A Neurophysiological Sensor-Equipped Head-Mounted Display for Instrumental QoE Assessment of Immersive Multimedia

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***Abstract*—The last few years have seen a drastic increase in the consumption of virtual- and augmented-reality (VR and AR, respectively) applications. Ultimately, the success of any emerging technology will rely on the experience it provides the end user, and not on the technology itself. Subjective methods for quality-of-experience (QoE) assessment have as main disadvantage that converting such human factors into a quality rating is difficult, particularly for everyday users. To overcome this limitation, recent research has explored the use of objective methods to monitor neurophysiological correlates of relevant perception processes. In this paper, we describe the development of a neurophysiological sensor-equipped head-mounted display that combines a consumer off-the-shelf VR headset, a modified low-cost portable device for electroencephalogram (EEG) acquisition repurposed to simultaneously acquire EEG, electrocardiogram (ECG), and electrooculogram (EOG) signals with high-quality dry electrodes. The device was evaluated under three different scenarios, each one designed to test the different ExG modalities. Initial tests showed promising results and allowed for (1) steady-state visually evoked potentials to be accurately measured from EEG, (2) heart rate variability measurements to discriminate between different affective videos, and (3) EOG measurements to monitor gaze direction and eye blinks, all while users were mobile. Being able to accurately monitor signals from the autonomic and central nervous systems in an unobtrusive and portable manner is an important step for instrumental QoE assessment of emerging VR/AR applications.**

***Index Terms*—augmented-reality, electrocardiography, electroencephalography, electroooculography, immersive-multimedia, psychophysiology, quality-of-experience, virtual-reality**

I. Introduction

Recent advances in computer graphics and sensors have led to the development of numerous consumer-grade head mounted displays (HMD) (e.g., the Oculus Rift and HTC Vive) which have paved the way for mainstream virtual- and augmented-reality (VR and AR, respectively) applications. Ultimately, however, the adoption of a new media does not depend solely on its technical capabilities, but on the quality of experience (QoE) it provides the user [1].

QoE has been recently defined as "the degree of delight or annoyance of the user of an application or service. It results from the fulfillment of his or her expectations with respect to the utility and / or enjoyment of the application or service in the light of the users personality and current state" [2]. Where "personality" makes reference to "those characteristics of a person that account for consistent patterns of feeling, thinking and behaving" and "current state" to the "situational or temporal changes in the feeling, thinking or behavior of a person". Hence, QoE is a combination of three influential factors: system, context, and human. As such, the current state of the user can be a consequence of the experience, or an influential factor affecting the perceived QoE [2]. Human influence factors (HIF) of QoE perception can include "any variant or invariant property or characteristic of a human user", i.e., factors such as mood, affective state, expectations, previous user experience with the application, among others. Immersive VR/AR multimedia, in turn, elicits additional HIFs which are usually not present in traditional multimedia (video-audio), such as visual fatigue, motion sickness, cognitive/mental overload, and stress, to name a few.

Typically, QoE assessment relies on psychophysical (or subjective) methods, which evaluate the relationship between the cognitive processes of the user and the physical stimuli (application). These methods consist of open- and/or close-ended post-experience questionnaires that aim to collect the user's expectations, opinions, feelings and perceived quality of either an entire multimedia application or just parts of it [3], [4]. While subjective methods provide a direct window into the user's perceived QoE, they can present three main disadvantages: (1) it is difficult for naive users to convert human judgment and involved HIFs into a final quality rating, (2) post-experience questionnaires typically just provide a snapshot of the overall perceived experience, and (3) to overcome (2), continuous quality rating experiments can be conducted, but these convey extra cognitive workload and are overly fatiguing to the viewers, thus can have detrimental effects on the media experience per se, such as the loss of immersion in VR/AR applications.

To overcome these limitations, objective (or instrumental) methods which measure quantitative features related to the application have been the focus of recent research. As QoE assessment depends on user perception, and since immersive media involves numerous HIFs, psychophysiological (objective) methods have gained a lot of attention in the last couple of years. Such methods explore the relationship between the cognitive state of the users and the effects it has on their physiological signals [5]. More specifically, psychophysiological methods aim to find correlates between perceptual QoE features and physiological metrics. Some of the physiological signals that have been shown useful in QoE assessment are the electroencephalogram (EEG), electrocardiogram (ECG) and measured heart rate (HR) or heart rate variability (HRV), electrooculogram (EOG) and eye blinks, electrodermal activity (EDA) or galvanic skin response (GSR), and cerebral bloodflow measured via near-infrared spectroscopy (NIRS) [6]. Moreover, physiological signals can be combined in multimodal models for deeper understanding of the perception process and a better estimation of the QoE [7], [8]. The interested reader is referred to these recent review papers on the topic of physiology-based QoE assessment [3], [9], [10].

Depending on the physiological phenomena under analysis, psychophysiological methods can be grouped into three classes, namely methods focused on: (1) the central nervous system (CNS), (2) the autonomic nervous system (ANS) and (3) eye measurements [3]. While existing works with immersive media have explored HR and EDA responses to monitor a users affective/stress levels [11], other key cognitive factors that rely on e.g., EEG, ECG and eye tracking are still missing. Such limitation is due mostly to the nature of immersive VR/AR applications, where the user is allowed and encouraged to move during the experience. Movement introduces a major challenge in the acquisition of EEG, ECG and EOG as these modalities are easily corrupted by movement-related artifacts. This is not an issue with conventional video QoE where users typically sit still in front of a screen [10].

Having this said, the ultimate goal of this paper is to present the development of a neurophysiological sensor-equipped head-mounted display able to accurately monitor physiological signals related to the CNS, ANS and eye-measurements in an unobtrusive and portable manner. Across three validation tests, we show that accurate EEG, ECG and EOG can be measured, thus providing an important step for instrumental QoE assessment of emerging VR/AR applications.

II. Experimental Setup

This section presents firstly the development of the neurophysiological sensor-equipped HMD device, and then a description of three scenarios proposed for the evaluation of the acquired physiological signals: EEG, ECG and EOG.

A. Experimental device

The proposed experimental device combines an off-the-shelf VR headset with a modified low-cost portable EEG device and high-quality dry electrodes. The VR HMD used in this study was the Oculus Rift (Development Kit 2). Among its specifications[1], it possesses a frame rate of 75 Hz, and a field of view (FOV) of 100°. The Emotiv-Epoc[2], in turn, is a 14-channel portable low-cost EEG device with a sampling frequency of 128 Hz, that has been proven useful across different EEG studies (e.g., [12], [13]). In this work, we were inspired by [13], and modified an Emotiv-Epoc for two main reasons: to remove the limitation of fixed electrode positions imposed by the headset's original design and, to render the device compatible with different standard electrodes[3]. The modified portable EEG device served as an acquisition system for EEG, ECG and EOG, and sensors were placed directly onto the HMD, as shown in Fig. 1. Three different types of electrodes were utilized, as follows: (1) eight Ag/AgCl flexible dry electrodes[4] for EEG locations with presence of hair, namely, Fz, FCz, Cz, PO7, O1, Oz, O2 and PO8; (2) five flat Ag/AgCl dry electrodes[5], three of these for EEG (and EOG) in Fp1, Fpz and Fp2 locations, and two more near the left and right outer canthi to record left and right horizontal EOG respectively; and finally, (3) three disposable electrodes, two placed on the mastoids for the reference connections, namely common mode sense (CMS) and driven right-leg (DRL), and one placed in the left collarbone for ECG. The collarbone electrode is proposed to acquire reliable ECG signal without adding discomfort to the used, compared with chest-located electrodes. Fig. 1 depicts the proposed sensor-equipped HMD device, and shows the electrode placement. A step-by-step description of how this was achieved will be made available online.

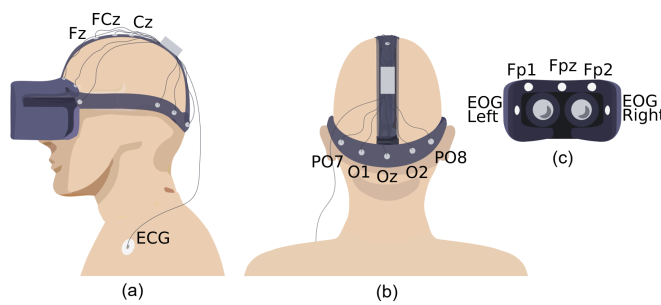

Fig. 1. Proposed sensor-equipped HMD device, (a) profile view, (b) posterior view, and (c) electrode placement for EOG signals.

B. Validation scenarios

Prior to utilizing the developed prototype into full immersive QoE experiments (future work), it is paramount to validate the recorded modalities by QoE-relevant experiments. In this paper, we describe three such tests. First, we measure steady-state visual evoked potential (SSVEP) responses to verify the accuracy of the collected EEG. Next, we validate the measured ECG via a HR/HRV experiment with users watching affective videos. In this case, participants also wore a research-grade ECG chestband (Zephyr Bioharness 3) with a sampling frequency of 250 Hz, in order to validate the HR/HRV readings of the proposed setup. Lastly, an eye-gaze task was used to verify the accurate acquisition of the EOG signals.

[1]https://xinreality.com/wiki/Oculus_Rift_DK2
[2]https://www.emotiv.com
[3]http://www.castoriscausa.com/posts/emotive-epoc-hack
[4]http://www.cognionics.com
[5]http://thoughttechnology.com

All scenarios were created in the Unity3D development platform and physiological signal synchronization was performed using an open-source wearables streaming platform called MuLES [14]. In our experiments, a NVIDIA GTX1070 GPU was utilized and the HMD frame rate was kept stable at 75 Hz. After each scenario, participants were asked if they felt comfortable with the experimental device. A total of 5 participants (1 female; mean age 30 years, 5.3 *s.d.*) underwent this pilot experimentation, which lasted roughly 30 minutes for each participant. The next subsections describe the three validation experiments in more detail.

1) SSVEP scenario: A common paradigm in EEG experiments is the detection of SSVEPs, which correspond to evoked responses in the visual cortex induced by flickering visual stimuli. SSVEPs are periodic with stable amplitude and phase and have been widely utilized to study visual attention [15] and, in the context of QoE, to study the quality perception of images [16] and video [17]. The SSVEP validation scenario consists in a virtual 3D environment where the participant undergoes three 30-second stages, (1) open eyes, (2) presentation of a blinking sphere at 12.5 Hz, and (3) closed eyes. To assess the SSVEP response, the signal-to-noise-ratio (SNR) at the stimulus frequency was computed as:

$$\mathrm{SNR} = \frac{n \times X(f_s)}{\sum_{k=1}^{n/2} \left[X\left(f_s + (\Delta f \times k)\right) + X\left(f_s - (\Delta f \times k)\right) \right]}, \quad (1)$$

where X is the power spectrum density (PSD) of the EEG signal, the numerator is the power at the stimulus frequency f_s, the denominator corresponds to the mean power in the n neighboring spectral components, which are not related to the stimulus, with n equal to 8, as the window for analysis is 4 seconds, and Δf = 0.25 Hz.

2) HR/HRV affective video scenario: The use of affective videos has been probed successfully via HR/HRV changes [18]. As such, this scenario consisted in a virtual 3D dark cinema theater, where only the screen is visible. Participants watched six 3-minute film clips, from the FilmStim database [19], divided equality into two categories: videos that elicited tenderness and videos that elicited fear. For each video, the instantaneous HR was obtained, and the last 2 minutes were used to calculate traditional time- and frequency-based HRV metrics [20] with the software Kubios [21].

3) Eye-gaze scenario: The knowledge of gaze direction can give valuable information for QoE assessment, such as overt visual attention [10]. In VR/AR applications, gaze direction can be inferred from the center of the FOV displayed in the HMD; however, this approach does not provide information of where specifically in the FOV the participant is looking. The amplitude and sign of the EOG signal depends on the rotation angle of the eyes and also the position of the electrodes. Thus, EOG signals can be utilized to infer eye gaze (location and trajectory) as well as blinking [22], hence providing valuable information on the undergoing perception process.

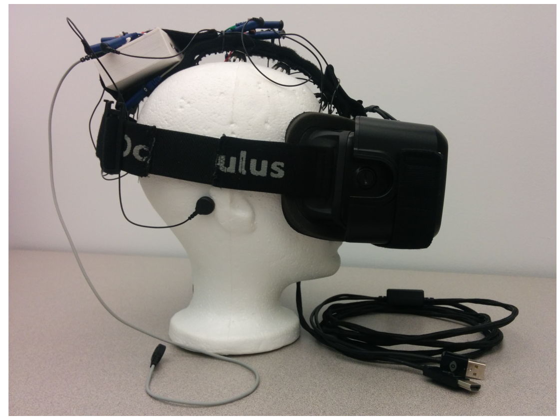

Fig. 2. Photo of the proposed sensor-equipped HMD.

TABLE I
AVERAGE SNR VALUES FOR ELECTRODES O1, OZ AND O2.

	O1 (dB)	Oz (dB)	O2 (dB)
Open eyes	-0.21	-1.71	-0.94
SSVEP 12.5 Hz	3.39	3.09	4.55
Closed eyes	-1.23	-1.90	-0.81

Eye blinking rate can also be indicative of visual fatigue, drowsiness, and mental workload, which are important HIFs that can influence immersive QoE [23]–[25]. This eye-gaze scenario was designed to elicit EOG responses related to the gaze point in the FOV. For this purpose, the participant was indicated to follow with her gaze a target moving in 4 positions (right, up, left and down) inside the FOV, with 20 repetitions for each direction.

III. EXPERIMENTAL RESULTS

Figure 2 shows a pictures of proposed sensor-equipment HMD. In the rest of this section, we report the results obtained across the three validation tests, as well as candid feedback from the participants on the usability of the prototype.

A. SSVEP scenario

The PSD of the EEG signal was computed in 4-second windows every second for electrodes O1, Oz and O2. Fig. 3 shows the spectra for one window in each phase, for the electrode Oz for one participant. The empirical distributions of the SNR computed during each phase for all the participants are depicted in Fig. 4. The average SNR across windows and across subjects is presented in Table I. The obtained SNR values are in line with those presented in the literature [26].

B. Affective videos: HR/HRV

With the developed prototype, for usability purposes, we decided to place the ECG sensor on the left collarbone. As this morphology does not correspond to any lead in the Einthoven's triangle (widely used in clinical practice), it is important that the quality of the ECG and the R-peak detection accuracy be quantified. To this end, Fig. 5 depicts an 8-second

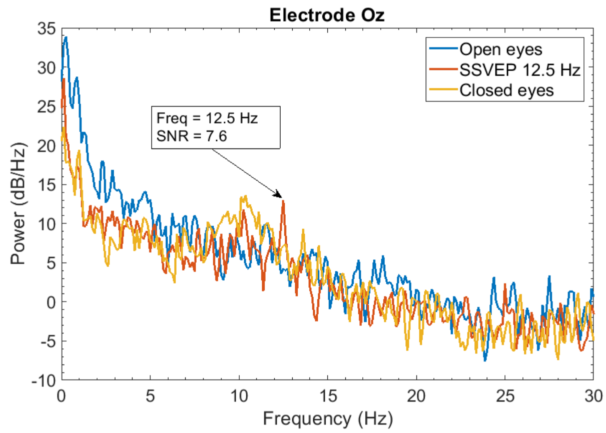

Fig. 3. Spectra for electrode Oz, for a 4-second window in each SSVEP scenario phase. The SNR is indicated for the stimulus frequency, 12.5 Hz, during the SSVEP phase.

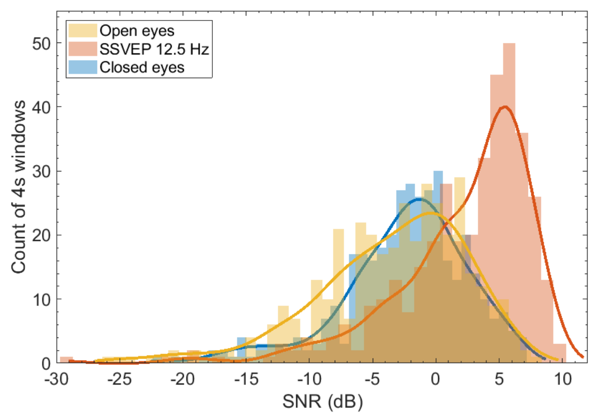

Fig. 4. Histograms of the SNR values for all the electrodes (O1, Oz and O2), for all participants during each SSVEP scenario phase.

segment of the ECG obtained via collarbone sensor and the reference ECG signal acquired with the Bioharness chestband for comparison. The modified Pan-Tomkins algorithm [27] was used to detect R-peaks and the corresponding RR-curves. For the five participants, a total of 5650 beats were detected, analyzing the instantaneous HR values obtained with the proposed sensor-equipped HMD and the reference chestband device, a correlation coefficient of 0.995 was achieved. Finally, HRV features were computed from the last 2-minute window of each video. Table II presents the mean and standard deviation of different HRV metrics for the tenderness and fearful videos.

C. Eye-gaze

With the proposed electrode setup (see Fig. 1c), five electrodes contain EOG information. We were able to identify the directions of the eye movements to describe the trajectory of gaze displacements. Fig. 6 presents the time-aligned EOG signals of the 20 repetitions for each direction for each EOG-related channel, as well as the median across repetitions for

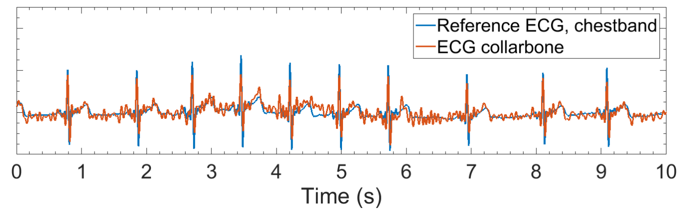

Fig. 5. 8-second segment for comparison of raw ECG signal obtained with the reference ECG device, and the proposed electrode in the left collarbone.

TABLE II
STATISTICS OF HRV METRICS

HRV metric (units)	Video category: Tenderness	Video category: Fear
Mean HR (bpm)	70.10 (8.77)	72.95(10.41)
s.d. HR (bmp)	3.65 (1.44)	4.04 (1.34)
RMSSD (ms)	48.51 (45.86)	49.63 (52.33)
Mean RR interval (ms)	869.95 (120.85)	838.71 (123.95)
s.d. RR interval (ms)	41.79 (24.73)	43.51 (29.85)
Low frequency power (ms^2)	708.76 (748.02)	667.33 (550.50)
High frequency power (ms^2)	1260.66 (1964.77)	1644.17 (2837.39)
LF/HF (adimensional)	1.89 (2.11)	1.76 (1.11)

one subject. The acquired EOG signals perfectly fit with the ones presented in the literature [22].

D. Candid usability feedback

The addition of the portable EEG device, cables and electrodes added 150 g to the total weight of the HMD. Four of the five participants considered the sensor-equipped HMD comfortable enough to be worn for an undefined period, whereas the other participant considered the experimental device uncomfortable after 10 minutes, due to the pressure exerted by the flexible dry electrodes on the back of the HMD. With use of the HMD-mounted EEG device and dry electrodes, preparation setup time was approximately 3 minutes. This is significantly lower than with conventional EEG studies using gel-based sensors.

IV. DISCUSSION

The sensor-equipped HMD was found to be comfortable and easy to wear for the majority of the participants. Notwithstanding, further modifications have been made to the headset strap by adding an extension. This has alleviated some of the pressure and allowed for longer duration recordings without any negative feedback from the participants. Moreover, the design of the experimental device allowed for a short preparation time, around 3 minutes. With such brief preparation time, we expect that cognitive states such as boredom and frustration will be avoided or diminished, as these states are frequently

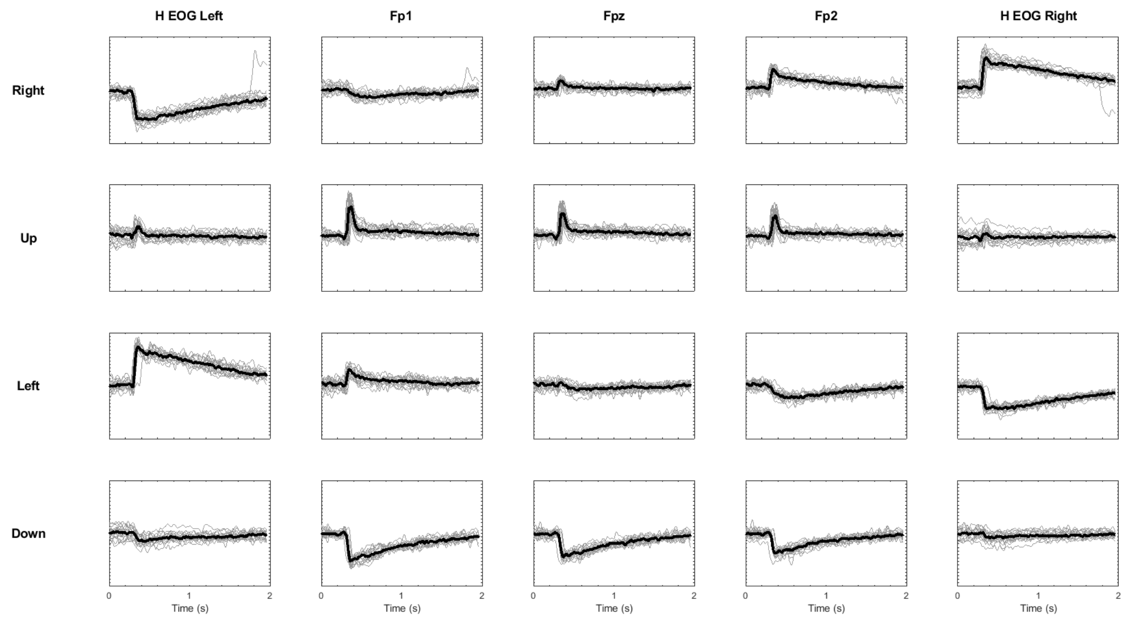

Fig. 6. Example of EOG signals in the electrodes: left eye outer canthus (H EOG Left), Fp1, Fpz, Fp2 and right eye outer canthus (H EOG Right), for the 4 proposed directions, right, up, left and down. Each of the repetitions is depicted with a gray waveform, and the average across repetitions with the wider black line.

observed in common EEG experiments where a preparation time greater than 20 minutes is the norm. This can play a crucial role in immersive QoE experiments.

The experimental tasks described herein have validated the quality and usability of the obtained ExG signals. While SSVEPs showed to be accurately detected during natural head movement, long-term EEG recordings can also play a critical role in immersive media QoE. In the past, EEG signals have been used to monitor emotions, mental workload, and stress, to name a few HIFs [3]. High-quality dry electrodes are achieving accuracies close to those obtained with gel-based sensors [28] and future work in QoE monitoring can also rely on advanced EEG enhancement strategies, such as the wavelet-based independent component analysis, which does not require human intervention [29].

Next, the experimental task with HR/HRV also showed the measured ECG signals to be highly correlated with those measured via a research-grade chestband. HR has been used in the past for immersive QoE assessment [11]. Previous works, however, have relied on users wearing additional devices, such as a fitbit bracelet. Having all sensors embedded into the HMD and synchronized using the same software makes for simpler setup, reduced synchronization errors, and reduced burden on the end user. Moreover, HRV has been used in the past to monitor not only HIFs, such as user affective states [30], but also for gaming QoE [31]. In the pilot experiment herein, HRV was explored as a discriminatory feature between two different affective videos. While the obtained values showed some difference between the two videos, the difference was not deemed statistically significant. This could be due to two factors: (1) comparisons are only performed with five participants, thus providing low statistical power, and (2) due to the videos used, HRV was computed over a 2-minute duration ECG segment. The HRV Task Force, however, has suggested that more reliable measures are obtained with segments greater than 5 minutes [32]. As such, future QoE research looking into HRV differences should pay close attention to video clip duration.

Lastly, there has been a recent trend to add eye tracking capabilities to HMDs. Examples include the FOVE HMD with eye tracking capabilities or Tobii, which can customize their eye tracking solutions to a customer's HMD. While an eye tracking enabled HMD may allow users to operate games using their gaze, it comes at a high financial cost. Moreover, for QoE assessment, such high-resolution gaze tracking may be overkill, especially if we are interested in monitoring HIF-related information. Using EOG to monitor eye gaze movements and blinks/blink rate can allow factors such as visual fatigue, drowsiness, and workload to be assessed.

One important factor within immersive media that was not explored in this pilot study was that of motion sickness, or the so-called cybersickness. It has been shown that between 50-80% of participants will feel some sort of cybersickness within the first 10-20 minutes of experiencing immersive content [33]. Recently, HRV was shown to discriminate between content that elicited motion sickness [34]. EEG metrics, in turn, have been shown useful for detecting and quantifying cybersickness [35], [36]. Moreover, eye gaze angles and fixation have also shown to be strong correlates of visually-induced motion sickness [37]. As such, the developed prototype measures all the key modalities needed for cybersickness assessment, thus may indeed play a key role in instrumental QoE measurement of emerging immersive multimedia.

V. Conclusion

This paper has described a sensor-equipped HMD for instrumental QoE measurement of immersive multimedia content. The device monitors scalp EEG, ECG and EOG wirelessly via sensors embedded into the HMD's strap and face piece. Three validation experiments are described showing accurate measurement of the three ExG modalities, thus showcasing the potential of the device for QoE measurement tasks.

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