Realter: An Immersive Simulator to Support Low-Vision Rehabilitation

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Abstract. The project REALTER (wearable egocentric altered reality simulator) exploits immersive technologies and extended reality (XR) environments to support low-vision rehabilitation, by offering an immersive simulator of low-vision conditions. Perceiving and navigating the world as low-vision individuals has the potential of being a useful tool for ophthalmologists and visual rehabilitators to increase empathy with the assisted population and to improve the existing therapeutic techniques. Additionally, by analyzing ocular movements acquired during experimental sessions with healthy-sighted individuals in a condition of simulated low vision, researchers may collect quantitative data to extend the state of the art in understanding the behavioral changes of low-vision persons. The project involved the implementation of an immersive system by using commercial device tools currently available on the market. The hardware consists of an immersive virtual reality (VR) headset with an integrated eye tracker and a pair of external cameras, to provide gaze-contingent altered/extended reality (XR) content by a pass-through modality. The software can realistically simulate several low-vision conditions, such as age-related macular degeneration, glaucoma, and hemianopsia, and simultaneously acquire eye and head movements for data analysis.

Keywords: Extended Reality (XR) · gaze-contingency · low-vision rehabilitation

1 Introduction

In 2014 the number of visually impaired persons (VIPs) worldwide was estimated to be 285 million, of whom 39 million were totally blind and 19 million were children below the age of 15 [1]. Many persons who are registered as blind nevertheless retain some residual vision and are said to have "low vision". In most cases, low vision concerns damage – or in some cases loss – of the peripheral or central vision. The specific form of visual impairment varies according to the individual medical condition, but often low-vision people experience an extreme loss of high spatial frequencies perception and a

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reduction of the field of view (FOV). Depending on the specific pathological conditions, this loss affects the central area of the FOV (maculopathy), the peripheral area (tubular vision), or half of the vertical FOV (hemianopsia). Individuals affected by maculopathy show symptoms as a distorted vision in the form of metamorphopsia in addition to the appearance of a dark-grey spot [2]; tubular vision, also known as "tunnel vision", is the loss of peripheral vision with retention of central vision, resulting in a constricted circular tunnel-like FOV [3]; hemianopsia is a loss of vision or blindness (anopsia) in half the visual field, usually on one side of the vertical midline [4]. The acquisition of rehabilitation techniques requires a strong immersion in the reality of daily life to understand how patients experience their low vision condition. If simulating absolute blindness is achievable with empirical methods, simulating low vision is much more complicated but fundamental for the accurate training of the rehabilitation operator. This is even more complicated given the wide variety of low-vision symptoms, which makes it hard for rehabilitators to figure out how their patients perceive the environment. This difficulty inevitably causes "gaps" in rehabilitators' training path. Past attempts to simulate visual impairments using immersive technology such as virtual reality (VR) and augmented reality (AR) have already been made. Jones et al., [5] developed gaze-contingent simulations of visual impairment presented using head-mounted displays (HMD). They concluded that the simulator could replicate and objectively quantify some of the key everyday difficulties associated with visual impairments. Starting from the advantages described by Jones, our research project aims to create an immersive extended reality (XR) experience in order to simulate the effects of low vision for rehabilitators of VIPs. Differently from Jones et al. which explored both VR and AR with emphasis on glaucoma, we focused on an AR approach. Specifically, we addressed the idea of measuring visually guided behavior in a real environment in the presence of several low-vision disabilities (see Sect. 3) and the possibility of simulating low vision conditions monocularly or binocularly. In this paper, we introduce this eye-contingent, binocular simulation, in which the view of the real world is altered in real-time in a controlled and personalized way, and we refer to it as *alTered Reality* (TR).

2 Project Requirements

The project was conducted in collaboration with ophthalmologists from the *Chiossone Institute for Blind and Low-Vision Individuals* in Genoa.

The *Chiossone Institute* is familiar with the training of ophthalmologists based on "analogic" tool simulating low-vision conditions, such as spectacles with semi-transparent lenses to simulate a loss in acuity, or cardboard masks covering part of the field of view. The objective of the project REALTER is to make the training more effective, efficient, and intuitive, improving the empathy level of the rehabilitators towards the people they assist. To achieve this goal, the project investigates how to replace these tools with TR immersive simulation and improve the realism of the simulation by exploiting eye-movement contingency. Starting from the need for assessing the best rehabilitation strategy according to the specific pathology, REALTER project adopted TR for altering normal sight and rendering the perception of several low-vision conditions.

In the current state of the art, XR is defined as an umbrella term to group all immersive technologies as virtual reality (VR), augmented reality (AR), and mixed reality (MR) [6].

The peculiarity of immersive technologies is the ability to elicit a sense of immersion and presence. Immersion intended as a physical phenomenon is a unique feature of immersive technologies, (immersion as a mental phenomenon is proper of other media) and it is achieved when a user interprets visual, auditory, and haptic cues to gather information and navigates and controls objects in the synthetic environment [7]. On the other hand, presence is defined as a person's subjective sensation of being in a scene depicted by a medium, usually of virtual nature [8].

According to Azuma et al. [9], "The basic goal of an AR system is to enhance the user's perception of and interaction with the real world through supplementing the real world with 3D virtual objects that appear to coexist in the same space as the real world". REALTER required interaction with the real world, altered by simulated low-vision diseases. For this reason, we employed a peculiar form of AR in which the real world is not augmented, but altered by computer graphics, in order to resemble the reality of low-vision individuals. Most AR head-mounted displays (HMD) adopt optical see-through (OST) displays to allow the users to see the real world with their own eyes through a transparent lens. Differently, REALTER employs stereoscopic video see-through (VST) HMDs, in which the user's visual perception of the 3D world is mediated by two different optical systems, i.e. the acquiring camera and the visualization display [10]. Indeed, OSTs are unable to display image effects in the proper way due to the incapacity of displaying black or opaque contents [11]. In the low-vision rehabilitation scenario, where accuracy and realness of simulations are required at the highest level, OST limitations cannot be ignored. For these reasons, even if both technologies are currently used for augmented reality applications [12], HMD with pass-through cameras was chosen instead of OST for the current study.

To realistically simulate low-vision conditions and meet the *Chiossone Institute* needs, we identified the following hardware and software requirements:

1. An *immersive portable system* able to acquire images from the real world and display content in real-time and in an immersive way.
2. An *eye tracker* to record users' ocular movements and enable the gaze-contingent paradigm as human-computer interaction.
3. A *software able to acquire and process images* of the real world in real-time, to alter reality to simulate low vision effects through the gaze-contingent paradigm.
4. *Gaze-contingent paradigm* to update the position of the disabilities according to the current subject's fixation point.
5. *Binocular image processing* to simulate realistically low-vision conditions. Since low-vision conditions affect each eye differently, we managed to render images to the left and right eye separately.
6. *Ocular movements data* storage to conduct quantitative analysis, such as the detection and characterization of saccadic eye movements and fixations.

3 Research, Design, and Measurements

3.1 User Research

Thanks to a close partnership with ophthalmologists and rehabilitators of the *Chiossone Institute for Blind and Low-Vision Individuals*, the project design followed a user-centered design approach divided into three stages:

1. **Identification stage**: involving ophthalmologists' background knowledge to understand the effects of low-vision disabilities. The ophthalmologists identified the low-vision diseases more widespread and difficult to empathize with. Binocular maculopathy, tubular vision, and hemianopsia were chosen for the simulator (Fig. 1).
2. **Simulation stage**: By implementing shader graphics and 2D images overlapping the images acquired through the cameras, it was possible to recreate an altered reality that resembles the point of view of several low-vision individuals. All simulations used the gaze-contingent paradigm.
3. **Evaluation stage**: Every low-vision simulation was qualitatively evaluated by ophthalmologists wearing the immersive system, in order to approve or edit the realness of the simulation in terms of appearance and behaviors (Fig. 2).

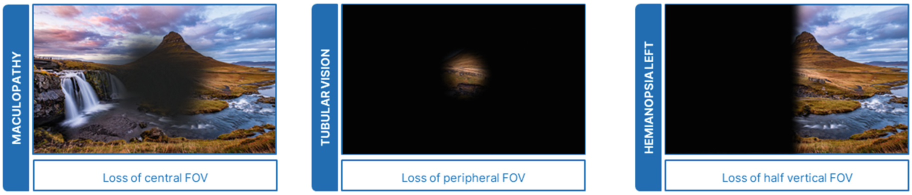

Fig. 1. The three groups of low vision disabilities are currently implemented in REALTER portfolio. Loss of central FOV (left), loss of peripheral FOV (center), loss of half FOV (right).

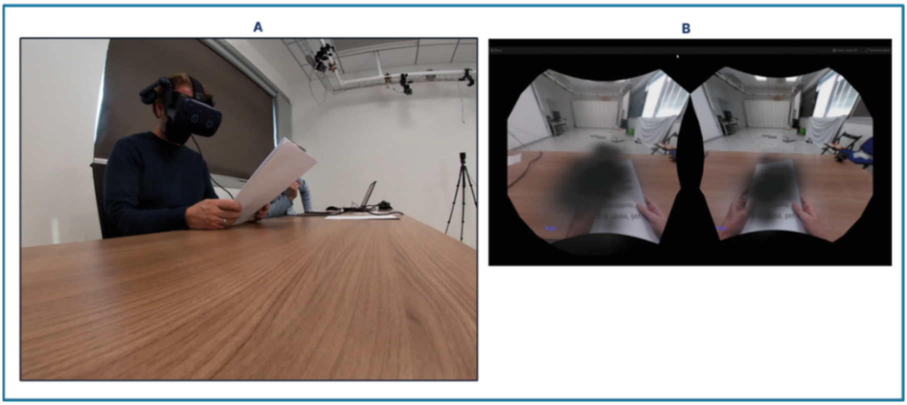

Fig. 2. Evaluation stage with Chiossone Institute's ophthalmologists. **Panel A**: frame extract from video recorded with an external camera. **Panel B**: immersive experience recorded from headset.

3.2 Immersive System Design

From the hardware perspective, at the current state REALTER is composed of:

- **HTC Vive Pro Eye**: an immersive VST HMD. This headset is equipped with a dual 3.5-inch screen size with resolution 2880 × 1600 pixels, which is split into two

displays with resolutions 1440 × 1600 pixels per eye and pixels density equal to 615 pixels per inch (PPI). HTC Vive Pro Eye is able to reproduce contents with a refresh rate of 90 Hz and diagonal FOV of 110° and requires a connection with a computer and two external base stations. The device is also equipped with an integrated Tobii eye tracker with an estimated accuracy of 0.5°–1.1° and a sampling frequency of 120 Hz. SteamVR Tracking, G-sensor, gyroscope, proximity, inter-pupillary distance (IPD) sensor, are also included in the headset to track head movements and rotations. HTC Vive Pro Eye, as XR headset, ensures the possibility to exploit the altered world through a totally immersive experience.
- **Stereolabs Zed Mini**: external cameras to provide high resolution images of the real world. Adopting Zed Mini as replacement of the embedded HTC Vive Pro Eye AR cameras improved the maximal spatial resolution (from 480p to 720p), at the expense of field of view (from 96° to 90° in horizontal FOV; from 80° to 60° in vertical FOV). Despite the loss of FOV, the replacement of cameras for AR allows a higher visual acuity and reduces the motion sickness effects.
- **HP VR Backpack G2**: wearable computer wired to HMD and cameras. PC uses Windows 10 as operating system, Intel Core i7-8850H as processor, NVIDIA GeForce RTX 2080 with 8 GB dedicated GDDR6 as graphic card, and Mini DisplayPort 1.4, USB Type-C Thunderbolt 3 enabled with DisplayPort 1.2, DisplayPort 1.2 on HP Z VR Backpack Dock as video outputs. By deploying a wearable PC, it is possible to make the system portable (Fig. 3).

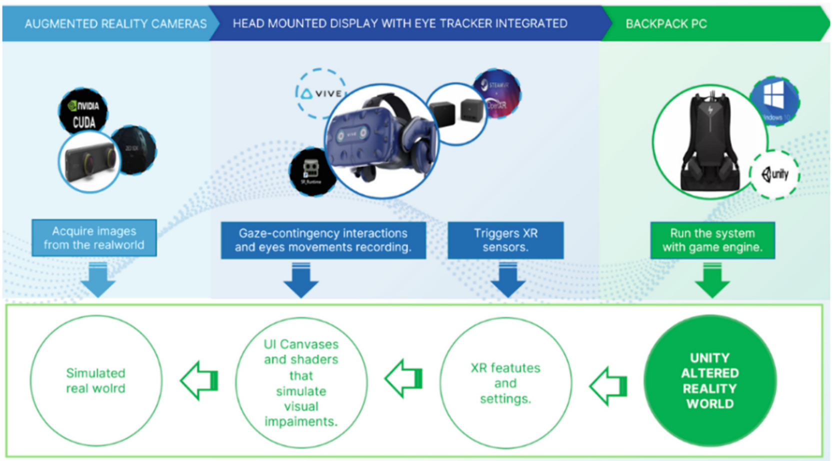

Fig. 3. The REALTER architecture.

The software was developed in Unity game engine with C# as programming language (version 2021.3.3f1). The system requires the installation of ZED SDK 3.7.0, Cuda 11.6.1, SR Runtime, SteamVR 2.7.3. Unity game engine also requires several SDKs: OpenVR through importing in project SteamVR v1.14.15, ZED SDK v3.7, and SRanipal v1.3.6.

The eye tracker integrated in the HMD allows the storage of data about subjects' ocular movements and the design of gaze-contingent simulations. Since most low-vision diseases affect the same part of the retina while the eyes are moving, a gaze-contingent paradigm is required to update the position of the disability according to the subject's fixation point (Fig. 4, Panel A shows fixation points). By combining gaze information from SRanipal and head movements from SteamVR, it is possible to integrate a gaze-contingent paradigm. To simulate low-vision diseases in AR, 2D images and 3D game objects rendered with shaders are overlaid onto real-world images captured by Zed Mini cameras. Each visual condition required specific techniques to be implemented.

The computer keyboard was chosen as a tool for interacting with the interface: by pressing the keyboard button is possible to trigger low-vision disabilities and functionalities, such as start/stop storing data or launch eye calibration. All instructions are stored in a specific menu (Fig. 4, Panel B).

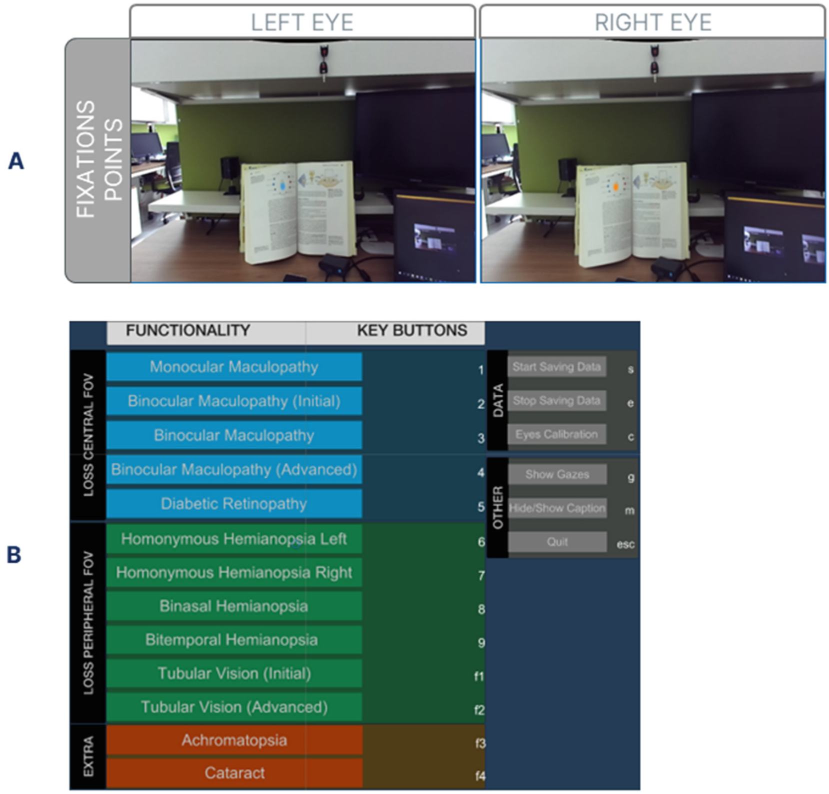

Fig. 4. REALTER functionalities. Panel A: Fixation points (blue left eye, orange right eye). Panel B: main menu. (Color figure online)

3.3 Gaze-Contingent Simulations

3.3.1 Maculopathy

Maculopathy can affect one or both eyes. For this reason, REALTER is equipped with a simulation of both monocular and binocular maculopathy (BM).

- **Monocular maculopathy:** the right eye is affected by a form of maculopathy that manifests itself as an image distortion and blur effect at the center of both eyes FOV (Fig. 5, Panel A).
- **Early-stage BM**: both eyes are affected by a form of maculopathy that manifests itself as an image distortion and blur effect at the center of both eyes FOV (Fig. 5, Panel E).
- **Medium-stage BM**: both eyes are affected by a dark-grey spot at the center of the FOV and a warping distortion at the spot edge (Fig. 5, Panel C).
- **Advanced-stage BM**: both eyes are affected by a dark-grey spot at the center of the FOV and a warping distortion at the spot edge. All the background is rendered with a blurred effect and a yellow-based filter effect. (Fig. 5, Panel B).
- **Multiple maculopathy**: both eyes are affected by multiple dark-grey spots all over the FOV. The background is rendered with a blurred effect and color loss (Fig. 5, Panel D).

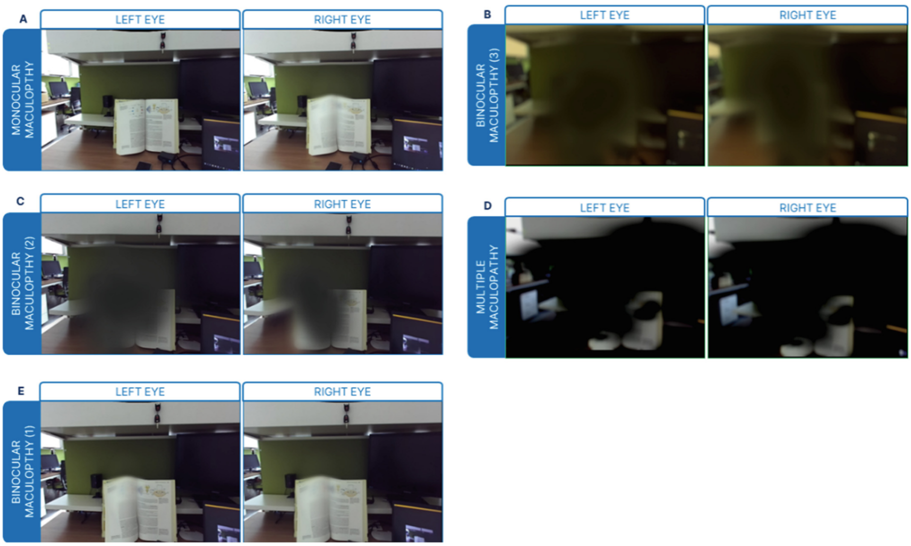

Fig. 5. Examples of different maculopathy simulations. Panel A: monocular maculopathy on the right eye. Panel B: advanced status of binocular maculopathy. Panel C: common binocular maculopathy that simulates age-related macular degeneration. Panel D: multiple maculopathy that simulates an advanced status of diabetic retinopathy. Panel E: early-stage binocular maculopathy.

3.3.2 Hemianopsia

Since, during the identification stage of the design process, it has emerged that hemianopsia affecting one eye is quite rare, all the simulations of hemianopsia involved both eyes. Namely, REALTER simulates homonymous and heteronymous hemianopsia. All hemianopsia are simulated by a 3D object in front of the camera's FOV, rendered with a shader that blurred the specific image portion.

- **Homonymous Hemianopsia Left**: both eyes are affected by the loss of the left half of the field of view. (Fig. 6, Panel A).
- **Homonymous Hemianopsia Right**: both eyes are affected by the loss of the right half of the field of view. (Fig. 6, Panel C).
- **Heteronymous Bitemporal Hemianopsia**: the left eye is affected by the loss of the left field of view; the right eye is affected by the loss of the right field of view. Namely, individuals affected by this form of hemianopsia suffer from loss of FOV close to the temples (Fig. 6, Panel B).
- **Heteronymous Binasal Hemianopsia**: the left eye is affected by the loss of the right field of view; the right eye is affected by the loss of the left field of view. Namely, individuals affected by this form of hemianopsia suffer from loss of FOV close to the nose (Fig. 6, Panel D).

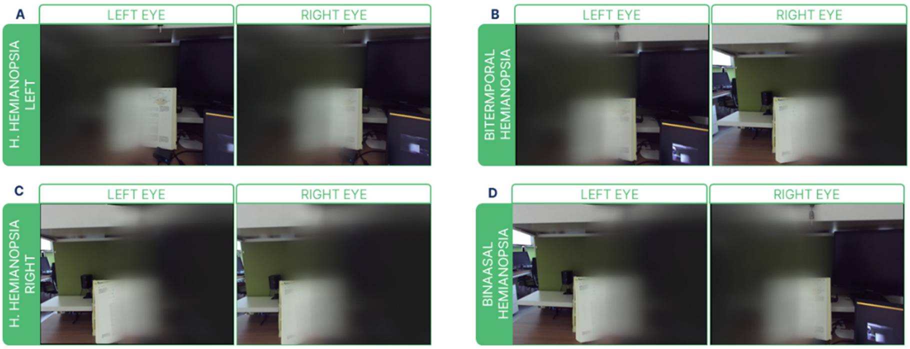

Fig. 6. The different types of simulated hemianopsia. Panel A: left homonymous hemianopsia. Panel B: heteronymous bitemporal hemianopsia. Panel C: right homonymous hemianopsia. Panel D: heteronymous binasal hemianopsia.

3.3.3 Tubular Vision

REALTER implements two types of simulations for binocular loss of peripheral vision. Both simulations are obtained by overlapping a virtual object in front of the cameras:

- **Early-stage tubular vision**: both eyes are affected by a peripheral loss that manifests itself as a blurred effect. The left eye is affected by the loss of the left peripheral FOV; the right eye is affected by the loss of the right peripheral FOV (Fig. 7, Panel A).
- **Advanced-stage tubular vision**: both eyes are affected by a significant loss of peripheral FOV. The FOV lost is perceived as totally dark grey (Fig. 7, Panel B).

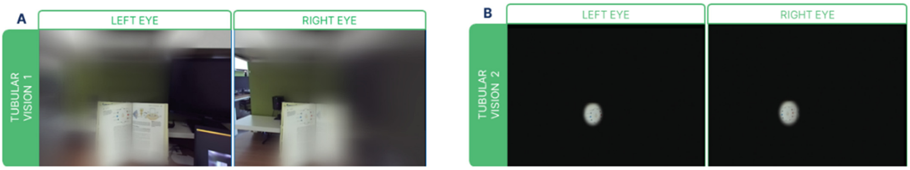

Fig. 7. The two simulated conditions of tubular vision. Panel A: tubular vision at an initial stage. Panel B: tubular vision at an advanced stage.

3.4 Data Acquisition and Storage

Time information is obtained by either the timestamps from SDK SRanipal or Time.fixedTime from Unity Engine. Since the employed version of SRanipal has not been improved from a timestamp bug as reported by Imaoka et al. [15], we preferred to use the time data from Unity.

Eye movement data from both the left and right eye were read from VerboseData in the struct data of ViveSR.anipal.Eye.EyeDatav2 as Imaoka et al. already validated: validity of eye data, eyes openness, pupil diameter ([mm]), pupil position (normalized vector between −1 and 1), gaze origin ([mm]), and gaze direction (normalized vector between −1 and 1). The possibility to store ocular data is a core feature of the system to get quantitative measurements. Gaze origin and gaze direction information enable to quantify distinctive features of ocular movement such as saccades and fixations. Investigating eye movements for each simulated low-vision disability, in terms of occurrence, duration, and amplitude could be relevant to understand how low-vision conditions affect the performed eye movements. For example, when reading a text, a healthy-sighted individual alternates fast horizontal linear saccades and long fixations [13]. During the same task, in the condition of simulated or real binocular maculopathy, we expect a different behavior, such as a higher number of nonlinear saccades, and shorter periods of fixations [14]. Basically, we aim to underline the differences in ocular behaviors between all simulated low vision conditions and healthy sight. When making comparisons, it's important to take into account the limited resolution of the cameras used in the developed system. Therefore, it would be more appropriate to consider the condition of vision through the cameras without any simulated low-vision conditions as the "healthy sight" condition.

Moreover, head data can be stored from Unity.Engine.XR in the struct data of InputTracking.GetLocalPosition(XRNode.CenterEye). Head data are crucial to quantify and describe how low-vision disabilities affect head kinematics in VIPs and the behavioral strategies they apply to compensate for their disability.

All data listed above can be stored in a.xlsx file for processing.

3.5 Preliminary Results

Although a quantitative evaluation of REALTER is currently missing, in this section, we present some preliminary results collected during the validation stage of the immersive system. To assess qualitatively the different low-vision conditions, an ophthalmologist from the Chiossone Institute was asked to perform a reading test. Being in a sitting position and keeping the head fixed, the ophthalmologist was asked to read a text in his mother tongue on an A4 format paper written in Times New Roman 72 (font). The test was performed wearing the REALTER system under three different low-vision conditions (one for each macrofamily presented in 3.3) and in a healthy-sight condition. Specifically, a medium stage of binocular maculopathy (Fig. 5, Panel C), homonymous hemianopsia right (Fig. 6, Panel A), and advanced-stage tubular vision (Fig. 7, Panel B) have been chosen as low-vision conditions. In the healthy-sight condition, the subject wore the system, but no visual warp has been applied. The focus of the test was to achieve preliminary knowledge about the different behaviors of the oculomotor system in the four different visual conditions, particularly in terms of saccades' number and magnitude, and scanpaths. To detect saccades, we used REMoDNaV [15], and existing software able to recognize and detect ocular movements from eye tracker data. In addition, plotting the fixation points in the visual scene, we extracted a scanpath of ocular movements.

The preliminary results showed significant alteration in the oculomotor system from healthy sight to low-vision conditions (Fig. 8). In particular, the healthy-sight condition showed linear saccades which follow the distribution of the words on the paper surface. Contrarily, the path of binocular maculopathy was unstable, with several and wide saccades in different directions. Saccades in homonymous hemianopsia were more linear than in binocular maculopathy, and mainly restricted in the healthy side of the FOV. The amplitude of saccades was still higher than in the healthy-sight condition. Finally, tubular vision was overall the closest to healthy sight, both in terms of scanpath and in the properties of the saccades detected.

Starting from these results, future work will include the quantitative validation of the immersive system in a more comprehensive experimental session. Specifically, the focus will be to assess the real potential of REALTER to induce, in healthy sight subjects under simulated low-vision conditions, the same alteration detected in subjects affected by binocular maculopathy, homonymous hemianopsia, and tubular vision.

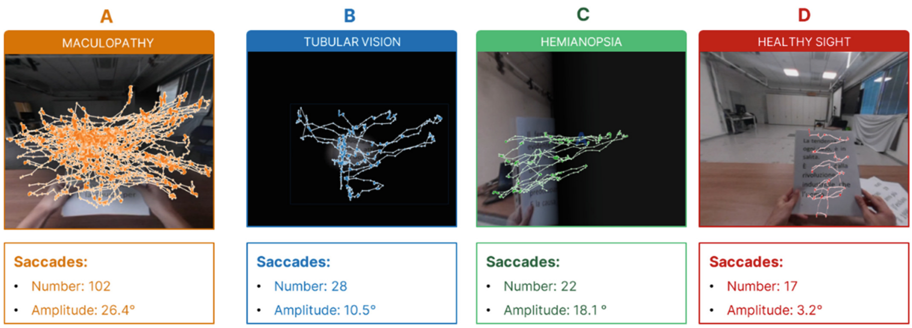

Fig. 8. Preliminary test results. Panel A: binocular maculopathy outcome. Scanpath (above); saccades detection (below). Panel B: tubular vision outcome. Scanpath (above); saccades detection (below). Panel C: homonymous hemianopsia outcome. Scanpath (above); saccades detection (below). Panel D: Healthy sight outcome. Scanpath (above); saccades detection (below).

4 Conclusions

The presented work involved the development of a system able to arouse a sense of immersion and presence in order to let users experience the condition of disability brought by several different low-vision impairments. Thanks to the active involvement of the ophthalmologists from Chiossone Institute, it was possible to develop an exhaustive simulator of low-vision conditions based on a peculiar form for XR that we called TR. Several user tests conducted on ophthalmologists validated the system as a simulation tool for low-vision conditions. What is currently missing is the quantitative assessment of the validity of REALTER as a system able to reproduce with high accuracy ocular movements performed by low-vision individuals. In order to do this, future perspectives will consist of 1) a collection of experimental data from healthy-sighted subjects in simulated low-vision conditions during the performance of daily activities such as reading a text, navigating the space, and manipulating objects; 2) the interpretation of the data collected under different simulated low-vision conditions and the comparison between them and with the behaviors of visually-impaired people with an equivalent level of disability.

Nonetheless, there are some limitations inherent in the hardware components that must be appointed. Previous studies consider 250 Hz as the threshold to separate eye trackers with low-speed sampling frequency from high-speed sampling frequency [16]. With its sampling frequency of 120 Hz, HTC Vive Pro Eye belongs to the first category. Despite HTC Vive Pro Eye as a tool to assess saccadic movement in VR was already explored with optimal results from Imaoka et el [16], employing this type of eye tracker brings some limitations when considering eye movements different from fixations or saccades. Eye trackers employed in the research field to detect microsaccades have a minimum sampling frequency of 200 Hz [17]. Analogously, eye tremors present an average frequency of 90 Hz: since according to the Nyquist-Shannon theorem a sampling frequency at least twice as large as the frequency of the recorded movement is needed, eye trackers required a sampling frequency of 180 Hz to detect tremors [17].

However, there are a number of commercial eye-tracking tools with frequencies lower than 250 Hz employed for measurements in the research field and not only as instruments for human-computer interaction or gaming [18]. HTC Vive Pro Eye belongs to this group, and it is intended for measuring slower eye movements such as those in the range of speed of saccades or fixations. In the future, the replacement of the Tobii eye tracker with another one with a sampling frequency higher than 250 Hz should be considered.

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