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Eye Movements and Vestibulo-Ocular Reflex as User Response in Virtual Reality

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Abstract- Virtual reality (VR) is increasingly being used for gaming, training, and health-related applications. However, the level of immersion and presence provided by VR can have a major impact on the user and their ability to achieve desired goals. As a result, methodologies for determining levels of immersion and presence must be established. In this work, we investigate the vestibulo-ocular reflex (VOR) and saccadic eye movements in different VR-exposed patients to see if VR elicits these responses in the same way as real world does. We used an HTC VIVE Pro Eye headset and Tobii Pro Lab software to record head and eye movements while watching a 3D video of a roller coaster ride. Our findings reveal that important parts in the video evoked VOR and saccadic eye movements in most individuals. The remainder paper is organized as follows. Section II presents related works and a comparison of them. Section III introduces the followed methodology in our evaluations and describes the differences on head and eye displacement. Section IV describes the tests performed and the conditions. Section V presents the results obtained from the video and data tests. Section VI presents a discussion on the significance of the obtained results. Section VII presents our conclusions.

Index Terms --Eye movements, head movements, virtual reality, vestibular-ocular reflex, saccadic movements, virtual-reality immersion, measurement of level of immersion.

I. INTRODUCTION

Virtual reality (VR) technology creates a three-dimensional interface that mimics the spatial, temporal, and motion properties of actual reality [1]. VR has been widely adopted to enhance the sensation of unreal circumstances in video games among enthusiasts.

Virtual reality has been shown to improve health outcomes in therapeutic and diagnostic contexts [2]. There is still a need to develop methods for assessing user immersion and presence in virtual reality (VR). Experts in VR technology distinguish two terms: Immersion refers to a user's sense of being fully involved and present in a virtual environment while presence refers to their physiological responses while experiencing VR. The quality of VR scenes affects immersion, although individual users may perceive varying amounts of presence [3],[4]. Humans orient themselves in space using three systems: proprioceptive signals, vestibular apparatus, and visual signals [5, 6, 7]. Using a VR headset might impact visual inputs and vestibular signals due to the presence of video and sensors that simulate a 3D environment [2], [8]. These modifications of reality. Vestibulo-ocular reflex (VOR). This reflex causes the eyes to travel in the opposite direction as the head. Maintaining consistent amplitude of motion allows for visual fixation on a target of interest [13–17]. Daily actions, including driving, often involve motions that gather comprehensive information about the environment [18]. Researchers are increasingly interested in participants' responses during VR encounters.

Pfeil et al. [19] compared head and eye movements in virtual and practical reality situations. This research presents experimental evidence indicating a high correlation between VOR and saccadic movements reflect a person's immersion in virtual reality. A commercially accessible VR headgear with built-in eye-tracking sensors is used to watch and measure saccades. In experiments, people are shown a film of a roller coaster with images that challenge their upright stance as markers to trigger and detect response

II. RELATED WORK

Various methods and tools for tracking eye movements while using a VR headset, or a head-mounted display (HMD), have been studied and analyzed, including an eye-tracking tool, like Tobii and Pupil Labs. However, the VR environment still requires more in-depth study on eye-tracking [27], [28]. For example, Imaoka et al. [29] validated the use of the VIVE Pro Eye headset as a saccadic eye movement recording tool through statistical analysis by reporting results that are within the range of previously reported studies [30].

TABLE 1. Comparison of existing works.

Tracking Tool	Movements	Objective	Pros	Cons
EOG technique, electrodes and HMD motion sensor [31]	Eye & head	Relationship between head and eye movements while stimulus on a HMD	VR scene adaptable Low cost tracking eye system	Electrode sensitive No head movement No VR use
HTC Vive with eye tracker Tobii Technologies and Unity3D engine [19]	Eye & head	Comparison between real & virtual reality	Adaptable scenes	No VOR detection Single scene
Glasses & portable camera [32]	Eye	Gaze estimation accuracy improved by VOR	Low cost	No head movement No VR
Tobii Pro Glasses [33]	Eye & head	Cognitive task triggered by VR	Portable & applicable to reality	No VR
Pupil Labs-HTC Vive Eye Tracking Head mounted display (HMD) sensor for head movement [34]	Eye & head	Effect in eye & head movements while using HMD	Adaptable to VR	Limited to target object No video
This work HTC Vive Pro	Eye & head	Saccadic movement VOR during VR use	Track movements while using VR CAVE combinable	Only eye & head

Shiraishi and Nakayama [31] examined the relationship between head and eye movements in subjects wearing a HMD, employing the EOG technique for eye tracking and the HMD motion sensor for head movements. Pfeil et al. [19] compared the head movements in subjects exposed to real and virtual environments, using eye and head tracking in HTC Vive Eye. They observed that subjects moved their head more when exposed to VR than when exposed to physical activity. Aharonson et al. [32] developed a methodology for gaze estimation using an eye tracking camera, Logitech C270, mounted on a pair of glasses designed for eye tracking. Kono et al. [33] investigated the VOR in subjects performing outdoor and mental activities, utilizing Tobii Pro Glasses 2 for eye-head tracking.

Although these studies demonstrate the wide diversity of research objectives and equipment used in eye and head tracking, the investigation of VOR in subjects exposed to a full VR scene has not been addressed. Our work presented in this paper aims at filling that void. In the proposed approach, we use both eye and head tracking using the Tobii Pro bar and the HTC Vive eye tracking to determine levels of immersion and presence during the time an individual experiences VR by analyzing VOR and saccadic movements. Table 1 compares these approaches, highlighting the objectives and tools employed and the novelty of our work. This table also highlights the pros and cons of all described methods.

III. METHODOLOGY

This work involved human subjects in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board (IRB) of New Jersey Institute of Technology - No. 2106008422. We used the VR headset HTC VIVE Pro Eye for the detection of the displacement of the head and eye movement. Data was recorded by a Tobii Pro Lab kit for further processing. This software allowed us to record 210 samples per second of sensor data generated by the VR headset. To be able to graph the responses of head and eye displacement at angles, we converted quaternions to Euler angles to evaluate head rotation and to calculate of the angle of eye displacement where the physical dimensions and resolution

The VOR gain is calculated as:

$$G_{VOR} = \frac{A_e}{A_h} \qquad (1)$$

where Ae is the amplitude of the largest eye movement, and Ah is the amplitude of the head movement. The Anova coeficient (F) is calculated as:

$$F = \frac{MS_B}{MS_E} \qquad (2)$$

where MSB is the mean square group error is defined as

$$MS_B = \frac{SS_B}{k-1} \qquad (3)$$

and MSE is the mean square error, which is defined as:

$$SS_B = \frac{SS_E}{N-k} \qquad (4)$$

where k is the number of groups and N is the number of observations. Here, SSB and SSE are calculated as:

$$SS_B = \sum n_j(\bar{X}_j - \bar{X})^2 \qquad (5)$$

$$SS_E = \sum (\bar{X} - \bar{X}_j)^2 \qquad (6)$$

where nj is the sample size of the jth group and X¯ is a data point in the jth group, and X¯ is the mean, or:

$$X = \frac{1}{j}\sum_{i=1}^{j} X_i \qquad (7)$$

A. EYE DISPLACEMENT

With the Tobii Pro Lab software, the eye displacement measurements were recorded as normalized pixels. The dimensions of the screen are 2880 × 1600 pixels with a resolution of 615 pixels per inch (PPI), the distance from the subject eyes to the screen is 2.9 inches (in). We calculated the angle of displacement of the eye through geometry with screen and separation data using a screen of size 2.3 × 2.6 in.

B. HEAD DISPLACEMENT

Head rotation, in quaternions, recorded by the Tobii Pro Lab kit was stored. To represent the rotation of the head in Euler angles, the conversion was done using MatLab. The collected data is and code for processing it is anonymized and available [36].

IV. TEST PROCESS

The test consisted of recording the displacement of the head and eye of the subject under test while the subject used the VR headset. First, the displacement of the eyes was calibrated and then a video of a roller coaster was projected. The development of the test was based on using the Tobii Pro Lab software.

The first part of the test consists of calibrating the detection of the eye displacement, for the subject followed nine points with the subject's eyes. After a successful calibration, the test followed, as the reproduction of a video of a roller coaster. The video lasts approximately 2 minutes and 12 seconds. Before starting the experiment, the subject is briefed that a video of a roller coaster would be screened in the VR headset. Then, the subject is instructed to wear the headset, whose screen distance is adjusted according to the subject eye vision. In total, 10 people participated, and the test was performed three times, each on a different day. Figure 1 shows the final testing setup.

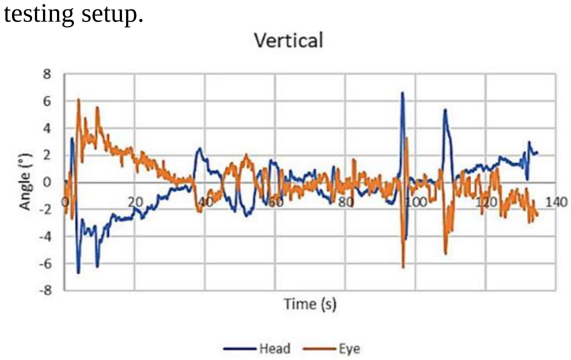

FIGURE 3. Vertical responses corresponding to head and eye displacements. This graph shows the complete data record. The amplitude and direction of head and eye movements show correlation to the VOR. However, an analysis by scenes is required to confirm the occurrence of this reflex.

V. RESULTS

To represent the movement of the eyes and the head as angles and to perform the VOR analysis, it was necessary to obtain the displacement angles from the collected data. The horizontal and vertical responses obtained during a complete recorded test are shown in Figures 2 and 3, respectively, where horizontal response corresponds to head and eye displacements. We observe that detailed analysis requires the identification of data points on the critical scenes of the video. Both cases show a similar response to that of the VOR, but because the amplitude of the signals is not always constant, a further analysis is carried out to determine when the response corresponds to the VOR and to study the responses of displacement and eye movement.

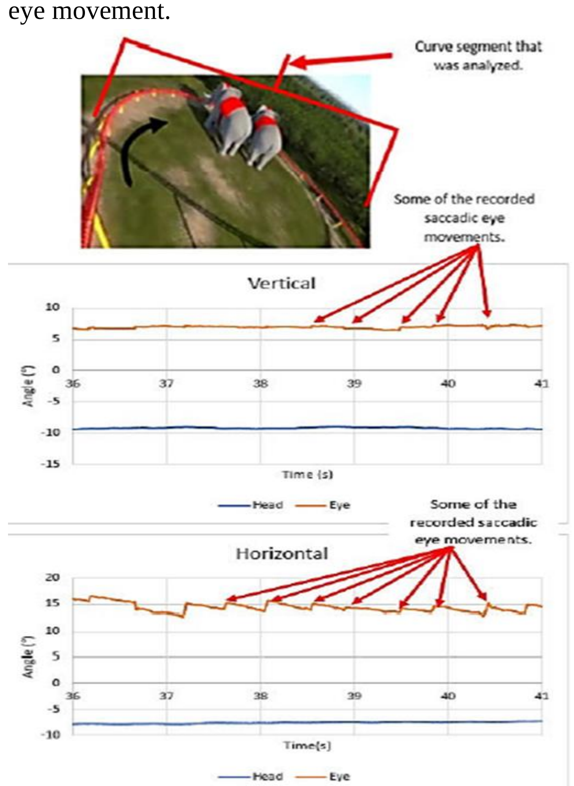

FIGURE 7. Segment extracted from the register corresponding to a roller coaster descent (vertical plane).

Finally, according to Table 3, we observe that the means of the VOR gain range from 0.97604 to 1.17630, values associated with presence. For the analysis of the descent, a 5-second fragment was processed (i.e., the time the car takes to reach the lowest point of the descent). The average of the gain in that path was far from 1 in both the horizontal and vertical planes. Because in the vertical plane the average gain was above 1, one can infer that the displacement of eye is greater than that of the head in that section of the video on the vertical plane. All examples showed a similar pattern from second 35.9 to second 36.3. In other words, both the saccadic eye movements and the vertical VOR with an average gain of 0.9033 were identified. This route lines up with the point in the movie where the descent was at its lowest, which was also the moment where it was going to terminate. The registered vertical displacements of the head, and eye, and the capture of the video segment under analysis are displayed in Figure 7.

VII.CONCLUSION

In this study, we demonstrated that the degree of immersion experienced by an individual may be ascertained by measuring the VOR while they are wearing a virtual reality headset. The methodology presented in this research also makes it possible to measure the degree to which participants have adapted to unbalanced postures and other difficult virtual-reality situations, including those found in flight simulators or episodes of cyber sickness.

The examination of the participants' horizontal and vertical VOR after watching a roller coaster film is also presented in this paper. According to our research, participants were significantly affected more by vertical plane movements than by horizontal plane movements. Furthermore, we saw that the horizontal VOR did not have a common point of intersection.

Technique to ascertain whether an individual is immersed in virtual reality. Our findings demonstrate that these responses behave similarly in important video situations across a range of participants.

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