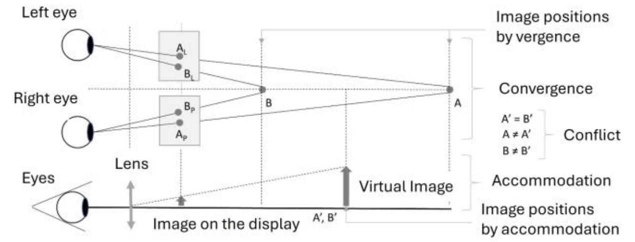

Fig. 3. Visualize the conflict of vergence and accommodation

Visual stimuli synthesized for the left and right eyes, which indicate object positions at varying distances based on vergence mechanisms, are inconsistent with the accommodative response of the eyes. In current HMDs, all objects are rendered on a single focal plane at a fixed distance, typically ranging from 1.5 to 2 meters, depending on the model or specific device.

Existing scientific literature explores various approaches to addressing the vergence-accommodation conflict through advanced display technologies, including multifocal, varifocal, light field, holographic, and other mechanisms [12,13,14]. From an optometric perspective, the integration of additional features into HMDs (such as eye-tracking, pupil diameter analysis, and accommodation assessment) would be highly beneficial. While some of these functionalities, such as eye-tracking, are already implemented in certain devices, others remain in the research and development phase. The authors of this study are actively engaged in research on HMDs designed to enable dynamic adjustment of the distance at which the virtual image is formed, coupled with the capability to monitor changes in ocular accommodation. A conceptual overview of this system is provided in Fig. 4 [15].

Based on the data presented, it is clear that no existing hardware platform currently satisfies all the requirements necessary for the comprehensive implementation of diagnostic and therapeutic procedures in vision therapy using VR technology. However, excluding certain diagnostic tests that rely on accommodation, such as assessments of visual acuity or accommodative function, there exists a subset of tests unaffected by these limitations, allowing for feasible VR implementation. These include, for example, tests for determining ocular dominance, simultaneous perception, and stereoscopic vision.

Additionally, a wide array of vision therapy tests is well-suited for virtualization. In response to this potential, implementation efforts have been initiated, and examples of selected solutions are presented in the following section.

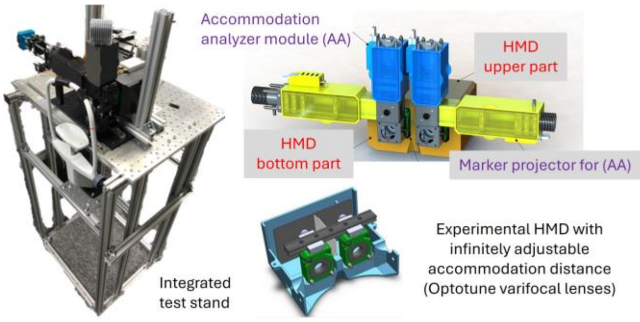

Fig. 4. Experimental HMD workstation with programmable accommodation distance of the synthesized image and integrated left eye accommodation measurement module.

Examples of virtualization of optometric solutions

The implementation of individual tests focused on the following key aspects:
- ensuring fundamental functionality to maintain the test's utility and alignment with its physical counterpart,
- integrating automated result evaluation mechanisms to minimize patients' interaction with specialists can increase access to medical care especially in areas where there is a deficit of specialists:
- prioritizing solutions with relatively low computational complexity within the VR environment to ensure seamless operation on wireless HMD devices,
- automatically adjusting test parameters to accommodate the test subject's height and spatial orientation.

Each VR test is developed based on the synthesis of images generated in a virtual environment, adapted to the left and right eye where the distance between the virtual cameras is the equivalent of the Interpupillary Distance (IPD)(Fig. 5).

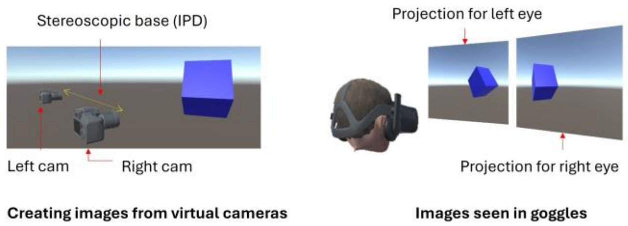

Fig. 5. VR image synthesis and projection in HMD

The implementation of various applications is further facilitated by the advanced measurement capabilities of HMD devices, which allow for real-time monitoring of parameters such as head position and rotation (via the HMD) and hand movements (via controllers). These capabilities enable sophisticated 3D analyses that enhance both the execution of vision tests and the acquisition of test results.

For example, in an ocular dominance test (Fig. 6), the collision of the directional vector from the left or right eye (represented by the corresponding virtual camera) with an observed object (viewed through an aperture controlled by the test subject) can be analyzed to provide a direct and automated determination of the dominant eye. The visualization of the right eye as dominant, presented in the figure, is related to the fact that at the same time point P1 (is seen by the right eye) and it belongs to surface F2 while point P2 is formed on the surface of the aperture (test card) outside the hole. The belonging of the above points to specific surfaces is detected in the virtual environment and is the basis of the analysis result.

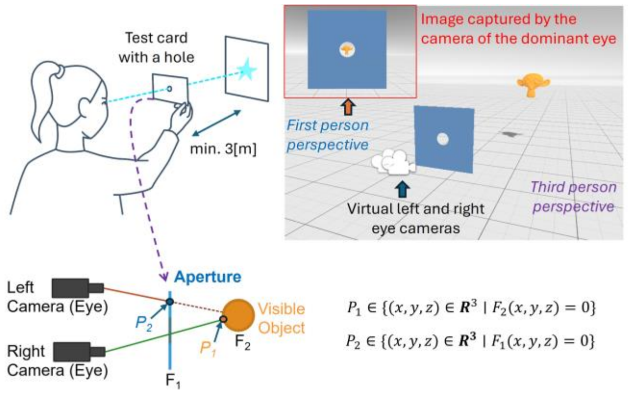

Fig. 6. Determining the dominant eye

Software development platforms such as Unity 3D, which was utilized to develop the software for HMDs, offer advanced tools for designing virtualized vision systems. In the context of diagnostic and therapeutic vision tests, the focus is directed toward configuring the parameters of cameras used to synthesize images for the left and right eyes.

Within the Unity 3D environment, the parameters of stereoscopic rendering cameras can be precisely adjusted using the Unity XR system by manipulating the projection matrix, which defines how the 3D world is projected onto a 2D screen for each eye, and the view matrix, which determines the position and orientation of the cameras in the 3D environment. These adjustments enable control over key parameters such as the stereoscopic base (stereoSeparation) and the fixation point distance (stereoConvergence). The above parameters are part of the Camera class (the default camera for the Unity3D physics engine). Controlling the position and possible orientation of the cameras rendering the image for the eyes (for example, in the case of Meta Quest goggles), is better implemented using a dedicated library (Meta XR Core SDK), which replaces the conventional Unity camera. For this purpose, you can use OVRCameraRig and the camera-related elements rig.leftEyeAnchor/rig.leftEyeAnchor.

Access to these matrix parameters facilitates not only the simulation of human visual function but also the emulation of various optometric devices used in diagnostic and therapeutic tests, thus expanding the scope and versatility of virtual vision systems.

In addition to the previously discussed matrices, the process of rendering "appropriate images" for the left and right eyes can also utilize advanced programming techniques, including spatially and temporally selective synthesis. Spatially selective synthesis leverages a layer-based approach, where distinct layers contribute to the construction of a 3D scene, with specific elements visible exclusively to either the left or right eye. Temporally selective synthesis, by contrast, involves sequential rendering of images for the left and right eyes, with programmatic access enabling targeted modifications to the scene between the rendering of each eye's image.

In the context of stereoscopic visualization, translating traditional (physical) clinical tests into VR-based equivalents primarily entails determining the specific visual content to be displayed to each eye [8]. In conventional clinical setups, the separation of visual stimuli between the eyes is often achieved using devices such as anaglyphs (e.g., the Worth test), polarizing filters (e.g., the Fly test), or complex optical systems (e.g., a phoropter). These solutions rely on hardware of varying complexity [4]. In contrast, the proposed VR-based approach offers a significant advantage: all these tests can be conducted using a single device - a wireless HMD VR headset. The remaining implementation tasks are reduced to software development using the tools provided by the VR environment.

Examples of such implementations include the simultaneous perception and fusion test (e.g., the Worth test) and stereoscopic vision tests utilizing various stereograms (Fig. 7). In each case, the left and right eyes are presented with distinct images, with their synthesis managed through the same VR-based software tools, offering an efficient and versatile solution for vision therapy.

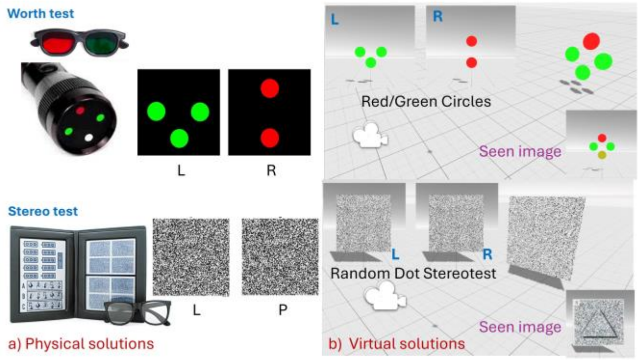

Fig. 7. Tests of simultaneous perception, fusion and stereo.

The aforementioned tests can also be adapted to include alternative configurations, such as vergence and accommodation settings corrected for a distance of approximately 1.6 m, or vergence settings designed for near (0.4 m) and far (6.0 m) distances.

Beyond the examples of conventional optometric diagnostic tests, there is significant potential for implementing vision therapy solutions in virtual environments. These tests can range from general applications, such as the presentation of simple 2D geometric shapes or 3D solids, to more specialized and thematically tailored scenarios designed for specific occupational groups. Visual content for these tests may include both image sequences and video materials. A key component of such tests is the interaction required from the user in response to the presented stimuli.

In virtualized tests, this interaction is most effectively facilitated using standard VR equipment, including handheld controllers. These controllers allow users to perform tasks such as identifying and selecting objects or figures specified in the exercise instructions. Utilizing the measurement capabilities inherent to the VR environment, this interaction enables the assessment of reaction times, response accuracy, precision, and task execution methodology. For instance, monitoring the trajectory of controller movements provides valuable diagnostic insights into task performance. Examples of VR content designed for hand-eye coordination tests are presented in Fig. 8.

Ongoing implementation efforts for selected gamified elements are aimed at enhancing key functions of the visual system, including visual memory, hand-eye coordination, peripheral stimulus sensitivity, reaction times, fusional ranges, and the development of accelerated visual analysis capabilities. Furthermore, these efforts extend to the development of profession-specific solutions, utilizing photographic and video content derived from highly realistic VR environments, as detailed in the subsequent section.

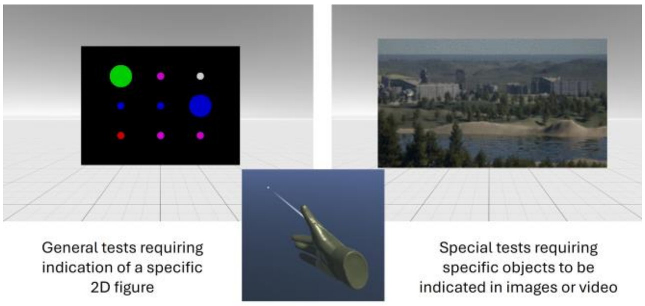

Fig. 8. Example implementations of eye-hand tests.

System concept - state of implementation

The proposed experimental setup is conceptualized as a modular system, suitable for both research applications and clinical vision therapy, integrating presentation, measurement, and control functionalities. It comprises four primary components:

User Component: A wireless HMD VR device designed for the presentation of specialized optometric tests to participants.

Operator Component: A workstation dedicated to the individual supervising the test procedures, such as an optometrist in a clinical setting or a researcher in a laboratory environment.

Network Module: A system enabling coordination between the user and operator components, capable of functioning within a local network or a global network via a web server, database access, and FTP server.

VR Server: A high-performance computing unit configured with a realistic VR environment, serving as the source for generating and delivering training materials.

This system is designed to provide an adaptable and efficient platform for both vision therapy and experimental research applications.

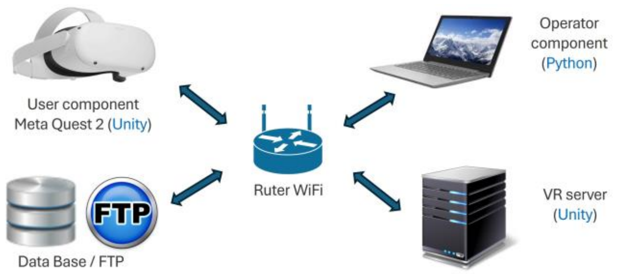

Fig. 9. Key components of the vision diagnostics, therapy and training stand.

The user component of the system is comprised of the wireless Meta Quest 2 headset and its accompanying controllers. The Meta Quest 2 is among the most widely utilized HMD VR devices, attributed to its affordability, availability of compatible software, and robust technical specifications, including 6DoF tracking, an 89-degree field of view, a screen resolution of 1832×1920 per eye at 90Hz, adjustable IPD settings (58 mm, 63 mm, 68 mm), and a lightweight design of 500 g. Furthermore, its programmability via popular platforms such as Unity 3D has significantly contributed to its widespread adoption.

The authors of the presented measurement system did not aim to develop an application for dedicated commercial deployment on HMDs. Instead, the focus was placed on creating a flexible framework capable of accommodating frequent and extensive modifications to both application functionality and the content it delivers. As a result, the application installed on the headset contains minimal preloaded presentation materials for optometric testing. Rather, it serves as a modular framework designed to dynamically receive externally sourced data specific to the requirements of each test, facilitated by advanced network communication capabilities.

From the perspective of the user operating the HMD, the application has been optimized for simplicity, limiting interactions to only those necessary for the execution of the specific tests, thereby ensuring an intuitive and streamlined user experience.

The operator component comprises an external desktop or laptop device responsible for managing the HMD application. The operator application is primarily designed to reduce the cognitive load on the user by automating tasks unrelated to the execution of the test itself. The operator overseeing the session—whether a clinical optometrist or a laboratory researcher—can modify test parameters and access results, along with integrated analysis tools.

The experimental system is designed to support both clinical and laboratory use, resulting in the development of two distinct variants of the operator application. The basic variant provides functionality for selecting tests from a predefined library and configuring their parameters, tailored for clinical environments and intended for use by optometrists. For laboratory settings, which require frequent modifications and testing of new functionalities within the experimental system, an advanced version of the application has been developed.

The operator application is built in Python and incorporates graphical user interface (GUI) elements optimized for both clinical and laboratory use cases, ensuring adaptability and usability across diverse operational contexts.

The network component is a public web server that provides access to a database and files hosted on an FTP server. The database contains critical information, including configuration settings for HMD devices used in the experimental system, details of available virtualized tests and their associated parameters, and records of completed studies and analyses involving test participants (e.g., obtained results and survey data related to test experiences and the use of VR headsets). Extensive data is stored in JSON files on the FTP server, which also houses all other files required by the HMD application to generate virtual scenes for each test.

This network component functions as a centralized data repository with three primary purposes: enabling research and facilitating the introduction of new solutions within the experimental system, providing the necessary data for the virtualization of individual tests using HMDs, and serving as a resource for assessing the diagnostic accuracy and therapeutic efficacy of vision therapy conducted within virtual reality environments.

The VR server is a dedicated high-performance computing unit optimized for rendering highly realistic 3D scenes. This system functions as a virtual vision platform, enabling the generation of photographic and video content for creating 2D and 3D visualizations compatible with HMDs. Currently, a single environmental model has been developed, featuring seasonal and time-of-day variations and encompassing a 6 km × 6 km area with diverse topography, forest cover, and built structures. Visual materials derived from this environment can be used to prepare training content for various professional applications.

Current development efforts are focused on creating training materials specifically designed for drone operators. Commands issued to the VR server facilitate the customization of flight paths and speeds, the positioning of objects of interest, and the adjustment of image parameters, including field of view, resolution, and contrast. In addition to generating the visual materials required for each test, the VR server produces a corresponding JSON file containing metadata essential for the automated analysis of individual user interactions within the test environment.

The optometric tests proposed so far do not require image streaming from a VR server (although such a possibility has also been implemented). The (highly realistic) pictorial training material prepared by the server is downloaded before the test begins and then displayed in the goggles when the test is run.

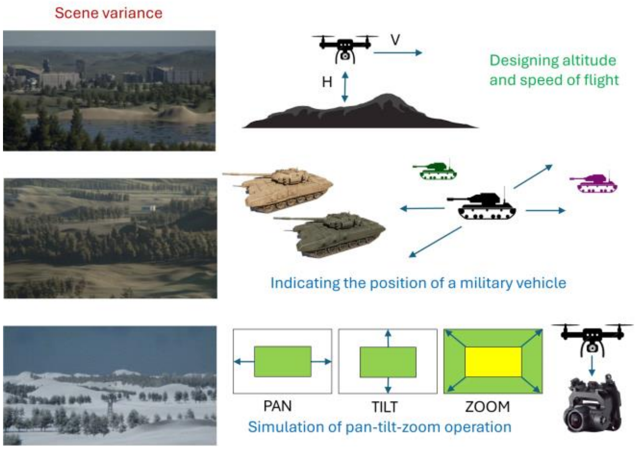

Fig. 10. Acquiring data from a VR server and using it for vision therapy.

The headset software is implemented as a first-person perspective application. The user's avatar is situated in a minimally detailed virtual environment designed to reduce distractions. Within the user’s field of view, floor-level markers are displayed to indicate the approximate locations where upcoming tasks will appear. The readiness of each test is signalled by the illumination of the corresponding floor marker. Tests are activated only when the user’s avatar enters the designated area. Prior to the commencement of the test, a brief instructional module (delivered in text or video format) is presented to familiarize the user with the test procedure and objectives.

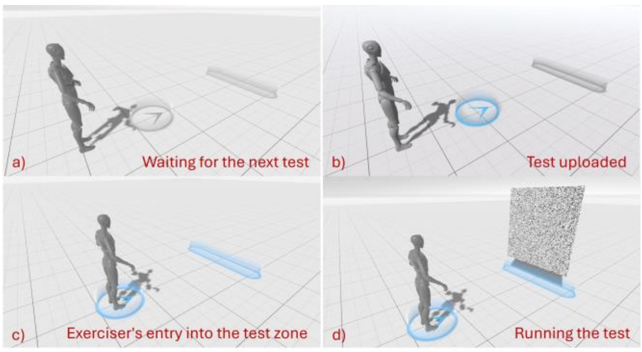

Fig. 11. Visualize key elements of vision diagnosis/therapy/training with HMD VR

Test subject wearing goggles with VR environment running, awaiting possibility of further testing. The operator (from his own GUI) decides which test will be activated and with what parameters. The relevant data for each test is sent using JSON structures via socket communication and/or entered into a database depending on the type of operator (lab / office). The test run in the goggles is automated and handled by the Unity environment, which executes the test procedure in an appropriate manner as well as reacts to the avatar's (test subject's) actions. Verified (successfully in the laboratory variant) were (among other things) the possibilities of streaming the image seen from the perspective of the avatar as well as transmitting on-lines only a limited amount of data in the form of position and rotation of controllers and goggles (with the possibility of synthesizing on this basis the view of the scene already on the operator's side - the scene seen from the perspective of the practitioner). However, there is no need to transmit this kind of data. The tests are relatively short, and it is sufficient to send at the end of each test the partial and summary data in the form of appropriate JSON structures (relative to each test). Therefore, the amount of transmitted data in the system has been reduced to the absolute minimum

The measurement capabilities of the VR system are primarily designed to establish temporal and spatial relationships between "purely virtual" objects within the VR environment (e.g., displayed stimuli) and the real-time virtualized coordinates of "physical objects," such as the HMD and controllers. Access to these data facilitates both real-time analysis (e.g., influencing the progression of a test, such as determining ocular dominance) and post-processing analysis, conducted on an external computational unit following the transmission and archival of data outside the HMD.

Preliminary test results

The primary aim of the initial tests involving virtualized elements of vision diagnostics and therapy was to evaluate the implementation with respect to the accuracy of the presented stimuli and their expected visual effects (e.g., stereoscopic visualization, simultaneous perception, and fusion) as well as the procedural flow of the tests (e.g., determination of ocular dominance). Comparative assessments were conducted using conventional stereopsis and Worth tests alongside their VR-based equivalents.

The study included 12 participants, 10 of whom exhibited normal binocular vision (demonstrating simultaneous perception, fusion, and stereopsis), while two participants had suppression in one eye due to strabismus (lacking simultaneous perception, fusion, and stereopsis). Results obtained from the conventional optometric tests and their VR-based implementations were found to be entirely consistent.

Furthermore, the effectiveness of virtual tools in enhancing visual skills was analyzed. A commonly used category of vision therapy exercises focuses on improving eye movements and hand-eye coordination. Examples include Marsden ball exercises involving oscillatory movements, perceptual-motor activities using a pen, and computer-based tasks with random visual stimuli requiring manual responses. These exercises aim to improve the eye-hand coordination, which is critical for activities such as handwriting (children), operating specialized tools (adults), or catching a ball (athletes). Virtual equivalents of these exercises were also developed.

One such virtual test involved the use of a controller to select newly appearing objects on a rotating disc. A key performance parameter measured during this test was reaction time, defined as the interval between the appearance of a stimulus and the user's selection of the object using a light beam representing the controller's directional vector. The average reaction time recorded during a session served as one of the primary metrics for assessing the participant's current skill level. Periodic evaluations of user performance were conducted to measure improvements in efficiency before and after therapy, with enhancements typically quantified by increased speed and accuracy in task execution.

This test was administered to a group of 10 students over five training sessions conducted at weekly intervals. A visualization of the stimuli presented within the HMD and the corresponding results are shown in Figure 12.

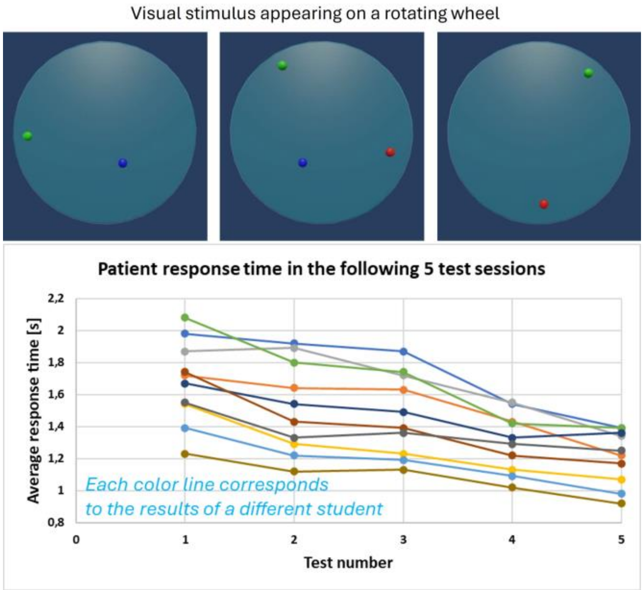

Fig. 12. Patients' reaction time results during the different training sessions.

The statistical analysis employed in this study utilized a paired t-test to assess the significance of observed changes. This method evaluates whether the mean difference between two sets of observations significantly deviates from zero and is commonly applied in experimental designs where the same individuals are measured twice, such as in pre-test and post-test comparisons.

For this test, the statistical analysis compared the results obtained by participants during the initial and final sessions. The paired t-test was used to determine whether the observed improvements were statistically significant. Key metrics include the calculated t-statistic and p-value.

$$(1) \quad t = \frac{\bar{d}}{\frac{s_d}{\sqrt{n}}} \qquad \bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_i \qquad s_d = \sqrt{\frac{\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2}{n-1}}$$

$$(2) \quad d_i = x_{i,\mathrm{post}} - x_{i,\mathrm{pre}}$$

The values x_{pre} and x_{post} denote the corresponding pairs of the first and last tests and *n* the number of pairs.

$$(3) \quad p = 2 \times P(T > |t|)$$

T represents the t-distribution with $n-1$ degrees of freedom and $P(T>|t|)$ is the probability of observing a value more extreme than the calculated $|t|$.

The t-statistic (T = 11.07), representing the magnitude and direction of the observed change, is substantially different from zero, indicating that the difference between pre-test and post-test results is unlikely to be due to random variation. Additionally, the p-value (P = 2e-6), significantly below the standard threshold of 0.05, confirms that the observed improvements are statistically significant, suggesting a meaningful effect of the therapy.

This analytical approach demonstrated that vision training using virtual reality can improve patients' reaction time, while providing researchers and clinicians with valuable insights into assessments of the effectiveness of the proposed therapy. In this instance, the successful application of a virtualized version of the test underscores the potential effectiveness of exercises leveraging virtual technologies in vision therapy.

Summary

Virtual technologies are increasingly applied across diverse fields, including medical diagnostics and therapy. Despite technical limitations in commercially available VR headsets—such as angular resolution below the visual acuity of the human eye and the presence of vergence-accommodation conflicts in devices like HMDs—both existing literature and the authors' findings indicate that the virtualization of optometric tests facilitates effective diagnostics and vision therapy.

To support advancements in this domain, the authors propose the use of the widely accessible Meta Quest 2 headset. While the device's ability to render complex and highly realistic 3D scenes is limited, this constraint is addressed by incorporating visual content (e.g., photographs and video sequences) generated by an external VR server. Unlike other VR solutions for vision therapy described in the literature, the proposed system minimizes the operational demands on the end user by delegating the majority of application management tasks to an operator station. This system configuration integrates communication tools and network resource access as central features. To reduce laboratory development timelines and accelerate the deployment of new solutions for clinical testing, the extended operator station is equipped with functionalities for the rapid preparation and dissemination of new tests via network resources.

The authors note that previous work and the solutions presented in the article did not require the collection and transfer of sensitive data (the test and the subject had randomly generated IDs, which are stored in a database for possible comparison of results, should the specifics of the test require it). Participants were introduced to the methodology and objectives of the tests, which focused on verifying the possibility of getting identical results (in a qualitative and quantitative meaning) for physical tests and their virtual equivalents. Current work on the proposed system, aimed at enhancing collaboration between research and optometric professionals, remains at an early stage. Similarly, the virtualization of tests has so far been limited to the development of foundational tools for their implementation in VR. Upcoming efforts will prioritize the broader incorporation of video content derived from realistic virtual environments managed by the VR server. An additional focus will be on developing tools for automating the analysis of patient data collected during tests. This includes creating systems for the simultaneous generation of metadata required for each test, particularly within the domain of vision therapy.

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