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RESEARCH ARTICLE

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

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board of New Jersey Institute of Technology (NJIT), Office of Research and Development.

ABSTRACT Virtual reality (VR) is increasingly used in gaming, training, and health-related applications. However, the level of immersion and presence generated by VR can significantly influence the user and the achievement of desired outcomes. Therefore, methods to assess levels of immersion and presence need to be established. In this paper, we investigate the vestibulo-ocular reflex (VOR) and saccadic eye movements in multiple subjects exposed to VR to determine if VR triggers these responses as in real life. Using an HTC VIVE Pro Eye headset and Tobii Pro Lab software, we record head and eye movements in response to a 3D video of a roller coaster ride. Our results show that critical scenes in the video triggered VOR and saccadic eye movements in most subjects, indicating a strong correlation between VOR and saccadic eye movements during VR immersion. These findings may have implications for the study of human behavior and suggest the use of eye movement measures as feedback mechanisms during VR experiences.

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) is a collection of technologies that enable the creation of a three-dimensional interface for a digitally generated world that replicates the spatial, temporal, and motion characteristics of physical reality [1]. VR has gained widespread adoption as a means of enhancing the experience of unreal scenarios in video games by numerous enthusiasts. Moreover, VR has also found application in therapeutic and diagnostic settings, where it has demonstrated significant potential for promoting positive health outcomes [2]. Nonetheless, techniques for determining the magnitude of immersion and presence encountered by users in virtual reality (VR) environments have yet to be devised. People knowledgeable on VR technologies identify these two terms: immersion, as the degree to which a user feels fully engaged and present in a virtual environment created by virtual reality technology, and presence, as the physiological responses manifested by people while experiencing VR. Although the quality of VR scenes plays an important role on the extent of immersion in a user, each user may experience different levels of presence [3], [4].

There are three systems that allow a human subject to orient himself in space: the proprioceptive signals, the vestibular apparatus, and the visual signals [5], [6], [7]. The presence of the video and sensors that give the sensation of experiencing a 3D environment affect the visual inputs and vestibular signals [2], [8] when the subject uses a VR headset. These alterations of reality in VR can also generate cybersickness that is sometimes manifested as nausea or ataxia [9], [10], [11], [12]. The vestibular apparatus can be represented by the movements of the eyeballs and the head through the

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vestibulo-ocular reflex (VOR). The function of this reflex is to elicit an eye movement in the opposite direction of the head movement, maintaining the same amplitude of motion and enabling the subject to maintain visual fixation on a target of interest [13], [14], [15], [16], [17]. Saccadic eye movements are rapid movements of the eyes that are performed as reflexes, although they can also be voluntarily induced. These movements, which allow us to capture detailed information of the environment, are frequently present in daily activities, such as driving a car [18]. The reflexes of subjects triggered during VR experiences are gaining increasing interest. Pfeil et al. [19] recently performed comparisons between head and eye movements within VR and physical reality settings. They found out that subjects move their heads more frequently in VR than in physical reality. Girolamo et al. [1] studied possible modifications of VOR after the subjects are exposed to a virtual environment by measuring the VOR gain before and after the use of VR. They found out that the VOR gain decreases right after experiencing VR, and it disappears after 30 minutes. Furthermore, saccadic eye movements have been considered for evaluating one's ability of driving a car [18], [20]. These movements have also been analyzed during the presence of VOR to determine the role of VOR during the occurrence of saccadic eye movements. However, no occurrences of the VOR were reported in such scenarios [13]. Ping et al. [21] studied the man-machine interaction and reported how users perceive depth using VR and augmented reality (AR). They found that depth estimation is higher in AR than in VR. Using VR, methods focused on vestibulo rehabilitation have been proposed for the study of cases such as Ménière's disease [22], effects of immersion on postural control [23] as well as the factors that can cause cybersickness [24]. Khamis et al. [25] proposed a study of the interaction of smooth pursuit of eye movements and VR in games based on tracking and analyzing the size of objects, where they observed that movements improve according to the size of the object. However, no studies that analyze the response of the VOR and saccadic eye movements during the use of VR have been reported. Such an analysis could indicate whether a person is immersed in a VR scenario and that could be used effectively in therapies or other medical applications. This paper aims at filling this gap.

By leveraging on the features of the VIVE HTC Pro Eye headset [26], we study whether the VOR response and the saccadic eye movements during the projection of a video in VR can serve as indicators of the level of immersion a person experiences in VR. In our experiments, we analyze the times at what the VOR and the saccadic eye movements are detected while the subject experiences a VR video of a roller coaster that challenges the balance of the subject. These tests are video scenes that places the user in a virtual out-of-balance posture, which is a condition we hypothesize triggers this reflex. We performed different tests and on multiple subjects to validate this hypothesis through rigorous experimentation.

Our contribution in this paper is the presentation of experimental results that strongly indicate that the VOR and saccadic movements indicate a level of immersion of VR of a person. These saccadic eye movements are observed and measured through a commercially available VR headset with built-in eye tracking sensors. In the experiments, subjects are presented with a video of a roller coaster with scenes that challenge the upright position of a subject as markers to trigger and detect such responses.

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.

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].

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. Shiraishi and Nakayama et al. [34] studied the effect of VOR in subjects using the eye tracking tool of the HTC Vive headset. Lohr et al. [35] indicated that the interest in studying human behavior when using a VR headset is increasing.

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

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

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 of the VR headset screen were considered. On the other hand, the software of the HTC VR headset allowed us to directly record fixation or saccadic eye movements.

The VOR gain is calculated as:

$$G_{VOR} = \frac{A_e}{A_h} \tag{1}$$

where A_e is the amplitude of the largest eye movement, and A_h is the amplitude of the head movement.

The Anova coeficient (F) is calculated as:

$$F = \frac{MS_B}{MS_E} \tag{2}$$

where MS_B is the mean square group error is defined as

$$MS_B = \frac{SS_B}{k-1} \tag{3}$$

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

$$SS_B = \frac{SS_E}{N-k} \tag{4}$$

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

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

and

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

where n_j is the sample size of the jth group and $\bar{X}$ is a data point in the jth group, and $\bar{X}$ is the mean, or:

$$X = \frac{1}{j}\sum_{i=1}^{j} X_i \tag{7}$$

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

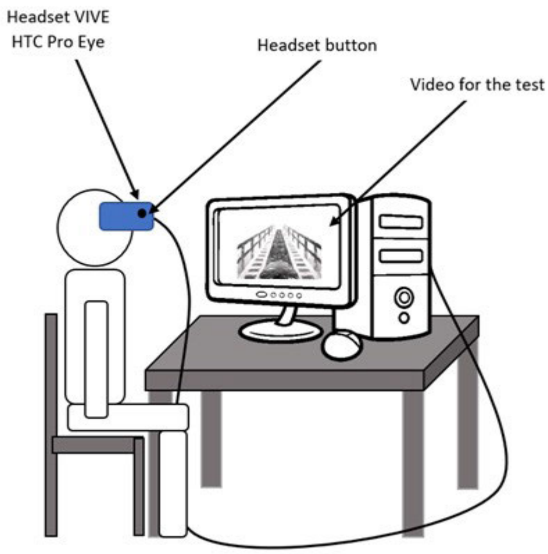

FIGURE 1. Set up of the VR and tobii sets for testing.

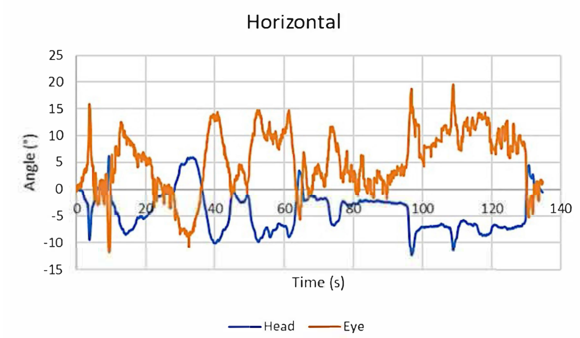

FIGURE 2. Horizontal response corresponding to head and eye displacement.

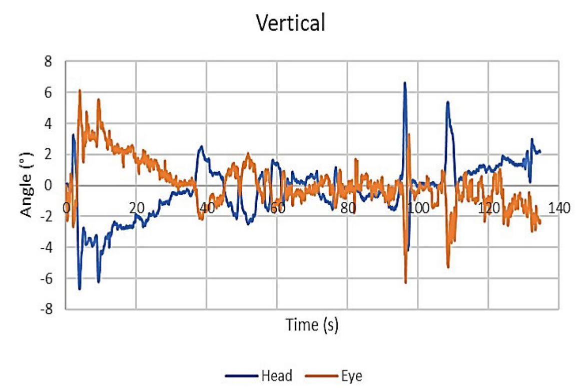

FIGURE 3. Vertical responses corresponding to head and eye displacements. This graph shows the complete data record. The amplitude and direction of head and eye movements show correlation to the VOR. However, an analysis by scenes is required to confirm the occurrence of this reflex.

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.

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. The analysis consisted of obtaining the gain between the movements of the eye and the head in strategic points of the video where we consider the presence of the VOR. We analyze the average gain, eye movements, horizontal VOR and vertical VOR at three specific points of the video: in an ascent, descent, and a curve of the roller coaster. To determine the presence of the VOR, we obtained the gain, which is the ratio between angle change of the eye and the angle change of the head. If the gain approaches 1, that means that a VOR occurs at that point or segment of the video because the amplitude of the eye and head movements have the same magnitude but the opposite direction. The objective of the analysis is to detect the presence of the VOR through the gain, which if approached 1.0, it indicates that such an occurrence takes place at that point. The data points where the VOR was detected were compared on different subjects to verify concurrency and to mark that point as a specific time where VOR occurred. Its frequent occurrence makes it a reference to determine if a subject was immersed in VR or not.

In the case of a roller coaster ascent, a fragment of the graph of approximately 17 seconds was obtained (i.e., the time the roller coaster car takes to reach the top of the track). The average of the gain recorded in those 17 seconds was larger than 1 on the vertical and horizontal planes. However, from second 13 to 13.48, a response corresponding to the VOR was detected on the vertical plane with an average gain of 0.90 as well as for saccadic eye movements. This time interval corresponds to the beginning of the ascent in the video. According to the gain averages obtained in this segment, the gains in the vertical plane tended to be larger than 1.0, which

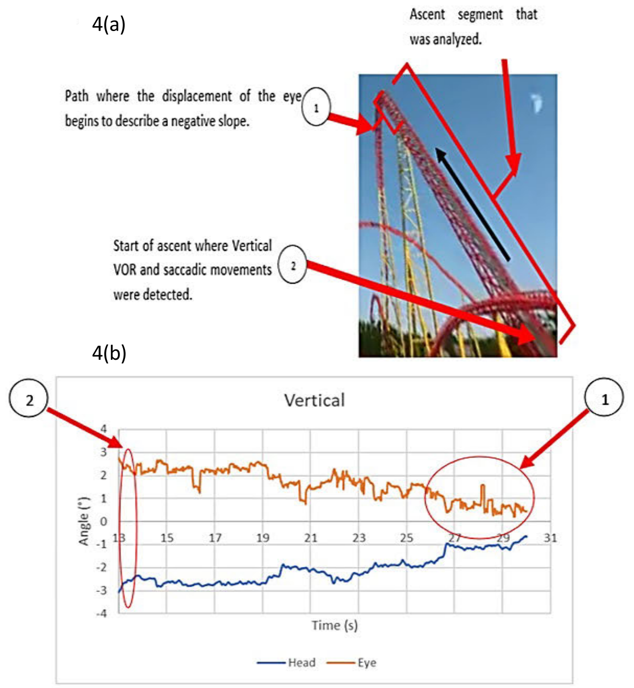

FIGURE 4. **(a) Segment extracted from the record corresponding to a roller coaster ascent (vertical plane). (b) Vertical responses corresponding to head and eye displacements.**

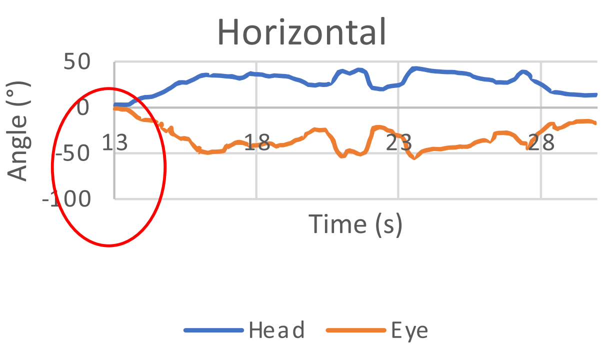

FIGURE 5. **Segment extracted from the register corresponding to a roller coaster ascent (horizontal plane).**

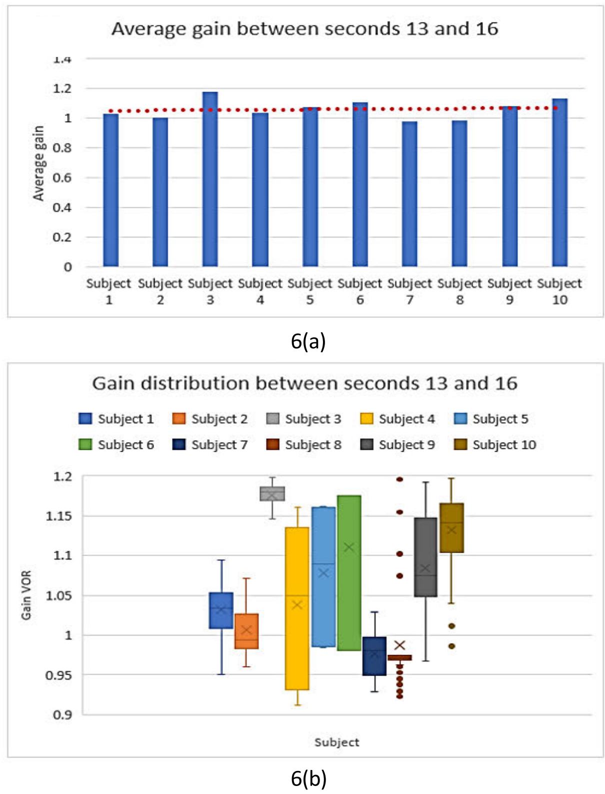

FIGURE 6. **(a) Bar graph of average gain and (b) Gain distribution. All reported data was extracted from the record between seconds 13 and 16.**

TABLE 2. **Summary of data, where μ means for Subjects 1 to 10.**

Subject	N	Mean	StD	SE Mean	95% CI of μ
1	130	1.03151	0.02775	0.00243	(1.02670, 1.03633)
2	104	1.00622	0.03191	0.00313	(1.00002, 1.01243)
3	120	1.17630	0.01297	0.00118	(1.17396, 1.17864)
4	126	1.03840	0.09960	0.01950	(0.99820, 1.07860)
5	096	1.07840	0.07920	0.03230	(0.99530, 1.16140)
6	093	1.11060	0.11210	0.06470	(0.83220, 1.38900)
7	118	0.97604	0.03063	0.00722	(0.96081, 0.99127)
8	150	0.98686	0.05801	0.00474	(0.97750, 0.99622)
9	114	1.08350	0.06920	0.01850	(1.04360, 1.12350)
10	555	1.13223	0.04631	0.00197	(1.12837, 1.13609)

indicates that there was a greater displacement/variation of the eye in the vertical plane on that path.

On the other hand, from second 26, it was observed that the eye displacement described the behavior of a negative slope (greater displacement gradually) until reaching the top, that is, right before the roller coaster started the descent.

In Figure 4, the registered vertical displacements of the head, eye and a video snapshot of the analyzed segment are shown. In Figure 5, the horizontal movements extracted from the record corresponding to a roller coaster ascent are shown. In this case, we found that between seconds 13 and 16 the VOR was detected in horizontal plane in the records of the 10 subjects. In Figure 6(a), a bar graph is shown with the average VOR gain recorded in this segment between seconds 13 and 16. In Figure 6(b), the data to obtain the average gain is shown.

According to the box plot, we can see that the amount of data is not the same in all cases because the VOR is detected but its duration varies for each subject. However, the tendency to values close to 1.0 is the same in all cases in the time interval between seconds 13 and 16. That is, in the same scene the VOR was recorded with different duration. In Table 2 we observe the VOR gains of the statistical data corresponding to the information presented in Figure 6.

In Table 2, the 95% confidence interval is determined by considering the standard deviation in each subject. In some

TABLE 3. Analysis of variance.

Source	DF	Adj SS	Adj MS	F value	P value
Factor	9	4.957	0.550819	267.71	0.00
Error	1116	2.296	0.002058		
Total	1129	7.254			

TABLE 4. Pairwise comparisons. Information using the Tukey method and 95% confidence interval.

Factor	N	Mean	Grouping
Subject 3	120	1.17630	A
Subject 10	555	1.13223	B
Subject 6	093	1.11060	ABCD
Subject 9	114	1.08350	C
Subject 5	096	1.07840	BCD
Subject 4	126	1.03840	CD
Subject 1	130	1.03151	D
Subject 2	104	1.00622	E
Subject 8	150	0.98686	F
Subject 7	118	0.97604	EF

cases, an overlap is recorded, for example, the mean of Subject 8 falls within the confidence interval of Subject 7. However, this overlap does not occur in all cases. Because of the same reason, an ANOVA analysis of variance was performed with a significance level of $\alpha = 0.05$ to determine if there is a statistically significant difference. Table 3 shows the obtained results.

The P value determines the probability of a null hypothesis; that all means are equal. However, because the P-Value obtained was less than $\alpha = 0.05$, it is determined that not all means are equal, so the Tukey method was used to perform grouping considering the means and confidence intervals. Table 4 shows the obtained results with a 95% confidence interval.

The letters in the grouping column indicate the overlap according to the means and confidence interval, for example, the data obtained in Subject 3 and Subject 6 are not significantly different, unlike Subject 3 with Subject 10, who do not share any letter within the grouping. However, all subjects at some point share a letter, and that indicates that there is no case that is considered totally independent or significantly different from the rest of the subjects. Also, it should be considered that the duration of the VOR reflection was not the same in all cases. Therefore, the amount of data used to obtain the mean is different as observed in the previous tables. 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

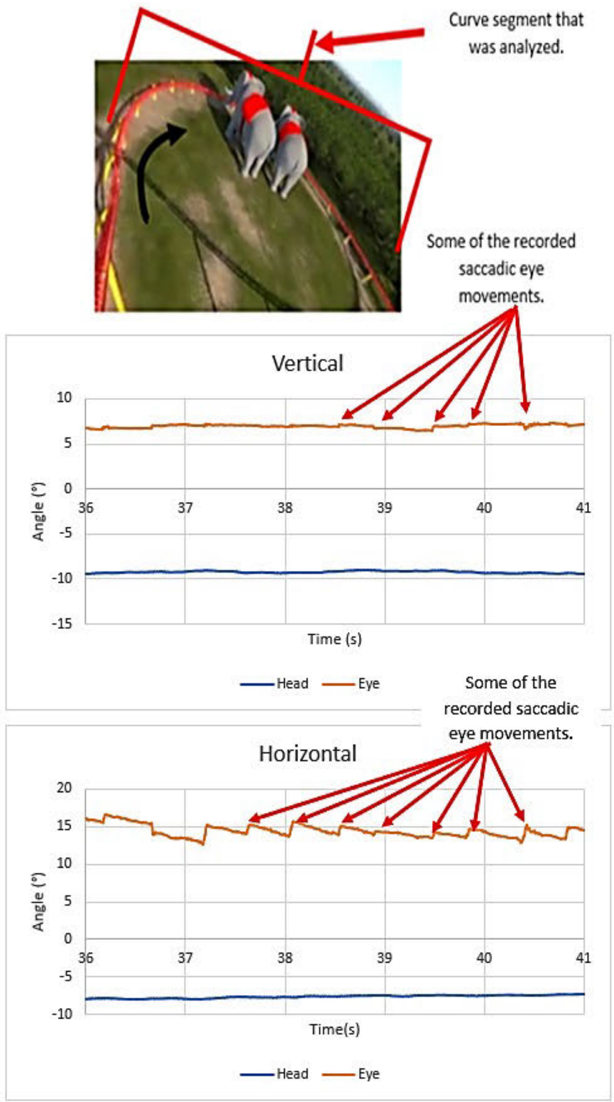

FIGURE 7. Segment extracted from the register corresponding to a roller coaster descent (vertical plane).

the head on the vertical plane in that segment of the video. From second 35.9 to second 36.3, a similar behavior was observed in all cases. That is, both the vertical VOR with an average gain of 0.9033 and the saccadic eye movements were detected. This path corresponds to the lowest point of the descent in the video; that is, when the descent was about to end. Figure 7 shows the registered vertical displacements of the head, eye, and the capture of the analyzed video segment.

For the analysis of a roller coaster turn, a segment of the 5-second fragment was extracted (the time it took for the car to travel that route). In this segment there was no detection of VOR in either of the two planes. However, it was the segment where the highest number of saccadic eye movements were recorded. The number of saccadic movements in this segment increased 90% over the tests performed as compared to the

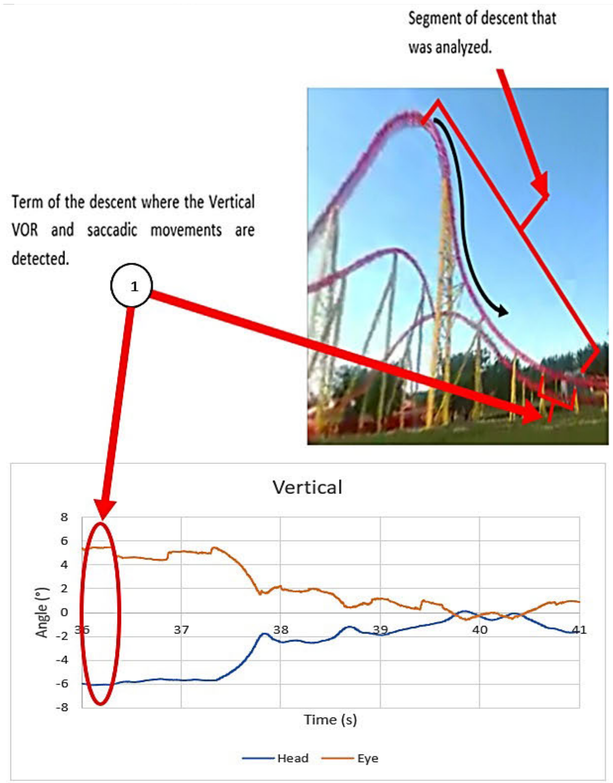

FIGURE 8. Segment extracted from the register corresponding to a roller coaster curve and the displacements recorded in the vertical and horizontal planes.

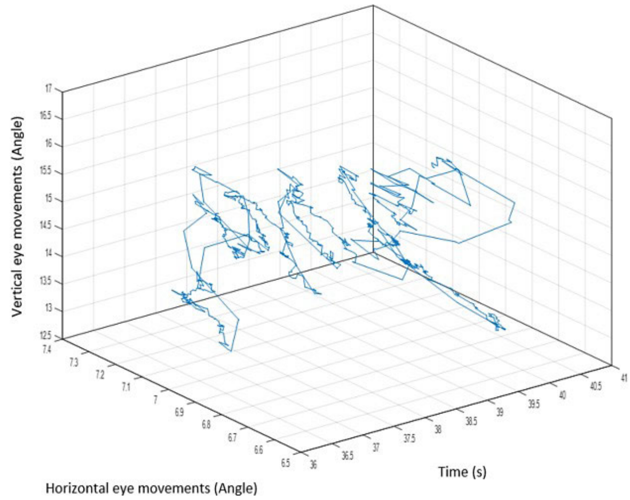

FIGURE 9. Horizontal and vertical saccadic eye movements.

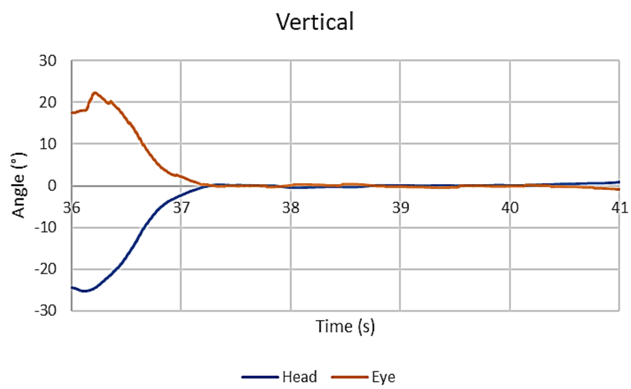

FIGURE 10. Segment extracted from the register corresponding to a roller coaster curve and the displacements recorded in the vertical plane where saccadic movements decreased as compared to Figure 8.

ascent and descent segments. In addition, it was observed that the eye displacement on this case tends to show greater variations due to the increase in saccadic eye movements. We analyzed two more curve segments and compared them with the reported curve segment shown in Figure 8. We found that this behavior was similar in the three curves segments analyzed, that is, an increase in saccadic eye movements.

Figure 9 shows the horizontal and vertical saccadic eye movements through time, where a spiral graph can be observed due to the variation of the saccadic eye movements in both planes. This graph corresponds to the complete data record of a subject, and it was used to support the detection of the regions where the saccadic eye movements were detected more frequently, and from there we selected the scenes for analysis as in the case of the curve scenes.

Figure 10 shows the case of a subject who did not experience saccadic movements in the segment corresponding to the curve of the roller coaster. Compared to Figure 8, the saccadic movements shown in Figure 10 decrease. In this case the subject mentioned not having dizziness using the VR headset. Therefore, one can determine that eye movements are related to the cybersickness that some people experience with a VR headset. On the other hand, the VOR was detected in this case, starting at second 36.2. According to this behavior, we determine that during the occurrence of VOR, saccadic eye movements tend to decrease.

VI. DISCUSSION

At the start of the ascent of the roller coaster, the presence of the vertical VOR was detected and between three and five seconds before reaching the top, the displacement of the eye gradually increased. In addition to the analyzed descents, two more descents were reviewed, and it was found that, in all cases, the vertical VOR is recorded at the point where the descent ends, as shown in Figure 7. At that same time, saccadic eye movements were detected. In the three different analyzed curves, saccadic eye movements are observed, as indicated in Figure 8. In addition, the figure shows increased saccadic eye movements in this segment as compared to those recorded in the ascent and descent. Because a similar behavior is observed in these analyzed points, the beginning of the ascent, end of the descent, and the saccadic eye movements in the curves, this analysis of VOR and eye movements can be used to determine when a person is immersed in VR. As we could see in the ascent and descent scenes, the vertical plane was the one that recorded the highest activity, especially as VOR occurrences, unlike the curve scenes, where the horizontal plane was the one that recorded the greatest variations of saccadic eye movements.

This work uses the response of a subject by monitoring eye and head tracking. However, some subjects may also show some responses with other biomarkers or different parts of the body. These different biomarkers may be investigated in future research.

A. APPLICATIONS

The correlation between VOR and VR can be applied in studies involving human behavior and human-computer interaction. For instance, investigations into VR immersion may include the utilization of a computer-assisted virtual environment (CAVE) [37] to provide full subject immersion. Additionally, while a subject is immersed in VR, physiological responses can be fully tracked and/or recorded in a CAVE environment, considering the proprioceptive and somatic nervous systems as supplementary signal inputs to the human body [38].

The utilization of VR and VOR is being increasingly recognized as a useful tool for the diagnosis and rehabilitation of certain disorders [39], [40]. Moreover, the impact of VR on sensory perception and its potential to enhance current training techniques and the learning process is still not fully understood, and requires further investigation [41].

VII. CONCLUSION

In this paper, we showed that through the measurement of the VOR during virtual reality headset use, it is possible to determine the level of immersion experienced by the individual. The methodology introduced in this paper also enables the detection of the extent of adaptation of subjects to out-of-balance postures and other challenging virtual-reality scenarios, such as those encountered in flight simulators or episodes of cybersickness.

This paper also presents an analysis of the horizontal and vertical VOR experienced by participants exposed to a roller coaster video. Our findings reveal that the vertical plane movements had a more significant effect on the participants than the horizontal plane movements. Moreover, we observed that there was no common point of intersection for the horizontal VOR among all participants, while the vertical VOR exhibited consistent patterns across all analyzed recordings.

These movements could be associated with the dizziness that some individuals experience after being exposed to similar movements outside virtual reality [42]. These symptoms may occur on some people who are more used to the movements in the horizontal plane than in the vertical plane. The vertical movements may be an indicator of why some people present dizziness after getting off a roller coaster; that is, because vertical VOR occurs more frequently than horizontal VOR [43], [44].

The study of eye and head movements as well as their relationship with the VOR can help establishing a methodology to determine if a person is virtual-reality immersed. Our results show that the behavior of these reflexes at key scenes in the video is similar for different subjects.

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