Assessment of sickness in virtual environments


* University of Belgrade – School of Electrical Engineering, Belgrade, Serbia
** Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia

nadica.miljkovic@etf.bg.ac.rs, nenad.pop92@gmail.com, milana@etf.bg.ac.rs, jaka.sodnik@fc.uni-lj.si

Abstract—Prolonged consumption of virtual reality systems is challenged by induced sickness (commonly termed cybersickness) with a variety of unpleasant symptoms (e.g. disorientation, headache, nausea, salivation, sweating). The development of novel methods to assess cybersickness is required for future improvements in design of virtual environments and driving and aircraft simulators. We propose and explore relatively simple assessment method based on electrogastrography procedure to record and analyze electrical activity of the smooth stomach muscles in order to enable simple and effective quantitative assessment of cybersickness. In order to test the applicability of the proposed method, we recorded signals in three individuals during two roller coaster virtual experiences developed for Oculus Rift platform. The results presented here suggest that electrogastrography is promising procedure for cybersickness assessment. Nevertheless, some precautions in interpretation of results and future combination with other psychophysiological parameters are suggested. In addition, future improvements of the proposed method and possible applications are thoroughly discussed.

I. INTRODUCTION

Motion sickness is physiological response usually associated with the seasickness and in some cases to airsickness, carsickness, trainsickness, and spacesickness [1]. Another form of sickness commonly referred as cybersickness is related to the similar physiological response in flight and driving simulators and in virtual reality (VR) systems [2-4]. Motion sickness and cybersickness share similar symptoms that are generally described by unpleasant feeling accompanied by dizziness, nausea, sweating, salivation, stomach discomfort, and even vomiting [3].

Despite constant efforts to increase performance and optimize user experience in VR systems (e.g. improvements in head position tracking [5]), cybersickness occurrence as the major drawback of VR systems still prevails [3, 6-7]. For example, in 2015 the developers of the horror exploration game set Routine (Lunar Software, UK) have dropped support for Oculus Rift due to sickness experiences [3]. Though it was concluded that VR boosts the user experience compared to traditional user interfaces, it was recommended to include variety of measurements procedures for cybersickness early in the VR design process [7].

There is still no consensus related to the causes of cybersickness and the underlying mechanisms are still poorly understood [3, 8-9]. Brain-gut and gut-brain interactions are probably responsible for cybersickness occurrence [10-11], but the exact relation is yet to be discovered. In addition, there is a prevailing lack of technology in assessment of cybersickness that would lead to effective design strategies of simulators and virtual environments [3].

Objective measures used to assess cybersickness include variety of measurements procedures for assessment of sweating, gastric myoelectric activity, eye blink rate, respiration, cardiac vagal tone, delta power of EEG, skin temperature, and other [3]. We aim at studying electrogastrography (EGG) for its potential to objectively measure stomach awareness and nausea occurrence during VR experience.

EGG is a method that records electrical activity of stomach smooth muscles by placement of surface Ag/AgCl electrodes over stomach [12]. EGG has been recognized as promising method that can provide an objective measure (bio-marker) for assessing nausea [3, 10]. These measures are usually related to the dysrhythmias in EGG signal that can be either faster (tachygastria) or slower (bradygastria) than normal EGG rhythm (2-4 cpm, cycles per minute) [10]. It has been reported that during motion sickness, total power spectrum increases [13].

In this paper, we used EGG to assess nausea in three subjects during two VR experiences by Oculus Rift headset. EGG based parameters reflecting changes in EGG rhythm and power spectrum for cybersickness detection are presented and thoroughly discussed.

A. Research questions

The key research questions presented in this paper are:

1. Can EGG effectively measure cybersickness caused by Oculus Rift application? Some investigators suggested that there is lack of overall relationship between nausea and EGG parameters [13], while others reported that it is possible to measure nausea by EGG [3, 10];

2. What is the appropriate measure of cybersickness by EGG? In [14] several parameters were suggested related to the power spectral density shape and total power spectrum both in the whole region and in relation with EGG ranges; and

3. Are there any EGG related individual characteristics in two similar VR environments? Individual, device related and task-dependant factors are known to influence the cybersickness [3, 13]. We aimed to check whether these changes can be revealed by selected EGG parameters.

In order to answer these questions, we measured EGG in three subjects during VR experiences by application of

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Oculus Rift headset. All subjects were evaluated during two separate sessions and for watching two roller coasters.

II. METHODOLOGY

A. Hardware and software setup

Oculus Rift Consumer Ver. 1 (Oculus VR, Facebook Technologies, LLC.) VR headset with 1080 × 1200 resolution per eye, 90 Hz refresh rate, 110° field of view, and stereo speakers with 3D audio effect (https://en.wikipedia.org/wiki/Oculus_Rift, assessed on December 16, 2018) was used in this paper. Constellation tracking system was placed in front of the subject (about 50 cm away from the headset) as shown in Fig. 1. We used Desktop computer with Windows 10, Intel(R) Core(TM) i7-3770K CPU @ 3.50 GHz with 24.0 GB of RAM with GeForce GTX TITAN graphic card.

In order to record EGG signals, we used surface Ag/AgCl hydrogel self-adhesive electrodes H92SG (Kendall/Covidien, Dublin, Ireland) with size of 57 × 34 mm. Electrodes were placed as recommended in [12] in proximity of lesser curvature of the stomach.

Despite recommendations for simple one-channel recordings [12], we chose to record three channels in order to compensate for possible noise occurrence (subject’s motion during VR experience) and to compensate for possible EGG alternations by posture. Namely, recommendations in [12] were provided for supine position solely and it has been reported that in most cases, EGG is recorded from subjects placed in comfortable position ranging from supine to 45° inclination [14]. Since, our subjects were seated during the recording session; we used setup with three EGG channels.

EGG signals were amplified and filtered with EGG device (see Fig. 1 and [12]) and digitized with NI USB 6210 A/D (National Instruments Inc., Austin, USA) with resolution of 16 bits and recorded for offline processing by custom-made LabVIEW software (National Instruments Inc., Austin, USA). Gain was set at 1000 and sampling rate at 2 Hz as recommended in [12].

B. Measurement procedure

We recorded EGG signals from three volunteers with ID = 1-3 (three Females with 29.0±2.6 years of age, 172.7±2.9 cm of height, and with weight of 68.0±7.0 kg). All subjects signed Informed Consents approved by the Local Ethics Committee in accordance with the Declaration of Helsinki. Inclusion criteria were no pregnancy as suggested by [10, 14], no known disorders of gastro-intestinal tract and vestibular system, and with no known chronic and acute pathologies. Subjects did not use any medications at least one week prior to testing [14].

Subjects were instructed to keep body position as constant as possible during complete recording session as recommended in [14]. After skin preparation (by optional application abrasive Nuprep gel as in [12]) and appropriate electrode application, we allowed a pause of 10-15 minutes (as recommended in [14]) to establish stable electrode-skin interface. Subjects were evaluated during two recording sessions (pause of 4 days between sessions was allowed for complete recovery from cybersickness) while experiencing two VR roller coasters with Oculus Rift headset.

The first session included Rock Falls VR (RF VR) roller coaster of 4 min duration and during the second session, subjects were given T-Rex Kingdom VR (TRK VR) roller coaster of 6 minutes and 20 s duration [15].

EGG signals were recorded from subjects comfortably seated in front of a computer screen with arms placed on chair arms and about 50 cm apart from the constellation tracking unit (Fig. 1). Firstly, EGG signals were recorded at rest for 5 minutes. Subjects were instructed to relax with open eyes. Then EGG signals during VRs were recorded with additional interval of 10 minutes immediately after the VR session. All subjects were asked to avoid any excessive movements and not to talk during the recordings. Investigators were instructed to watch closely subject’s reactions during VR experiences, since the agreed sign of cybersickness occurrence was raised right hand. Subjects were instructed to inform investigators immediately to help them exit the VR if they felt too nauseous to continue.

C. Outcome measures

All processing steps were done in Matlab ver. R2013b (The Mathworks Inc., Natick, USA). All quantitative parameters were calculated for channel 1 placed according to the recommendations from [12]. We chose channel 1, since no excessive noise (by visual inspection) was found in channel 1 in all recordings.

Figure 1. The measurement setup: EGG signals were measured by EGG device, digitized with NI USB 6210 A/D and presented on the screen of a computer while subject used Oculus Rift device (headset used by the subject and constellation tracking placed in front of a subject) with Rock Falls virtual reality (RF VR) Epic Roller Coaster [15] during the first recording session.
In order to reduce noise, EGG signals were filtered with 5th order Butterworth filter with cut-off frequencies of 0.0167 and 0.3333 Hz as these values correspond to 1 and 10 cpm (cycles per minute), respectively. Then, Welch power spectral density (PSD) estimate was calculated by `pwelch()` Matlab function that uses Hamming windowing with overlap of 50% in order to obtain averaged periodogram. Sample EGG signal with corresponding Welch PSD is presented in Fig. 2 for 4 minutes long intervals during rest, during VR experience, and post VR experience.

Spectral analysis is the most commonly used for EGG signals [11], so we calculated three parameters from the PSD in order to assess changes in power and in shape of the PSD (see Fig. 2). For power assessment we used total power and power in percentage for three EGG rhythm ranges; and for shape assessment we calculated median frequency (MF) and crest factor of PSD (CF). All parameters were calculated for three intervals: (1) resting period of 5 minutes duration, (2) VR sequence (for RF VR 4 minutes duration and for TRK VR 6 min 20 s duration), and (3) post-VR for 8 minutes duration.

**TABLE I. QUALITATIVE PARAMETERS**

<table>
<thead>
<tr>
<th>Subject</th>
<th>RF VR</th>
<th>TRK VR</th>
<th>history</th>
<th>naïve users</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID1</td>
<td>0 (0)</td>
<td>2 (1)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>ID2</td>
<td>7 (3)</td>
<td>5 (5)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>ID3</td>
<td>3 (1)</td>
<td>2 (1)</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

* Rock Falls Virtual Roller Coaster (4 min duration) [15]
* T-Rex Kingdom Virtual Roller Coaster (6 min 20 s duration) [15]
* History of motion sickness
* None of the subjects felt too ill to stop the VR session.

Figure 2. Signal in time domain (left panels) and estimated corresponding Welch’s power spectral densities (right panels) for signals recorded in subject ID2 during the second session (TRK VR). TRK VR lasted for 6 min and 20 s, but only the first 4 min of the VR session are presented. Likewise, relaxation (resting) sequence was recorded for 5 minutes, and only the first 4 min are presented. post-VR relates to the recordings performed immediately after VR session. Frequency is presented in cpm units (cycles per minute) instead in Hz.

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**TABLE I. QUALITATIVE PARAMETERS**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Subjective scale (0 = no nausea, 10 = almost vomiting). Number of self-reported cybersickness episodes are given in brackets.</th>
<th>history</th>
<th>naïve users</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF VR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRK VR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID1</td>
<td>0 (0)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>ID2</td>
<td>7 (3)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>ID3</td>
<td>3 (1)</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

* Rock Falls Virtual Roller Coaster (4 min duration) [15]
* T-Rex Kingdom Virtual Roller Coaster (6 min 20 s duration) [15]
* History of motion sickness
* None of the subjects felt too ill to stop the VR session.

Total power (TP) was calculated as the integral of Welch’s PSD for the three intervals. Then, powers in percentage of TP for three ranges were calculated: (1) for slow EGG waves i.e. bradygastric rhythm for 1-2 cpm, (2) for normal EGG waves for 2-4 cpm, and (3) for fast EGG waves i.e. tachygastria for 4-10 cpm.

Median frequency (MF) is commonly used parameter for describing properties of electrical activity of skeletal muscles in the frequency domain for decades [16-17]. It is defined as the frequency that divides power spectrum of the signal into two parts with the same integral [16]. Practically, MF is a measure of power shift in the power spectral density. Here, it is used as quantitative parameter of the energy shift i.e. for assessment of PSD shape. In order to decrease excessive peaks in PSD to influence MF, we calculated MF from PSDs normalized to its mean.

In order to assess changes of PSD shape related to the dominant peaks, we used crest factor (CF) as the ratio of peak amplitude and root mean square (RMS) value of the PSD, since it has been previously used to assess peak prevalence in a given sample series [18].

We performed simple qualitative self-assessment scale in order to compare outcome measures with ground truth as suggested in [3]. Subjects were asked to evaluate (after recording was over) their subjective sensation in a scale from 0 (no nausea) to 10 (almost vomiting). All subjects were asked to report history of motion sickness in childhood and were asked to provide notes related to their own experiences during measurements and to answer are they novice to Oculus Rift VR technology.

**III. RESULTS**

Qualitative measures that include subjective scale, self-reported history of motion sickness in childhood, and previous experience with Oculus Rift headset (naïve users or not?) are listed in Table 1. Notes from subjects (personal observations and comments) are:
TABLE II. QUANTITATIVE PARAMETERS

<table>
<thead>
<tr>
<th>Subjects</th>
<th>R1</th>
<th>VR</th>
<th>post-VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TP [mV²/Hz]</td>
<td>MP [Hz]</td>
<td>CF</td>
</tr>
<tr>
<td>ID1 (RF/TRK)</td>
<td>2.21/1.21</td>
<td>0.06/0.05</td>
<td>7.60/5.48</td>
</tr>
<tr>
<td>ID2 (RF/TRK)</td>
<td>3.20/0.91</td>
<td>0.06/0.06</td>
<td>5.21/7.26</td>
</tr>
<tr>
<td>ID3 (RF/TRK)</td>
<td>1.30/5.35</td>
<td>0.05/0.05</td>
<td>5.89/6.04</td>
</tr>
</tbody>
</table>

a Total Power, b Median Frequency, c Crest Factor, d Resting sequence, e Virtual Reality sequence, f Post Virtual Reality sequence, g RF/TRK, Rock Falls and T-Rex Kingdom Virtual Roller Coasters

(1) ID1: “Sudden cessation of movement was unpleasant.”
(2) ID2: “Sudden changes of acceleration and direction of movement (especially rotation) were unpleasant.”
(3) ID: “Negative prediction due to previous experiences caused unpleasant sensation.”

Total powers and percentages for three rhythmical ranges of EGG waves for signals recorded in all subjects, during two VR sessions, and calculated for three intervals: (1) resting period, (2) VR sequence, and (3) post-VR sequence are presented in Fig. 3.

Quantitative parameters (TP, MF, and CF) calculated in all subjects during two sessions (RF VR and TPK VR) and for three intervals (resting, VR, and post-VR) are presented in Table 2.

IV. DISCUSSION AND CONCLUSIONS

Although revealed in Fig. 2 by visual inspection (similar graphs are obtained for other subjects), MF failed to describe changes i.e. frequency shifts to tachygastric region, that are obvious in PSD shape (it remained unchanged 0.06 Hz during all three intervals, see Table 2).

On the other hand, CF showed more sensitive to PSD shape changes. More prominent peaks in PSD would result in higher CF. We hypothesized that during VR experience and nausea occurrence, PSD would have less prominent peaks. This was the case for subject ID2, but it wasn’t the case with all subjects and for all VRs (Table 2). These changes in shape of PSD have been previously reported by variation i.e. stability of dominant frequency (see [14] for detailed review).

The persistent change in all subjects (with and without nausea occurrence) was increase in TP as reported in [19]. We did not find any specific relationship between TP change and subjective measures. It was previously shown that change in TP of EGG correlates with motion sickness in 50% of subjects and with nausea in 13% of subjects [13]. This might be the case with our measurement, but we cannot state definite conclusion since we presented EGG only in three subjects.

Interesting fact is revealed by comparison of TPs during resting periods for two recording sessions (RF VR and TRK VR). The results are not in agreement in all three subjects (see Table 2). This suggests that in order to use TP as a valid parameter for comparison among sessions and among subjects, one should record either sequences of interest during one recording session or an adequate normalization should be applied. Also, one should have in mind that excessive TP might indicate noisy signal and amplitude alone cannot be used to interpret changes in EGG signal [11, 20].

Percentages of TP presented in Fig. 3 reveal decrease in normal EGG rhythms during VR experiences, except in one subject where slight increase can be noticed (from 37% to 41%). Dysrhythmia occurred in all subjects during VR experiences (for both VRs) and it was characterized either by increase of brady gastria or increase of tachygastria. It was suggested in [13] that in some cases proportion of power does not change significantly since the TP increased, so the relationship between TP and percentage of TP should be taken into account.

In [14] frequency and the percentage of normal and altered waves are reported to be reliable parameters for EGG application for gastric motility and gastric emptying. Our results presented in Fig. 3 suggest that VR experience affects gastric system (by non-consistent alteration in EGG waves, by decrease of normal gastric rhythm in most cases, and by increase of TP) in both nauseous and non-nauseous subjects (see Table 1 for qualitative parameters).

TP recovers i.e. decreases after the application of VR for approximately 10 min with dominant frequency restoration to normogastric rhythm (2.4 cpm) indicating improvements in nausea symptoms which is in agreement with [10]. We did not check for the duration of the changes induced by VR (they prevail for some time, see Fig. 1) as this might be promising parameter for future recordings.

We used simple survey for sickness self-report; however, there are questionnaires such as Pensacola Motion Sickness Questionnaire, Pensacola Diagnostic Index, Kennedy’s Simulator Sickness Questionnaire, Nausea Profile, Virtual Reality Symptom Questionnaire and other [3, 21]. The major drawback of surveys is that they cannot be administered during VR experience, since the user needs to move the attention from VR to questionnaire [6].

By more detailed examination of the self-reported episodes, we revealed that sudden cessation of movement and changes in alteration and direction of movement were the most unpleasant VR events. This is in agreement with reports that higher rates of linear and rotational acceleration would induce higher and faster nausea [2]. Further look into the moments where subject ID2 reported highest nausea episodes (during VR), we revealed that nausea was reported while subject was at the highest points in space. This wasn’t in agreement with the previously reported fact that low altitudes above the terrain at higher speed would produce higher nausea [2]. Additional interview with subject ID2 revealed that she has acrophobia (fear of heights). This fact led us to...
In order to get more insight into these sphere, we related simulators less susceptible to cybersickness, one between history of motion sickness as the research focused on assessment of our subjects were not specifically fidelity were excluded. Though, positive see products).

Informed Consent and was naïve for Oculus Rift and VR experiences signed (channel 1) proved to be the least susceptible position from [12]. However, the highest location on torso electrode is needed. In the present study, we did not perform any rigorous check on their eating habits as that would affect the EGG recording [11-12].

Conclusion that anxiety and emotions (or emotional arousal) may play an important role in EGG content. Future measurements of EGG and their comparison with anxiety questionnaires should reveal if there is some relationship between anxiety and EGG. In previous research [11, 13] it has been reported that stressors can alter EGG signals. However, to the best of authors knowledge, the proposed combination of emotional arousal and cybersickness hasn’t been studied before.

In order to get more insight into these sphere, we included subject ID4 for additional one-session measurement (Female, 24 years old, 162 cm height, and 58 kg, with no known history of motion sickness, and was naïve for Oculus Rift and VR experiences signed (Female, 24 years old, 162 cm height, and 58 kg, with no known history of motion sickness, and was naïve for Oculus Rift and VR experiences signed). Informed Consent and protocol was applied as for ID 1-3). This additional recording with RF VR scenario revealed immediate increase in EGG TP of PSD after application of Oculus Rift headset (before even roller coaster RF scenario begun as seen in Fig. 4). Future exploration of this phenomenon (excitement caused by VR experience in naïve users) for appropriate conclusion is needed.

Our hypothesis did not include influence of EGG electrodes positioning, since we applied recommendations from [12]. However, the highest location on torso (channel 1) proved to be the least susceptible position during EGG recordings in sitting position, and thus future studies should be focused on investigation on electrode localization for cybersickness detection.

A. Influence of VR and individual differences on EGG signal

Chosen VRs in this study had similar levels of fidelity [15], suggesting that difference in inducing cybersickness was not due to the realistic roller coaster representation as suggested in [3, 6]. In order to provide similar effects in subject we kept device factors known to influence cybersickness constant (e.g. calibration, field of view, ergonomics [3]).

The difference that allowed TRK VR to induce higher changes than RF VR is probably related to its longer duration. This was not the case with subject ID2, since we hypothesized that nausea and EGG changes were related to anxiety in this case.

Additionally, our subjects were not specifically instructed how to navigate VR (active and passive tasks in VR were not instructed), so we could not exclude individual differences related to their perception of VR environments.

Our subjects were of similar age, the same gender and race, and their posture was kept similar during repeated sessions, so these proven influences to cybersickness as reported in [3, 22] were excluded. Though, positive correlation was found between history of motion intolerance to present sickness susceptibility in [1], we did not find any specific relation in subject ID3 that reported positively on sickness history. Of course, larger sample is needed for more precise conclusions.

The interesting and yet not thoroughly explored individual differences are related to the emotions and anxiety in VR environments that can alter EGG signals. For more appropriate assessment and relation of EGG parameters with emotional arousal, other physiological parameters should be included and their relation to EGG investigated for predicting, preventing, and studying cybersickness [6, 23].

B. Future applications

Appropriate assessment procedures can contribute to better understanding of consequences, nature, and origins of cybersickness [2].

In general, the research focused on assessment of cybersickness is of great importance not just for boosting user experience in gaming industry, but for designing simulators as well. For example, by designing compact driving simulators less susceptible to cybersickness, one can perform a variety of tests without exposing drivers to real-world risks [4, 24].

Hence, aircraft and driving simulators are fundamental for future for current safe and affordable autonomous and non-autonomous public air and road travel (see products and projects from companies: https://www.nervtech.com/, https://www.v2c2.at/, http://www.jobyaviation.com/#join-us, all assessed on January 3, 2019).

C. Limitations of the presented study

Eating, deep breathing, gastric electrical simulation, and biofeedback can decrease cybersickness [11]. We did not control deep breathing nor biofeedback as our subject could employ these strategies to improve nausea symptoms. Future studies should be focused on possible strategies to control nausea symptoms.

Though, our subjects were instructed to have one hour of fasting period before recording sessions and they did not receive any food, we did not perform any rigorous check on their eating habits as that would affect the EGG recording [11-12].

Extensive validation and refinement by testing the proposed methodology in larger sample with balanced procedure is required for reliable recommendations on application of EGG for cybersickness assessment.

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Figure 4. Filtered EGG signal recorded in subject ID4. The vertical line in 450 s marks the application of Oculus Rift headset after the resting session.
REFERENCES


