How to Deal with Motion Sickness in Virtual Reality

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Abstract

In this paper we present a exploratory study on the physiological responses when experiencing motion sickness in Virtual Reality (VR). To this end, we developed a VR application that can induce motion sickness. Using it, an experiment was performed where a group of users were subject to different types of observable motions, and for each the reported sensations together with a set of bio-signals were registered. The analysis of the collected results enable us to establish a relationship between VR/Motion sickness and the principal elements that may cause it, as well as the existence of some correlation between the discomfort felt by the participants and detectable changes in measurable physiological data. These results can serve both as a guide to designing VR-based applications, complementing the existing ones, and to enable the development of automatically adaptable ones preventing or reducing the discomfort for the users of this type of technology.

Keywords

Motion Sickness, Virtual Reality, Bio-Signals, Usability.

1 INTRODUCTION

With the emergence of Virtual Reality (VR) into the more commercial mainstream, issues have begun to arise in relation to the wellbeing and comfort of its users. Recent studies have shown that the biggest barrier of using VR systems is the so called VR sickness, pointing that this kind of sickness may be limiting the effective use of training, rehabilitation or gaming tools in VR [Barrett 04, Brooks 10, Wiederhold 14]. Although there is still limited information about the related physiological mechanisms, there is evidence that it is a form of motion sickness caused essentially by the mismatch between the motion perceived visually and through the vestibular system [Reason 75]. In VR, it happens mainly when the visual system detects apparent motion, whereas the vestibular system informs the brain that no movement is occurring and that the body is standing still. This effect can also occur in situations where the perceived movement is caused by the user head movements. Apparently this should contradict the ”mismatch rule”, but there are at least two situations where it may occur: 1) low/variable screen update rate - this frequently happens due to high computational load of the scene rendering or due to limitations of the head mount display (HMD) hardware. The low/variable update frequency of the visualised scene, makes the human brain detect ”jumps” instead of perceiving a continuous motion as reported by the vestibular system. 2) high difference between the head rotation movements and the perceived motion of the objects. This is similar to the discomfort caused by new glasses where a change on their graduation (refraction), or the use of progressive lenses requires an adaptation period.

1.1 Motion Sickness and the Autonomic Nervous System

There are morphological and physiological connections between the vestibular and autonomic nervous system, including its sympathetic and parasympathetic divisions. Motion sickness, which is produced by conflicting inputs from visual, vestibular and somatosensory afferents, generally carries vestibule-autonomic responses in humans. Sympathetic (SNA) and parasympathetic nervous activity (PNA) contribute to those responses, such as, the heart rate variability, skin conductance variability or body temperature changes. While the PNA controls the body’s response in rest, SNA is responsible for the internal response in body’s fight-or-flight, meaning the reaction to a stimuli[Hu 91, Farmer 14].

1.2 Contribution and Structure of the Paper

The contributions of this paper are two-fold: it analyses the most common elements that are responsible to induce motion sickness in VR applications, and establishes a relationship between some motion sickness symptoms and measurable physiological responses. Both may contribute to improve the design of future VR applications aiming at reducing the discomfort that its use frequently induces in users.

The remaining of the paper is as follows: section 2 presents the experimental setup, describing both the built immersive application and the acquired physiological signals. Section 3, presents the experimental protocol and evaluation procedure. Section 4 shows the obtained results and analyses them. Section 5 concludes and presents future directions.

2 DEVELOPED SYSTEM

In order to achieve our goal we developed a set of scenarios, taking into account different assumptions for each of them. It is known that in VR, motion sickness occurs when there are asynchronous events between our inertial and visual system. In this case our visual system perceives the movement but our body does not.

2.1 Virtual Environment

The VR system developed for this study consists in a virtual environment presented to the user through a Head-Mounted Display (HDM) which tracks all head movements. The user is immersed and can freely look around in the virtual environment.
The virtual environment is a street with houses and the user moves along a clockwise circle trajectory around it. During the experiment different combinations of involuntary camera behaviours and virtual elements are presented to the participant in order to induce or reduce the (un)desire sickness. Let's define voluntary movements as all the camera movement that the user performs voluntary and involuntary movements as the random camera behaviour not controlled by the user. Figure 1 shows the involuntary movements that were tested.

The virtual element used as frame reference is a car cockpit. Figure 2 shows the point of view of the user without and with the virtual cockpit.

2.2 Physiological Data

Electrocardiography

Electrocardiography (ECG) is an exam able to register the variation in potential created by the heart beating. It can be used to assess the Heart Rate Variability (HRV) which is the study of the variations associated with the Heart Rate (HR).

The Heart Rate measures how many times the cardiac muscle contracts and relaxes per unit of time, triggering depolarisation and subsequent polarisation of the myocardial cells.

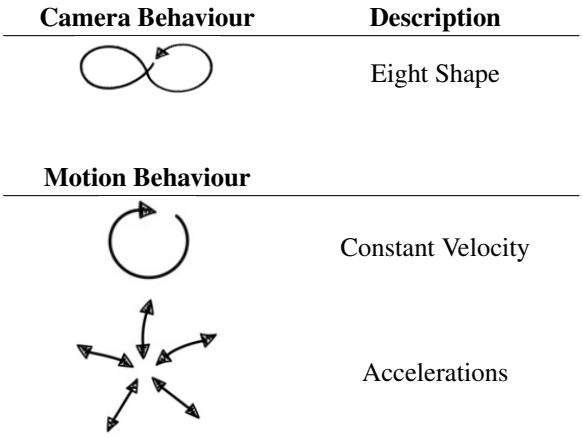

Figure 1: Involuntary camera and motion behaviour presented to the user.

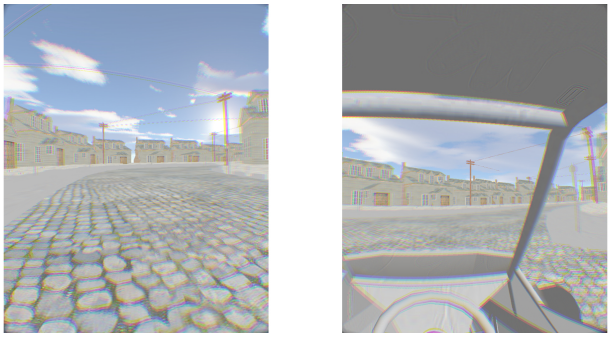

Figure 2: User point of view without cockpit (left) and with cockpit (right).

An ECG sample signal is better-known by its well defined QRS complex, which is the denomination given to the succession of the three deflections of a typical ECG wave-form (figure 3). The instant Heart Rate can be calculated by inverting the distance between R-peaks and multiplying it by 60. In situations of mental or physical arousal, the heart rate shall increase [Edhouse 02].

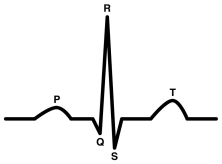

Figure 3: Illustration of the wave-form of an ECG signal.

Heart rate variability (HRV) is the consequence of the iteration of both sympathetic and parasympathetic halves of the automatic nervous system. The parasympathetic system shall slow the Heart Rate whereas the sympathetic accelerates it [Acharya 06].

Electrodermal Activity

Electrodermal activity (EDA), also known as Galvanic skin response, is related to the wet level of the sweat glands. These are controlled by the sympathetic system,

varying the electrical skin conductance, specially once an individual is presented a stimuli [Moore 03].

This measure is an indicator of the level of the person's arousal. EDA provides a reliable measure to assess the automatic nerve system function, providing an easy tool to get a person's internal state.

Physically, Galvanic skin response is often shown as a modification of the electrical features of the skin in response to a definite stimuli, capturing the variation of electrical potential from the skin surface. In fact, the increasing of EDA level depends more on the surprise effect of the stimuli than its strength [Ahuja 03, Tarvainen 01]. It is also known that EDA signal has the tendency to decrease once the person shows habituation [Hugdahl 96].

Body Temperature

Human body temperature varies depending on the place where it is measured. In this experiment the body temperature is measured upon the skin on the wrist. Nonetheless, the temperature tends to be lower in the surface than when measured internally, as an example below the tongue.

When a person is in some physical or mental stress, this measure tends to increase [Longo 11]. An increase in body temperature can be achieved for example by reduced convective heat loss via sympathetically controlled cutaneous vasoconstriction. Nevertheless, sweating can influence this measure. Sweating is a way our body uses to regulate our surface body temperature [Illigens 09].

Respiration Rate

The respiratory system has as primary function to supply oxygen to the blood in order to be delivered to all parts of the body. This is achieved through breathing. When breathing, we inhale oxygen and exhale carbon dioxide. This process involves the movement of the diaphragm which consequently is expressed in a movement of expanding and compressing of the rib cage.

Using an flex sensor, one can measure the amplitude and rate in which this process is carried by the person. This can be a good indicator of the person's internal state. It is known that a controlled rate of breathing can be a mechanism to control nausea, one of the symptoms of motion sickness [Farmer 14].

Body Acceleration

Accelerometers are inertial sensors used to measure three-dimensional accelerations. When placed on a moving body, it's capable of accurately sense it's movements.

In this case the two used accelerometers are attached one to the person's wrist so that he/she can signal simulation sickness episodes and the other one to the head of the person to trace motion artefact implied in the respiration signal.

2.3 Questionnaire

To assess the subjective level of the motion sickness symptoms we used the Motion Sickness Assessment Questionnaire (MSAQ). The participants were asked to rate how accurately the following statements describe their experience.
The scale goes from 1 to 9, where 1 means that the statement does not apply at all and 9 it severely occur.

1. I felt sick to my stomach (G)
2. I felt faint-like (C)
3. I felt annoyed/irritated (S)
4. I felt sweaty (P)
5. I felt queasy (G)
6. I felt lightheaded (C)
7. I felt drowsy (S)
8. I felt clammy/cold sweat (P)
9. I felt disoriented (C)
10. I felt tired/fatigued (S)
11. I felt nauseated (G)
12. I felt hot/warm (P)
13. I felt dizzy (C)
14. I felt like I was spinning (C)
15. I felt as if I may vomit (G)
16. I felt uneasy (S)

Note. G: Gastrointestinal; C: Central; P: Peripheral; S: Sopite-related.

The overall motion sickness score is obtained by calculating the percentage of total points scored: (sum of points from all items/144) x 100. Subscale scores are obtained by calculating the percent of points scored within each factor: (sum of gastrointestinal items/36) x 100; (sum of central items/45) x 100; (sum of peripheral items/27) x 100; (sum of sopite-related items/36) x 100.

3 EXPERIMENTAL PROTOCOL AND EVALUATION

3.1 Participants

Participants were eight volunteers (five male and three female, mean age of 25.75 and standard deviation of 2.49 years old). All participants reported healthy and normal or corrected to normal vision. Five had experience with video games and three of them had previous experience in immersive VR, but none had prior knowledge of the current experiment. All research ethical principles were attained.

3.2 Method (Procedure)

The experiment starts with the participant resting for a period of two minutes, followed by six minutes of VR exposure and it ends with a period of two minutes of rest, as illustrated in figure 4. Furthermore, participant's physiological data were collected during the full ten minutes of the experiment.

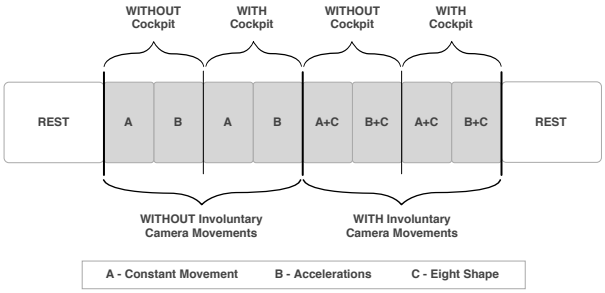

Figure 4: Experiment timeline.

At the end, participants were asked to remember and rate the best (as +1) and the worst (as -1) combination of camera behaviours and virtual elements during the VR exposure and fill a questionnaire (MSAQ) based on the worst experienced situation.

3.3 Measurements and Questionnaire

3.3.1 Physiological Signal Assessement

Willing to assess motion sickness, the signals acquired from the worn sensors must be preprocessed to remove any noise and analysed to extract some selected features. As the behaviour we want to assess has implicitly some duration in time, we perform analysis over samples that represent a sliding window of 45 seconds of activity with an overlap of 15 seconds.

Signal Preprocessing

Signal preprocessing can easily be divided into two main domains.

Signal filtering (Butterworph filter)

Signal filtering is used in this case to limit the bandwidth of frequencies allowed. A Butterworph Low pass filter is used to remove the noisy high frequency domain. In the same sense, some signals were filtered with a Highpass filter. This step is only used in the ECG signal as we can assume a tendency to zero, allowing the removal of the effect of baseline wander. This is important for a correct R-peaks detection, thus computing a reliable Heart Rate measure.

Baseline subtraction

A baseline is in this case defined as the value to which the signals will tend in a state of rest. Some of the signals, for instance EDA and Heart Rate, have a great interpersonal variation. Knowing this, one needs to remove this varying variable from the data. In this way, we will consider the rest state of the person as a zero baseline in the signal.

Features Extracted

In order to best capture the sense of the data, a set of features were calculated from the data window. These features are intended to best summarise the person's state in the window moment. Below we present selected metrics used from each of the bio-signals.

ECG features

In order to calculate ECG features, one has to detect R-peaks in signal. To better understand the technique, please refer to [Pedro 13]. Having detected the heart beats, one can compute the NN intervals, which is defined by the difference between successive normal R-peaks.

Heart Rate is defined by the number of times the heart beats per unit of time. It can be calculated by $\frac{1}{NN} \times 60$. This measure helps in the understanding of the anxiety and stress in the person.

RMSSD is defined by the Root mean square of the mean of successive NNs,

$$\sqrt{\frac{\sum_{i=1}^{n-1} D_i^2}{n-1}}. \quad (1)$$

This measure is known to be an accepted measure of parasympathetic activity [Sztajzel 04].

LF/HF ratio is the ratio of low-high frequency power. To calculate this measure it is necessary to analyse the frequency domain of the ECG signal, dividing the low frequency power by the high frequencies. It reflects the global sympatho-vagal balance (which is the balance between sympathetic and parasympathetic activity) and will be used as a measure of this balance [Sztajzel 04]. As it is known, the vagus nerve complex is related to the major reported motion sickness symptoms (e.g. nausea, disorientation and stomach awareness)[Hettinger 03].

EDA features

The number of peaks (nPEAKS) in the temporal window in analysis is used to analyse which period of time was most stressful for the user.

MAXMIN is the difference between the highest value of the window and the lower can assess the degree of change inside one window. If the maximum appear before the minimum the computation is a negative difference.

Mean The mean value of the window assesses the person's state over time.

The MEAN and the MAXMIN are extracted from both EDA and Temperature signals.

Respiration features

Rate or Frequency is used to analyse over time variation. Assuming breathing can be approximated to a sine function inside the temporal window, using FFT transformation, one can calculate the preponderant frequency in the spectrum. The variation of this measure can be related to the Heart Rate variation and so the autonomic nervous system activity.

4 RESULTS AND DISCUSSION

This section presents the results from both the bio-signal analysis and the subjects' questionnaire answers. We start by analysing the bio-signals, correlating those results with the participants subjective opinion of the best and worst reported scenarios.

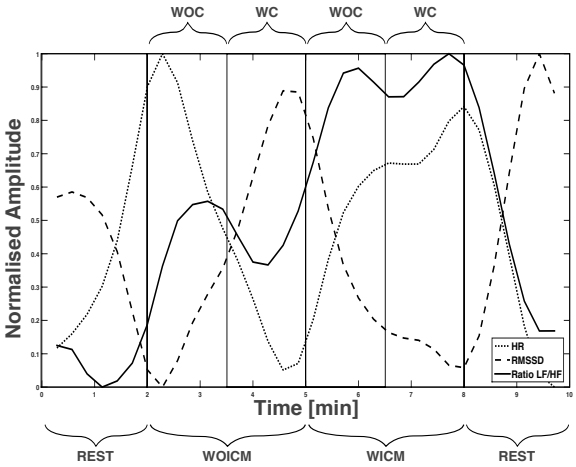

Figure 5: ECG results.

Figure 5 presents the result of the three ECG monitored features over time in the experiment. The measures are the mean values from all the subjects and are normalized to allow simultaneous illustration. One can start by noting the similarly of the measures tendency in the rest periods. Both *Heart Rate* (dotted line) and *LF/HF ratio* (dashed line) return to baseline value in the end of the experiment. In fact, *RMSSD* (solid line) value show an even higher parasympathetic activity (rest control) in the end of the experiment.

Being the first and the second scenarios (*WOICM*) evaluated as the most comfortable by the users (figure 7), one can see lower values of *LF/HF ratio* and higher *RMSSD* values, indicating a predominant activity of the parasympathetic system. Heart Rate rise in the first scenario can be explained by the subject's surprise and expectation in the beginning of the experiment. The worst reported scenario was the fourth (*WC & WICM*) showing higher *LF/HF ratio* and Heart Rate values as expected while low *RMSSD* value.

It is important to note a particular scenarios transition. The trend change in the three measures in the transition between scenario two (one of the best) and three (one of the worst), shows that the user's subjective opinion about the scenarios can be confirmed by the bio-signal analysis.

The illustration 6 presents the mean results for EDA features. It can be initially noted that values in both rest periods tend to some low value. Despite this, the mean value of EDA (solid line) starts higher, reason being for the initial enthusiasm of the subject before the experiment. Nonetheless, this value gets lower throughout the initial

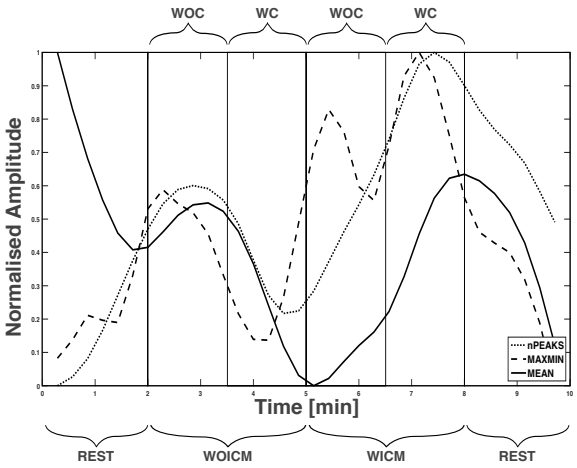

Figure 6: EDA results.

rest period.

One can see that all the values get higher in the beginning of the first scenario, due to the surprise effect. As it was stated in section 2.2, the effect gets weaker with time (stimuli habituation) and so, if we presented the same scenario to the user throughout all the experiment, one could expect a first EDA rise by the stimuli and a return to the rest state afterwards. As it can be seen, when the person enters the worst reported scenarios, all the measures rise, due to motion sickness discomfort. The number of peaks (dotted line) can be interpreted as sweating spikes, while the *MAXMIN* values (dashed line) show how severe these rises get. Moreover, the mean EDA values suggest the robustness of the previous two measures.

For respiration and temperature features, there were no significant changes over the experiment.

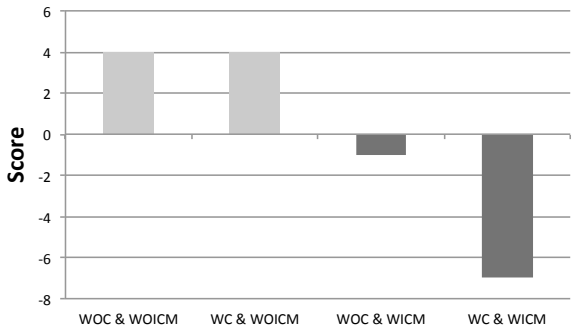

Figure 7: Best (light gray) and worst (dark gray) reported combinations.

Figure 8 presents the overall average score for motion sickness level before and after the experiment for the worst reported scenario. It is assumed that since the participants did not manifest any prior statements of motion sickness at the beginning, the score level starts at zero. At the end of the experiment, the overall average score rose to 36.02% with a standard deviation of 14.70%.

Finally, we present the results of the questionnaire's

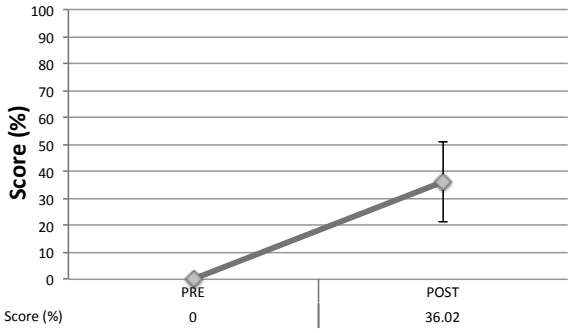

Figure 8: Overall average score of MSAQ.

answer into four different motion sickness sub-scales. In fact, motion sickness may be better quantified as a multidimensional scales, dividing it into different type of symptoms. The advantage of separating them is that the same overall score for two participants can be achieved by having different sub-scales scores. Figure 9 presents the average score for each of these four components. It is noticeable that the Central and Peripherical sub-scales, most related to Heart Rate and EDA measures, got higher scores.

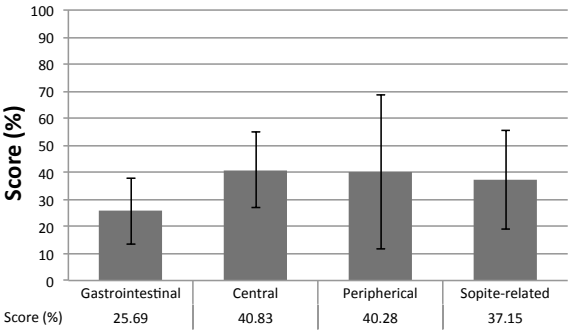

Figure 9: Sub-scales average score of MSAQ.

From the experiment results and observations, we can present some assumptions on how to induce or reduce motion sickness in a VR environment.

How to induce motion sickness

- Changing the head orientation without the user input;
- Modifying the field of view or zooming in and out;
- Variations in acceleration or speeding up and down.

How to reduce motion sickness

- Maintaining the immersion from the start until the very end of the experiment. There must be always a response to the user input (in loading screens, transitions, etc.), if the screen stops it give the sensation that the system is not responding, removing the immersion;
- Adding a frame reference also helps to prevent the user to feel unwell, as long as there are no involuntary camera movements (the user must be always on control of the camera). These kind of elements seams to work great because the user have a reference that connects him/her to the virtual environment. For example, a cockpit or a windshield that is with the user all the time in his/her peripheral vision work very well for this purpose;
- VR must be treated as theatre not as a film, so the user's head is someone eyes not a camera. Avoid camera animations and tricks, such as, zoom in and out, these can lead to the undesired sickness.

5 CONCLUSION

We presented a exploratory study on the physiological responses when experiencing motion sickness in Virtual Reality (VR). A VR application was developed to induce motion sickness. Using it, an experiment was performed where a group of users were subject to different types of observable motions, and for each the reported sensations together with a set of bio-signals were registered. The analysis of the collected results enabled us to establish a relationship between VR/Motion sickness and the principal elements that may cause it, as well as the existence of some correlation between the discomfort felt by the participants and detectable changes in measurable physiological data. These results can serve both as a guide to designing VR-based applications, complementing the existing ones, and to enable the development of automatically adaptable ones preventing or reducing the discomfort for the users of this type of technology.

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