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Use of physiological signals to predict cybersickness ☆

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ABSTRACT

Cybersickness is a common and unpleasant side effect of virtual reality immersion. We measured physiological changes that were experienced by seated subjects who interacted with a virtual environment (VE) first while viewing a display monitor and second while using a head-mounted display (HMD). Comparing results for these two conditions let us identify physiological consequences of HMD use. In both viewing conditions, subjects rated the severity of their symptoms verbally and completed a post-immersion cybersickness assessment questionnaire. In the HMD viewing condition but not in the display monitor condition, verbal reports of cybersickness severity increased significantly relative to baseline. Half of the subjects chose to exit the VE after six minutes of HMD use and reported feeling some nausea at that time. We found that changes in stomach activity, blinking, and breathing can be used to estimate post-immersion symptom scores, with R^2 values reaching as high as 0.75. These results suggest that HMD use by seated subjects is strongly correlated with the development of cybersickness. Finally, a linear discriminant analysis shows that physiological measures alone can be used to classify subject data as belonging to the HMD or monitor viewing condition with an accuracy of 78%.

1. Introduction

Virtual reality technology lets users feel present in simulated VEs [1]. Modern computer graphics and sonics provide near instantaneous updates of the audiovisual display in correspondence with movements of the viewer's head and body to create a compelling experience. This technology has proven useful in training simulations for the military [2], for medical procedures [3], and for the entertainment industry.

A side effect of virtual reality technology that has persisted throughout its existence is visually-induced motion sickness, often referred to as simulator sickness or cybersickness [1,4]. Symptoms include vomiting, nausea, and lightheadedness [1]. Other related physiological changes include facial pallor and sweating [4]. Research by Cobb and colleagues [6] indicates that 80% of participants show symptoms of cybersickness within ten minutes of immersion in virtual reality. Regan and Price [7] found that 60% of subjects who were immersed in a VE for twenty minutes showed cybersickness symptoms. These symptoms can last for up to five hours after exiting the VE [8]. While comfort has been increased by certain improvements in virtual reality technology, like minimizing the lag between head movement and visual display update and reducing HMD weight [9], sources of discomfort remain. Indeed, recent work by Davis and colleagues [10] suggests that virtual reality users are more likely to experience cybersickness as the realism of the environment is increased.

Although motion sickness symptoms are agreed upon [10–14], a consensus on their causes has yet to be reached. Treisman suggested that motion sickness is actually the body's adaptive response to a noxious stimulus [12]. Stoffregen and colleagues argue that maintaining stability of the body is critical and that prolonged postural instability may lead to and is a necessary prerequisite for motion sickness [15,16]. However, the notion that sensory mismatch can cause motion sickness is widely accepted [12,13,17–19]. Sensory mismatch occurs when the brain's predictions about upcoming sensory input do not match those associated with expectations generated by prior experience. The severity of cybersickness depends on the degree of sensory mismatch. The visual and vestibular systems are most frequently responsible for generating sensory mismatches that cause motion sickness.

The vestibular system, which is sometimes referred to as the "sixth sense" [15], serves three main functions: to sense motion and spatial orientation of the head, to maintain postural stability of the body [20–28], and to stabilize fixation of the eyes as the head rotates to provide a stable image on the retina [29–32]. The visual system processes optic flow to provide estimates of how a person

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moves through an environment [33]. Thus the common scenario, in which a user remains stationary in reality while experiencing a visual display that signals egomotion, creates a mismatch and induces sickness. A possible consequence of such discomfort is that people avoid using virtual reality technology [34]. Cybersickness research is important for the continued progress of the industry as well as for furthering our understanding of how the brain integrates information from multiple senses.

Established surveys concerning motion sickness exist and are in common use [35–37]. One drawback of lengthy surveys is that they cannot always be administered while a subject is participating in an experiment. Yet brief judgments of motion sickness severity on a 1–4 scale [35] provide useful information in such situations, although such judgments require the user to shift attention away from the experiment and toward how their body feels. Despite imperfections with these methods for evaluating motion sickness, the present study uses them to help determine the extent to which physiological measures can be used to predict cybersickness. Physiological indicators such as heart rate [38], respiration rate [39,40], galvanic skin response (GSR) [38,41], electrogastrogram (EGG) [18,42,43], and skin pallor [5], and even temperature [44] have all been shown to be related to or predictive of cybersickness.

This paper describes an experiment in which cybersickness is measured while users navigate about a VE. Subjects viewed a VE using a display monitor or a head-mounted display (HMD). We hypothesized that cybersickness would be caused by the sensory mismatch that is created when subjects remain stationary in the real world but move around in the virtual world. Verbal reports of cybersickness were collected alongside continuous records of several physiological measures. Each subject participated in two VE viewing conditions: viewing the environment using a display monitor, and viewing the environment using an HMD. By contrasting results found when viewing a display monitor and those found when using an HMD, we can distinguish effects of arousal caused by environment interaction from physiological effects associated with HMD use. Results show that physiological measures differ significantly between display monitor and HMD viewing conditions and can be used successfully to estimate the severity of cybersickness.

2. Methods

2.1. Virtual environment

We chose a modified free-use level [45] running on the Source Engine (Valve Corporation) to be the environment common to the two conditions: display monitor and HMD. A screenshot of the environment is shown in Fig. 1. During the display monitor condition, subjects viewed the environment on a Samsung S27A550H 27in LED display with a refresh rate of 60 Hz and a resolution of 1920×1280 pixels. Subjects sat approximately 57 cm away from the display, which provided a field of view of approximately 60° of visual angle horizontally by 40° vertically. For the HMD condition, subjects wore an Oculus Rift (Oculus VR, Development Kit 2). The HMD has a resolution of 960×1080 pixels per eye with a refresh rate of 75 Hz. The field of view is 100° horizontal by 100° vertical; head orientation is sampled at a rate of 1000 samples per second.

2.2. Questionnaires

Subjects started the experiment by completing the Motion Sickness Susceptibility Questionnaire (MSSQ), which was developed by Golding [37] to assess how susceptible a person is to motion sickness based on their past experience. It has two subsections. The first, called the MSSQA, concerns childhood experience of traveling and motion sickness before the age of 12. The second, called the MSSQB, concerns traveling and motion sickness over the last ten years. The questionnaire asks how often the subject felt sick or nauseated during different activities and is scored on a five point scale: 0 never, 1 rarely, 2 sometimes, 3 frequently, and 4 always [35]. The frequency of traveling in different vehicles is also tallied and used for calculating a final susceptibility score (see [37]).

Subjects also filled out the Simulator Sickness Questionnaire (SSQ) which was developed by Kennedy and colleagues [36]. The SSQ asks subjects to rate each of 16 symptoms on a 4 point scale: 0 absent, 1 slight, 2 moderate, and 3 severe. These ratings are used to generate scores on three sickness subscales: Nausea, Oculomotor, and Disorientation. Subjects filled out the SSQ after completing the display monitor condition and again after completing the HMD condition.

2.3. Procedure

All subjects completed the display monitor viewing condition before the HMD viewing condition. All rested during a five minute break between conditions. Before recording physiological data, subjects were shown how to move around the VE using an Xbox controller that was connected to the computer controlling the VE. Subjects explored the VE freely during display monitor and HMD viewing sessions. For each of the two conditions, baseline resting data were collected for two minutes while the subject

Fig. 1. Screenshot of the virtual environment used in the experiment: a Half Life 2 game level that was run on the Source Engine.