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Characteristic changes in the physiological components of cybersickness

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Abstract

We investigated the characteristic changes in the physiology of cybersickness when subjects were exposed to virtual reality. Sixty-one participants experienced a virtual navigation for a total of 9.5 min, and were required to detect specific virtual objects. Three questionnaires for sickness susceptibility and immersive tendency were obtained before the navigation. Sixteen electrophysiological signals were recorded before, during, and after the navigation. The severity of cybersickness experienced by participants was reported from a simulator sickness questionnaire after the navigation. The total severity of cybersickness had a significant positive correlation with gastric tachyarrhythmia, eyeblink rate, heart period, and EEG delta wave and a negative correlation with EEG beta wave. These results suggest that cybersickness accompanies the pattern changes in the activities of the central and the autonomic nervous systems.

Descriptors: Virtual reality, Cybersickness, A simulator sickness questionnaire, Gastric tachyarrhythmia, EEG, Autonomic nervous system

A virtual reality is a computer-generated, interactive, multisensory, three-dimensional environment in which a person is immersed (Barfield, Zeltzer, Sheridan, & Slater, 1995). Image projections forming the virtual environment are presented through either a head-mounted display or a multiple-screen projection system. With the help of the equipment, virtual reality system users can experience an immersive feeling as if they were in the reality. Virtual reality makes it possible to transmit vivid experiences within a short amount of time. Virtual reality systems are useful for training for driving simulation, machine operation, health therapy, design, and entertainment (Bayarri, Fernandez, & Perz, 1996; Haas, 1984; Lamson, 1997; Lin, Hon, & Su, 1996). It is generally expected that virtual reality will provide pivotal technology in the industry and education of the future.

Although this new technology is very promising, there exists a potential threat to the ultimate usability of virtual reality. Many users experience discomfort during, and sometimes after, a session in a virtual environment (Biocca, 1992; Cobb & Nichols, 1998; Hill & Howarth, 2000). It has been reported that 80% of all participants showed an increase in cybersickness symptoms within 10 min after becoming immersed in a virtual reality (Cobb, Nichols, Ramsey, & Wilson, 1999). Regan and Price (1994) reported that over 60% of individuals exposed to virtual reality for 20 min show increases in cybersickness symptoms. The term cybersickness has been used to describe motion-sickness-like experiences in a virtual reality, which can be distinguished from classical motion sickness experienced in transport systems (McCauley & Sharkey, 1992; Wilson, 1996). In a typical virtual reality, users often view moving scenes while they remain physically stationary. Although the symptoms may be similar, their origins can be different from each other. Whereas vestibular stimulation alone is usually sufficient to cause motion sickness (Money, 1970), there is no one exact cause of cybersickness. Cybersickness is more likely a result of the compounding of the visual and motion cuing and not due to merely the motion alone (Kolasinski, Goldberg, & Hiller, 1995). It is noted that side effects of cybersickness can persist for several hours (Nichols, 1999). Regan and Ramsey (1994) showed that subjects exposed to virtual reality reported the symptoms for up to 5 h of post-immersion.

The sensory conflict theory is generally accepted as the cause of classical motion sickness (Reason & Brand, 1975). Conflict sources are derived from discrepancies among multiple sensory inputs and/or sensory expectations on the basis of past experience. Cybersickness triggered by exposure to a moving visual environment can also be caused by ''sensory conflict.'' The typical case of visually induced sickness can be provoked with an optokinetic drum rotating vertically about a stationary subject's yaw axis. This situation can cause a compelling sense of self-motion (called vection). Vestibular cues indicate that the

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body is stationary, whereas visual cues report the body is moving (Howarth & Costello, 1997). Symptoms of cybersickness, such as nausea and dizziness, are similar to those reported during classical motion sickness (Howarth & Costello, 1997; Regan, 1995).

Many researchers have adopted questionnaires as subjective measures of motion sickness. A solid combination of objective and subjective measures may offer a better solution for the evaluation of motion sickness. Physiological measures would offer more precise objective measures of the sickness if found to be reliable and valid. The relative importance of autonomic nervous system responses in understanding and preventing motion sickness has been discussed (Graybiel & Lackner, 1980; Harm, 1990; Kohl & Homick, 1983; Money, 1970). Miller, Sharkey, Graham, and McCauley (1993) demonstrated the sensitivity of physiological measures to the severity of sickness with self-reports from U.S. Army helicopter pilots.

Prior researchers have shown that the motion-sickness-induced symptoms are associated with increased heart rate (Cowings, Suter, Toscano, Kamiya, & Naifeh, 1986), increased skin conductance (Hu, Grant, Stern, & Koch, 1991; Miller et al., 1993), increased gastric tachyarrhythmia (Hu et al., 1991), and increased plasma catecholamine levels (Koch et al., 1990). Changes in the activity of the human cerebral cortex have also been detected during motion sickness using electroencephalographic recordings (Chelen, Kabrisky, & Rosers, 1993).

There are different aspects of classical motion sickness and cybersickness. First, cybersickness is only visually induced. People do not suffer from cybersickness in a virtual environment if they close their eyes, whereas closing the eyes does not prevent classical motion sickness. Second, symptom profiles may differ (Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992). Although the main symptoms of motion sickness tend to be nausea, vomiting and retching, and drowsiness, other symptoms such as pallor, sweating, salivation, apathy, headache, stomach awareness, disorientation, postural instability, and residual aftereffects tend to be more prominent in people experiencing cybersickness. Third, many users experience discomfort during the virtual navigation despite a relatively short exposure of several minutes (Cobb et al., 1999). The exposure time inducing sickness symptoms is usually shorter in a virtual environment than in transport systems.

Habituation to the side effects of immersion in a virtual reality was studied in some research groups (Hill & Howarth, 2000; Stanney, Kennedy, Drexler, & Harm, 1999). They reported that habituation did occur when virtual reality was repeatedly presented. However, cybersickness can be potentially dangerous. In some cases symptoms can be present for hours or days and could have an effect on the user's subsequent ability to perform real-world tasks (La Viola, 2000). The severity and duration of these symptoms may be influenced by the length of exposure to the virtual reality and the intensity of the experience. Another consequence of cybersickness is that people who do experience symptoms may avoid using virtual reality in the future (Nichols, 1999).

We examined the psychophysiological characteristics of cybersickness with a combination of objective and subjective measures similar to those used in the studies of classical motion sickness. The two major purposes of this study were (1) to observe the relationships between physiological response patterns and subjective cybersickness severity during virtual navigation, and (2) to determine which variables might predict cybersickness severity with regression analysis. To accomplish these objectives, 61 subjects were immersed in a virtual reality for 9.5 min, physiological measurements were recorded before, during, and after the virtual navigation, and self-reports were examined to evaluate the effects of the virtual reality. The following physiological variables were measured: heart period, respiratory sinus arrhythmia, respiration rate, eyeblink rate, fingertip pulse volume, fingertip temperature, skin conductance, gastric tachyarrhythmia, and EEG power spectrum. Most of these variables have been used in previous studies on motion sickness and have shown significant correlation between the variables and severity of motion sickness (Chelen et al., 1993; Cowings et al., 1986; Drummond, 2004; Hu et al., 1991; Mekjavic, Tipton, Gennser, & Eiken, 2001; Miller et al., 1993). Furthermore, these variables represent different aspects of physiological change.

Method

Participants

Sixty-one (31 men, 30 women) undergraduate students participated in the study. None of the participants suffered from any vestibular dysfunction or were taking any medication during the experiment. The mean age was 23.08 years ($SD = 2.05$, aged 19–27 years). Participants fasted for at least 2 h before the experiment. Prior to the experiment, informed consent was obtained about the nature of the experiment and participant rights were fully explained. Participants were tested individually during the entire experiment session and received payment for their participation. None of the participants had experienced an immersion in virtual reality before.

Apparatus

Biosignal recordings were produced on a Biopac polygraph (BIOPAC Systems, Inc.). The polygraph was composed of couplers for electrocardiogram (ECG 100), electrooculogram (EOG 100), skin conductance (GSR 100), photoplethysmogram (PPG 100), skin temperature (SKT 100), electrogastrogram (EGG 100), respiration pneumogram (RSP 100), and nine electroencephalograms (EEG 100) with a 16-bit A/D converter-based MP 100 interface. Data were gathered with a sampling rate of 400 Hz. Electrode sites were cleaned with alcohol to ensure electrode impedances below 10 kΩ except for the skin conductance site. A ground electrode was attached to the middle of subject's forehead.

The amplifiers were set as follows: (1) Electrocardiogram was recorded through an Ag/AgCl surface electrode (8 mm diameter, BIOPAC Systems, Inc.) with a lead II configuration from the right wrist to the left ankle. A low-pass filter was set to 125 Hz (12 dB/octave) and amplification was set to 5000 × . (2) Electrooculogram was derived from 8-mm-diameter Ag/AgCl electrodes (BIOPAC Systems, Inc.) placed on the vertical midline of the right eye above the eyebrow and about 1 cm below the lower lid. Amplification was set to 2000 × and a low-pass filter was set to 30 Hz. (3) Skin conductance was recorded at a constant voltage of 0.5 V at the volar surfaces of the distal phalanxes of the second and third fingers of the right hand. Ag/AgCl electrodes (TSD 103, BIOPAC Systems, Inc.) had a surface of 0.38 cm^3; they were filled with conductance paste (Gel 100, BIOPAC Systems, Inc.). Sensitivity was 100 íS/V with a low-pass filter of 10 Hz. (4) Photoplethysmogram was detected at the volar surface of the distal phalanx of the right little finger. The signal was amplified 50 × and filtered with a low-pass of 10 Hz. (5) Skin temperature was measured at the volar surface of the right ring finger's distal phalanx with a TSD 102a fast response thermistor

(BIOPAC Systems, Inc.). Sensitivity was 5°F/V (with a midpoint at 89.96°F) and a low-pass filter was set to 1 Hz. (6) Electrogastrogram signals were collected by applying two Ag/AgCl cutaneous electrodes. The two active electrodes were attached to the subject's abdomen, one above the umbilicus at 25% of the distance between the umbilicus and the xipoid process and one on the subject's left side, just below the costal margin and 8 cm left of the midline. Amplification was 5000 × and a bandpass filter was set to 0.005–0.1 Hz. (7) Respiration was detected by a thoracic strain gauge around the subject's chest. Amplification was 10 × and a low filter was set at 10 Hz. (8) Eletroencephalogram (EEG) was recorded from nine scalp locations with Ag/AgCl electrodes. These electrodes were placed at F3, F4, Cz, T3, T4, P3, P4, O1, and O2 as defined by the international 10/20 system (Jasper, 1958) with a bandpass filter of 1.0–100.0 Hz and 60 Hz notch filter. Amplification was 20,000 × . A reference electrode was placed on a right earlobe for a monopolar recording.

The digitized data files were produced and stored by the software Acknowledge 3.5 (BIOPAC Systems, Inc.), which supported visual data display and ASCII or text file creation.

Virtual Reality System

Image projections forming the virtual environment were presented through a multiple projector system with a theater-type concave screen. The virtual reality system used in this study was the 3D Visual and Auditory Environment Generator, which had three channels with cathode ray tube image displays and was developed by the Korea Institute of Science and Technology (http://www.imrc.kist.re.kr). The systems were implemented on a Silicon Graphics Onyx Reality Engine 2 Workstation with full color, constant 30 frames per second, and high resolution (3840 × 1024 pixels). The field of view of the screen was approximately 150° horizontally by 45° vertically. The generator displayed 3D objects such as trees, bridges, a road, a river, and buildings. The virtual reality room was equipped with a video camera and loud speakers with electrical shielding. Users navigated the virtual environment using a steering wheel, a brake, and an accelerator. The experimental room was sound attenuated and air-conditioned.

Procedure

Participants were given a verbal briefing on the electrode attachment and recording procedure. Each participant completed a pre-immersion questionnaire. Electrode attachment was followed by a 10-min electrode stabilization period and a 5-min baseline period. During the baseline period, participants were instructed to observe the freeze-frame of the virtual reality. Participants were then exposed to the virtual reality for 9.5 min. After the virtual navigation, participants were instructed to observe the freeze-frame of the virtual reality for 1 min. Each participant completed a post-immersion questionnaire after the electrodes were detached. Prior to the navigation, participants were shown how to manipulate the handle in all directions (i.e., forward and backward, right and left turn) using their left hand. Participants were briefed on the tasks that they had to perform in the virtual environment. All participants were required to sit in an upright posture with restricted head and right hand movements during the navigation for electrophysiological recordings. During the navigation, participants were asked to find virtual objects (10 trash cans) placed randomly within the virtual environment. Participants were instructed to report whenever they felt sickness, which was defined as nausea, fatigue of eyes, and disorientation. Furthermore, participants were asked about the presence or absence of sickness at 2-min intervals during the virtual navigation. Physiological data were acquired for 5 min before, 9.5 min during, and 1 min after navigation in the virtual reality. The experiment was terminated when either (1) the participant requested termination or (2) vomiting occurred.

Pre- and Post-Immersion Questionnaires

Participants initially completed a 33-item pre-immersion questionnaire that included a motion sickness susceptibility questionnaire (MSSQ, 3 items; Golding, 1998) and an immersive tendency questionnaire (29 items; Witmer & Singer, 1998) before the virtual navigation. Each subject gave a pre-immersion rating on the malaise scale (Regan & Ramsey, 1996). After navigation, participants completed a 49-item post-immersion questionnaire that included a simulator sickness questionnaire (16 items; Kennedy, Lane, Berbaum, & Lilienthal, 1993) and a presence questionnaire (32 items; Witmer & Singer, 1998). Participants gave a post-immersion rating on the Anxiety scale from 0 to 6. The malaise scale had four categories: 0 = *no symptoms*; 1 = *some symptoms, but no nausea*; 2 = *mild nausea*; 3 = *moderate nausea*. A MSSQ is scored on a 5-point scale from 0 = *never* to 4 = *always*. A MSSQ provides a total nausea score from the frequency of nausea and vomiting experienced in the past when the participant was exposed to the following forms of transport: cars, buses, trains, airplanes, small boats, ships, swings, merry-go-round, and big dippers. In this article, MSSQ section B from the original questionnaire was used (Golding, 1998). The range of scores on MSSQ section B is from 0 to 95.04. A simulator sickness questionnaire contains a list of 16 symptoms, which are rated by the subject on a 4-point scale (0 = *absent*, 1 = *slight*, 2 = *moderate*, 3 = *severe*). The three subscales derived from prior factor analysis were labeled as: Nausea (Cronbach's alpha, 0.86); Oculomotor (Cronbach's alpha, 0.82); and Disorientation (Cronbach's alpha, 0.85). The subscales, Nausea, Oculomotor, and Disorientation, were computed by summing the ratings of all symptoms and multiplying this value by the appropriate weight. This weight was 9.54 for Nausea, 13.92 for Disorientation, and 7.58 for Oculomotor. The total severity of cybersickness (Cybersickness) was computed by adding the sums of the symptom ratings for Nausea, Oculomotor, and Disorientation and multiplying this value by 3.7. The ranges of scores on Nausea, Oculomotor, Disorientation, and Cybersickness are 0–200.34, 0–159.18, 0–292.32, and 0–235.62, respectively.

The present study used the presence questionnaire to measure the feeling of presence in the virtual environment and immersive tendency questionnaire to measure the involvement tendencies of individuals in an immersive environment. A 7-point scale was used to obtain participants' feeling ratings (1 = *do not agree at all*, 7 = *completely agree*) by means of the immersive tendency questionnaire and presence questionnaire. The ranges of scores on the immersive tendency questionnaire and presence questionnaire are 29–203 and 32–224, respectively. The four subscales derived from prior factor analysis of the presence questionnaire data were labeled as: Control factor, Sensory factor, Distraction factor, and Realism factor. In the immersive tendency questionnaire, three subscales were labeled as: Involvement, Focus, and Games.

Data Quantification

All data, except electrogastrogram from before and after the navigation, were calculated as mean values for 60-s epochs. For the navigation phase of 9.5 min, data were calculated as mean values. Furthermore, all physiological parameters were averaged

for the initial minute of navigation, the middle minute of navigation, and the final minute of navigation. Data analysis was conducted with the script of Matlab version 6.1 (Mathwork, Sherborn, MA).

The electrogastrogram data were analyzed for 4-min epochs before the navigation and for the initial 4 min of navigation and the final 4 min of navigation. The electrogastrogram was spectrally decomposed using the Fast-Fourier Transform with a Hamming window (size of 96,000 samples), yielding power estimates for every 0.25 cpm from 0.25 to 15 cpm. Spectral estimates were totaled for the following bands: 3 cpm (2.5–3.75), tachyarrhythmia (4.0–9.75 cpm), and total power (0.25–15 cpm). The ratio of total power found in the 3-cpm and tachyarrhythmia bands was calculated. Because the respiration signal can be confounded in electrogastrogram recording, it is helpful to discern whether the electrogastrogram signals are contaminated by respiration. Respiration was recorded so that any portions of the electrogastrogram recordings that were contaminated with respiratory artifacts could be identified and deleted.

Heart rate and heart period were extracted from the electrocardiogram signal using the R peak detection algorithm (Park, 2004; Park, Park, & Kim, 2001). Respiratory sinus arrhythmia was calculated from the heart period time series for each minute of baseline, the experimental period, and the post-immersion period. Respiratory sinus arrhythmia was obtained using Complexity version 2.0 (LAXTHA Inc., Deajeon, Korea; www.laxtha.com) with the method of Gianaros, Quigley, Mordkoff, and Stern (2001). There is a limitation to using the term *respiratory sinus arrhythmia* in the present study. Because there is no control of respiration, the term *respiratory sinus arrhythmia* in the present study does not index tonic parasympathetic cardiac control (Berntson, Cacioppo, & Quigley, 1993), but rather is an index of heart rate variability.

The electrooculogram was averaged for each sampling period. The number of eyeblinks per minute (eyeblink rate) was detected from the electrooculgram data. Eyeblink rates are evaluated using by ECG's R peak detection algorithm (Park, 2004; Park et al., 2001).

The skin conductance level (in microsiemens) and fingertip skin temperature (in degrees Fahrenheit) were averaged for each sampling period.

Pulse volume amplitude was extracted from the photoplethysmogram signal. The maximum amplitude and the peak-to-peak amplitude reflected changes in vasodilation of the fingertips. Using the ECG R peak detection algorithm (Park, 2004; Park et al., 2001), the photoplethysmogram's positive and negative peak difference was detected. Because the bandwidth of the photoplethysmogram is less than 20 Hz, a low-pass filter was applied.

EEG signals without artifacts relating to movement and other factors were analyzed. Spectral analysis was performed by Fast Fourier Transform in the 0–50-Hz band. These spectral estimates were used to calculate delta (0.2–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), slow alpha (8–10 Hz), fast alpha (10–13 Hz), beta (13–30 Hz), slow beta (13–20 Hz), fast beta (20–30 Hz), and gamma (30–50 Hz) power at each electrode site, respectively. The mean percentage of relative power at each scalp location was defined as (absolute power within the band at the location/total power across all bands at the location) $\times$ 100%. This yielded 81 scores: nine frequency bands $\times$ nine regions.

The hit rate of task performance was computed by the number of virtual objects that participants found within 9.5 min divided by the number of total virtual objects (that is, 10).

Physiological parameters were evaluated by a Greenhouse and Geisser (1959) corrected univariate ANOVA using Period (within-subject factor, baseline, the initial, middle, and final minute of navigation, and post-navigation.) as factors. In the Results section, original degrees of freedom, corrected probability values, and epsilon value of the correction factor (ε) are presented. Follow-up tests are based on Bonferroni adjustments. Prior to correlation analysis, physiological changes from the baseline to the virtual navigation in all physiological parameters were calculated. Whether any correlations existed between the simulator sickness questionnaire and physiological changes from the baseline to the virtual navigation was evaluated with Pearson's correlation coefficient r. Bonferroni corrections of probability level were used in addition to the normal $p < .05$ criterion to adjust for the number of comparisons made. In EEG analysis, however, the different electrodes were intercorrelated and the ranges in nine frequency bands were redundant (e.g., the range of alpha wave contains slow alpha wave and fast alpha wave), and this correction method may therefore not be entirely appropriate. A stepwise multiple regression analysis was used to predict participants' cybersickness scores from changes of physiological parameters and subjective variables. The criterion probability of statistical tests reported in this paper is $p < .05$. The value of eta-squared (η^2) was used as a measure of the size of experimental effect.

Results

All subjects reported no symptoms on the pre-immersion rating of the malaise scale. Four subjects (6.6%) among a total of 61 subjects withdrew from the experiment because of an acute cybersickness episode of vomiting during the virtual navigation. So, data from 57 subjects (29 men, 28 women) were analyzed.

The Frequency of Cybersickness

Forty-five subjects (78.9%; 24 women) among a total of 57 subjects reported cybersickness during the virtual navigation. On average, subjects reported the symptom of cybersickness verbally over five times during the virtual navigation of 9.5 min.

The Profile of Simulator Sickness Questionnaire Scores

The mean Cybersickness was 39 (*SD* 15.16). The profiles of the postexposure sickness subscores showed that Disorientation (mean 49.72, *SD* 21.24) was greater than Nausea (mean 32.75, *SD* 13.83) and Nausea was greater than Oculomotor (mean 26.83, *SD* 10.23).

Psychophysiological Changes during the Virtual Navigation

Autonomic Variables

Electrogastrogram 4–9.75 cpm (gastric tachyarrhythmia). Figure 1 shows the development of tachyarrhythmia of all participants over the course of the virtual navigation. Tachyarrhythmia increased gradually during the virtual navigation. ANOVA analysis indicated that there was a significant Period effect, $F(2,112) = 8.07$, $p = .001$, $\varepsilon^2 = .981$, $\eta^2 = .126$. Follow-up comparisons indicated that tachyarrhythmia significantly increased in the first 4 min of navigation and continuously increased until the final 4 min when compared to tachyarrhythmia levels at the baseline.

Eyeblink rate. Figure 2 shows the change patterns of eyeblink rate over the course of the virtual navigation. There was a

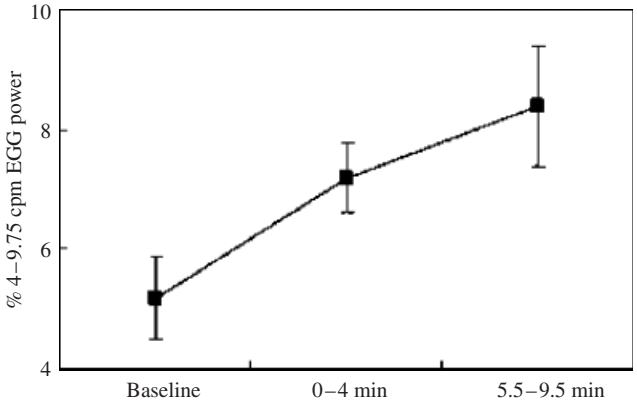

Figure 1. Mean gastric tachyarrhythmia across three time blocks of the virtual navigation: baseline, first 4 min of the navigation, and last 4 min of the navigation ($n = 57$). Error bars present the standard deviation of the mean.

significant Period effect, $F(4,224) = 3.60$, $p = .012$, $\varepsilon^2 = .830$, $\eta^2 = .060$. Follow-up comparisons showed that the mean eyeblink rate significantly decreased at the initial minute of navigation when compared to the baseline rate and it was significantly greater at the middle minute of navigation than the baseline.

Skin conductance level. A one-way ANOVA analysis in skin conductance indicated that there was a significant Period effect, $F(4,224) = 25.36$, $p = .000$, $\varepsilon^2 = .645$, $\eta^2 = .312$. Skin conductance level increased during the virtual navigation (Table 1). Follow-up analysis indicated that the skin conductance value significantly increased in the final minute of navigation when compared to the baseline value.

Heart period. The heart period was much shorter during the virtual navigation than the baseline period. There was a significant Period effect, $F(4,224) = 25.13$, $p = .000$, $\varepsilon^2 = .662$, $\eta^2 = .310$. Follow-up comparisons showed that the heart period significantly decreased at the initial, middle, and final minutes of navigation when compared to the baseline value. Heart period rapidly returned to the baseline value in the post-navigation minute (Table 1).

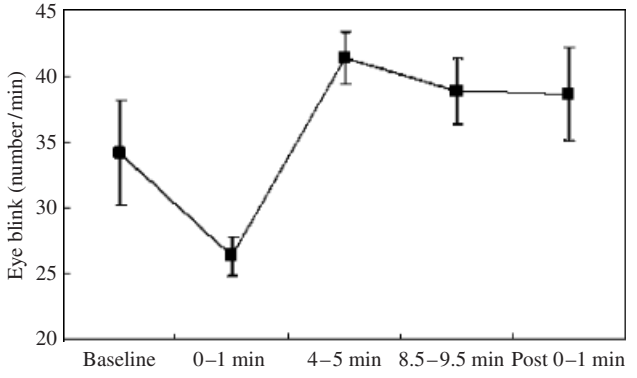

Figure 2. Mean eyeblink rate across five time blocks of the virtual navigation: baseline, first 1 min of the navigation, middle 1 min of the navigation, last 1 min of the navigation, and post-navigation ($n = 57$). Error bars present the standard deviation of the mean.

Respiratory sinus arrhythmia. Respiratory sinus arrhythmia increased during the virtual navigation. There was a significant Period effect, $F(4,224) = 17.53$, $p = .000$, $\varepsilon^2 = .806$, $\eta^2 = .238$. Follow-up analysis showed that respiratory sinus arrhythmia values significantly increased in the final and middle minutes of navigation when compared to the values of the baseline and in the initial minute of navigation. Mean respiratory sinus arrhythmia values increased from the initial minute of navigation (6.1 In units) to the final minute of navigation (7.7 In units; Table 1).

Fingertip skin temperature. Fingertip skin temperature decreased during the virtual navigation. There was a significant Period effect, $F(4,224) = 19.59$, $p = .000$, $\varepsilon^2 = .461$, $\eta^2 = .259$. Follow-up comparisons indicated that fingertip skin temperature significantly decreased at the middle minute of navigation and maintained lower values until the post-navigation when compared to the baseline value (Table 1).

Photoplethysmogram maximum amplitude. Photoplethysmogram maximum amplitude decreased during the virtual navigation. There was a significant Period effect in photoplethysmogram maximum amplitudes, $F(4,224) = 6.756$, $p = .000$, $\varepsilon^2 = .328$, $\eta^2 = .108$. Follow-up comparisons showed that photoplethysmogram maximum amplitude significantly decreased at the initial, middle, and final minutes of navigation when compared to the baseline value. At the post-navigation, photoplethysmogram maximum amplitude returned to the baseline level (Table 1).

Respiration rate. During the virtual navigation, respiration rate decreased when compared to the baseline rate (Table 1). However, there was no significant Period effect, $F(4,224) = 1.77$, $p = .147$, $\varepsilon^2 = .853$, $\eta^2 = .031$.

EEG Parameters

F3 and T3 relative delta power. Delta power in the F3 and T3 sites increased during the virtual navigation. In F3 relative delta power, there was a significant Period effect, $F(4,224) = 24.11$, $p = .000$, $\varepsilon^2 = .602$, $\eta^2 = .301$. Follow-up comparisons indicated that F3 relative delta power was significantly greater in the final minute of navigation when compared to the values in the baseline and the initial minute of navigation. Figure 3 shows the development of relative delta power in the T3 site over the course of the virtual navigation. There was a significant Period effect, $F(4,224) = 6.95$, $p = .000$, $\varepsilon^2 = .946$, $\eta^2 = .110$. Follow-up comparisons indicated that the T3 delta power was significantly greater in the middle and final minutes of navigation than the baseline value and that of the initial minute of navigation. Relative delta power of the T3 locus increased from mean 52.0% at the initial minute of the virtual navigation to mean 69.3% in the final minute of the virtual navigation. The percentage of relative delta power rapidly decreased after the navigation. Follow-up comparisons showed that the T3 delta power was significantly reduced at post-navigation when compared to that of the final minute of navigation.

F3 relative slow beta power. The relative power of slow beta in the F3 and P3 sites decreased during the virtual navigation. In F3 relative slow beta power, there was a significant Period effect, $F(4,224) = 3.25$, $p = .019$, $\varepsilon^2 = .825$, $\eta^2 = .055$. Follow-up comparisons indicated that F3 relative slow beta power significantly decreased in the final minute of navigation when compared to that of the initial minute of navigation. The relative slow

Table 1. *Mean Values (Standard Deviation) of Autonomic Nervous System (ANS) Variables for Each of Five Time Blocks of Virtual Navigation: Baseline, First 1 Min of the Navigation, Middle 1 Min of the Navigation, Last 1 Min of the Navigation, and Post-Navigation (n = 57)*

ANS variables	Baseline	0–1 min	4–5 min	8.5–9.5 min	Post 0–1 min
Skin conductance level (μS)	3.82	4.63	4.58	4.88	4.43
	(0.56)	(0.55)	(0.54)	(0.54)	(0.52)
Heart period (ms)	822.43	763.02	778.14	785.94	846.31
	(62.91)	(59.33)	(56.48)	(54.10)	(58.48)
Respiratory sinus arrhythmia (In units)	6.45	6.14	7.56	7.72	7.37
	(0.76)	(0.77)	(0.96)	(1.02)	(0.89)
Fingertip skin temperature (°F)	88.95	88.92	86.86	86.73	86.75
	(3.94)	(3.98)	(4.04)	(4.36)	(4.35)
Photoplethysmogram maximum amplitude	0.77	0.44	0.52	0.60	0.71
	(0.18)	(0.07)	(0.06)	(0.08)	(0.07)
Respiration rate (number/min)	15.03	14.22	14.89	12.02	13.69
	(5.66)	(8.18)	(8.34)	(8.45)	(6.12)

beta power of the F3 locus decreased from mean 4.2% in the initial minute to mean 2.2% in the final minute of the virtual navigation.

T3 relative beta power. The mean relative beta power in T3 was obtained before, during, and after the virtual navigation (Figure 3). There was a significant Period effect, $F(4,224) = 14.98$, $p = .000$, $\varepsilon^2 = .795$, $\eta^2 = .211$. Follow-up comparisons of the Period factor showed that T3 relative beta power significantly decreased in the final minute of navigation when compared to that of the baseline and the initial minute of navigation. The T3 beta power rapidly returned to the level of the baseline after the navigation.

Cybersickness and Physiological and Subjective Parameters

Correlations between physiological parameters and simulator sickness questionnaire scores. A Pearson two-tailed correlation analysis was performed to compare simulator sickness questionnaire scores to physiological parameters. Physiological changes from the baseline to the virtual navigation in all physiological parameters were used in the correlation analysis. Table 2 shows the significant correlation results for each variable of the autonomic nervous system with each of the simulator sickness questionnaire subscales. According to Kennedy et al. (1993), scores on the Nausea subscale are based on the report of symptoms that relate to gastrointestinal distress such as nausea, stomach awareness, salivation, and burping. Scores on the Oculomotor subscale are based on the report of symptoms such as eye strain, difficulty focusing, blurred vision, and headaches. Scores on the Disorientation subscale are related to vestibular disarrangement such as dizziness and vertigo. The Cybersickness scores had a significant positive correlation with gastric tachyarrhythmia, eyeblink rate, respiration rate, respiratory sinus arrhythmia, and heart period. That is, the greater subject's changes from the baseline to the virtual navigation in tachyarrhythmia, eyeblink rate, respiration rate, respiratory sinus arrhythmia, and heart period, the more the subject reported cybersickness symptoms. Moreover, significant correlations were found in change from the baseline to the virtual navigation for EEG spectral power (Table 3). For EEG spectral power, 29 among the multiplication 81×4 correlations were significant ($p < .05$). Five of these still were significant after the Bonferroni correction ($p < .0002$). The more cybersickness subjects tended to report, the more relative delta power changed in the F3, T3, and O1 sites and relative theta power changed in the P3, and the less relative beta power changed in the F3, T3, T4, and O1 sites, and relative gamma power in the F3 site was increased.

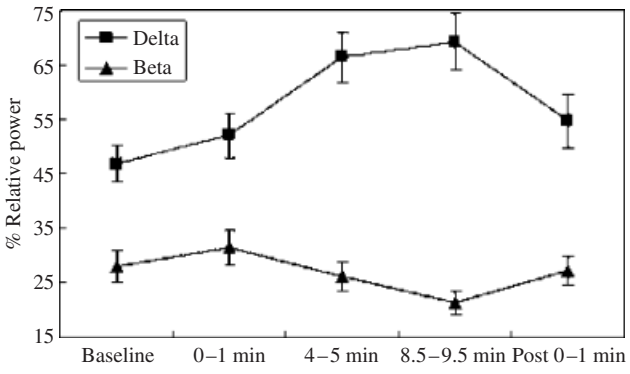

Figure 3. Mean relative delta power and beta power of T3 across five time blocks of the virtual navigation: baseline, first 1 min of the navigation, middle 1 min of the navigation, last 1 min of the navigation, and post-navigation ($n = 57$). Error bars present the standard deviation of the mean.

Associations between subjective ratings and cybersickness symptoms. Pearson correlation coefficients were computed to determine the association between simulator sickness questionnaire scores and the following subjective variables: the frequency of cybersickness that was reported, motion sickness susceptibility scores from the MSSQ, Anxiety scores, Involvement factor scores from an immersive tendency questionnaire, and Control factor scores from the presence questionnaire. As expected, the frequency of cybersickness was positively correlated with Cybersickness scores of simulator sickness questionnaire, $r = .455$, $p = .000$. Moreover, significant correlations were found between Cybersickness and MSSQ scores, $r = .426$, $p = .001$; Cybersickness and Anxiety scores, $r = .472$, $p = .000$; Cybersickness and Involvement factor scores of immersive tendency questionnaire, $r = .346$, $p = .008$; Cybersickness and Control factor scores of presence questionnaire, $r = -.369$, $p = .005$; and Cybersickness and the hit rates of task performance, $r = -.366$, $p = .000$.

Development of a Regression Model for Cybersickness

To determine which variables might be predictive of cybersickness severity, a stepwise regression was undertaken using the

Table 2. *Significant Correlations between Autonomic Nervous System (ANS) Variables and Simulator Sickness Questionnaire Scores (n = 57)*

ANS variables	Simulator sickness questionnaire scores			
	Nausea	Oculomotor	Disorientation	Cybersickness
Gastric tachyarrhythmia (%)	$r = .359^{**}$	$r = .229$	$r = .303^{*}$	$r = .317^{*}$
Eyeblink rate (number/min)	$r = .186$	$r = .265^{*}$	$r = .303^{*}$	$r = .267^{*}$
Respiration rate (number/min)	$r = .342^{**}$	$r = .386^{**}$	$r = .382^{**}$	$r = .392^{**}$
Respiratory sinus arrhythmia (In units)	$r = .330^{*}$	$r = .277^{*}$	$r = .238$	$r = .298^{*}$
Heart period (ms)	$r = .354^{**}$	$r = .426^{**}$	$r = .285^{*}$	$r = .373^{**}$

$^{*}p < .05$ (two-tailed); $^{**}p < .01$ (two-tailed).

Cybersickness score post-navigation as the criterion variable. Independent variables were entered in descending order of their correlations (criterion to enter = .20) with the dependent variable. Subjective variables were MSSQ score, Anxiety score, and Involvement factor score of immersive tendency questionnaire; autonomic variables were (change from base) gastric tachyarrhythmia, respiration rate, heart period as autonomic variables; EEG variables were F3 relative delta power, T3 relative delta power, F3 relative slow beta power, P3 relative slow beta power, T3 relative beta power, and O1 relative slow alpha power. Four variables had an adequate predictive value to enter into the multiple regression equation: the MSSQ score, heart period, T3 relative delta power, and T3 relative slow beta power (Table 4). These variables predicted 46% of the variance in the severity of cybersickness symptoms. Reported higher levels of motion sickness susceptibility from past experiences, an increase in heart period, increases in T3 delta power, and decreases in T3 beta power predicted increases in the severity of cybersickness symptoms that the participant reported.

Discussion

The primary emphasis of this study was to investigate the relationship between cybersickness and physiological responses. During the virtual navigation, gastric tachyarrhythmia, skin conductance, respiratory sinus arrhythmia, and relative delta power of F3 and T3 sites were significantly greater than the baseline values. Heart period, fingertip skin temperature, photoplethysmogram maximum amplitude, and relative beta power of F3 and T3 sites significantly decreased compared to the baseline value. There were significant positive correlations of Cybersickness score with gastric tachyarrhythmia, the eyeblink rate, respiration rate, respiratory sinus arrhythmia, and heart period. A greater level of tachyarrhythmia and the frequency of eyeblinks experienced during the virtual navigation are associated with more cybersickness symptoms reported by subjects. Several studies have shown that the expression of gastric tachyarrhythmia is associated with an increase in sympathetic and a decrease in parasympathetic activation when nausea is induced (Koch & Stern, 1996; Stern & Koch, 1996). The positive correlation between tachyarrhythmia and cybersickness suggests that the autonomic nervous system plays a part in the occurrence of cybersickness, and the activation pattern of the autonomic nervous system consists of an increase in sympathetic and a decrease in parasympathetic activation. The mean of respiratory sinus arrhythmia during the virtual navigation was greater than that of the baseline. The respiratory sinus arrhythmia in a virtual environment not only reflects the change of respiration, but also autonomic responses to various types of stimuli. A change in emotion and the occurrence of a stressful event could also affect respiratory sinus arrhythmia (Baldaro et al., 2001; Buss, Hill Goldsmith, & Davidson, 2005; Kettunen, Ravaja, Naatanen, & Keltikangas-Jarvinen, 2000).

In this study, the mean Cybersickness of the simulator sickness questionnaire was 39 after the virtual navigation for 9.5 min. It is comparable to the published data documented by Lo and So (2001) in which the mean Cybersickness was 35 after a virtual navigation for 20 min using a head-mounted display. Moreover, many studies using head-mounted displays showed that Cybersickness was lower than 39 after an exposure of over 20 min (Cobb, 1999; Cobb et al., 1999; Regan & Ramsey, 1996; Stanney et al., 1999). The mean Cybersickness of 39 indicated that participants rated symptoms on more than 8 items among the

Table 3. *Significant Correlations between EEG Relative Power Variables and Simulator Sickness Questionnaire Scores (n = 57)*

EEG (%) variables	Simulator sickness questionnaire scores			
	Nausea	Oculomotor	Disorientation	Cybersickness
F3 delta power	$r = .258^{*}$	$r = .269^{*}$	$r = .295^{*}$	$r = .291^{*}$
T3 delta power	$r = .307^{*}$	$r = .215$	$r = .228$	$r = .266^{*}$
O1 delta power	$r = .335^{*}$	$r = .305^{*}$	$r = .283^{*}$	$r = .326^{*}$
F3 beta power	$r = -.264^{*}$	$r = -.330^{*}$	$\underline{r = -.384^{**}}$	$\underline{r = -.346^{**}}$
T3 beta power	$r = -.319^{*}$	$r = -.255$	$r = -.281^{*}$	$r = -.303^{*}$
T4 beta power	$r = -.297^{*}$	$r = -.247$	$r = -.238$	$r = -.262^{*}$
O1 beta power	$\underline{r = -.393^{**}}$	$r = -.330^{*}$	$r = -.249$	$r = -.342^{**}$
F3 gamma power	$r = -.172$	$r = -.319^{*}$	$r = -.322^{*}$	$r = -.287^{*}$
P3 theta power	$r = .335^{*}$	$\underline{r = .363^{**}}$	$r = .378^{**}$	$\underline{r = .387^{**}}$

Note: Underlined: Bonferroni corrected probability levels ($p < .0002$).
$^{*}p < .05$ (two-tailed); $^{**}p < .01$ (two-tailed).

Table 4. *Stepwise Regression Analysis Predicting Cybersickness Score of Cybersickness from MSSQ Score, Heart Period, and Delta Power and Slow Beta Power of T3 Site*

Variables	β	r	t	P	Partial R^2
MSSQ score (0–95.04)	.428	.426	4.516	.000	.206
Heart period (ms)	.253	.317	2.636	.011	.103
T3 relative delta power (%)	.291	.266	3.081	.003	.080
T3 relative slow beta power (%)	− .265	− .303	− 2.628	.011	.061

Note. MSSQ: Motion Sickness Susceptibility Questionnaire. $R^2 = .46$. $F(4,51) = 11.10$, $p = .000$.

16 items of the simulator sickness questionnaire. This experiment used the virtual reality system that provided a field of view (FOV) of $150^\circ \times 45^\circ$ through a multiple screen projection system. The FOV of this virtual reality system is relatively wider horizontally than that of a virtual reality system using head-mounted displays, which generally provide a FOV of $40^\circ \times 30^\circ$ (Howarth & Finch, 1999; Lo & So, 2001; Owen, Leadbetter, & Yardley, 1998). Simulators with a wide FOV generally generate higher incidences of simulator sickness than do those with a narrow FOV (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989; Lin, Duh, Paker, Rached, & Fumess, 2002). Furthermore, it was reported that a narrow and restricted visual field slightly reduced vection whereas it reduced symptoms of motion sickness greatly (Stern, Hu, Anderson, Leibowitz, & Koch, 1990). Upon using the system used in this experiment, many subjects actually reported severe cybersickness within 5 min and withdrew from the experiment of the virtual navigation after 10 min (our unpubl. data). These results suggest that a virtual reality system with a relatively wide FOV with multiple screen projection can provoke cybersickness within a short period of exposure.

In this study, we observed a sudden rise in the frequency of eyeblinks at the middle minute of the virtual navigation. According to Tecce (1992), an increased eyeblink frequency generally reflects negative mood states, such as nervousness, stress, and fatigue. Eye fatigue is included in side effects associated with an immersive virtual environment (Kennedy et al., 1993; Regan & Price, 1994). The observed rise in eyeblink frequency after the middle of the virtual navigation suggests that subjects were fatigued with the stress response of cybersickness. There has been no report about eyeblinks in motion sickness studies before. However, the result of eyeblinks suggests the possibility of the use of the eyeblink variable as one indicator of cybersickness symptoms.

Early motion sickness research efforts failed to find a significant electroencephalographic response (Cipriani & Morton, 1942; Jasper & Morton, 1942). However, after the 1950s, several studies noted a slowing of the dominant wave frequency (Chinn, 1950; Morales, Chelen, & Kabrisky, 1990; Wood et al., 1990). Chelen et al. (1993) reported that mean power spectral energy in the delta band during motion sickness increases more than that of the baseline, and they also suggested that the electrophysiology of motion sickness might be a variant of seizure activity. Similar to symptoms of motion sickness, classical migraine headaches and partial seizures are sometimes associated with transient EEG slowing and gastrointestinal symptoms. Moreover, some researchers have suggested that greater delta power may reflect the stress component of human responsivity (Chen, Dworkin, Haug, & Gehrig, 1989; Dzhebrailova, 2003; Golikova & Strelets, 2003). In the stress condition, the relative power of delta activity in occipital and temporal, right parietal and central areas was higher (Dzhebrailova, 2003). Before examination, the spectral power of EEG activity of the slow wave increased and beta rhythms decreased as compared to the usual baseline condition (Golikova & Strelets, 2003). In this study, subjects showed increases in delta power and relative decreases in beta power in the F3 and T3 sites at the final minute of virtual navigation.

At the initial minute of the virtual navigation, eyeblink rate decreased and EEG beta power increased. A rise in eyeblink rate during the performance of a task is generally accepted to coincide with an increase in cognitive demand, which directs attention to the task-relevant stimuli (Bauer, Strock, Goldstein, Stern, & Walrath, 1985; Goldstein, Walrath, Stern, & Strock, 1985). Moreover, Valentino and Dufresne (1991) reported that an increase in beta power during a task is associated with the process of attending to the stimuli of the task. Subjects particularly attend to the visual stimuli of a virtual reality at the initial stage of a virtual navigation to find virtual objects. The physiological responses at the initial stage of the virtual navigation reflect that subjects have a greater need to pay attention in order to perform the task. These results suggest that a reduction in eyeblink frequency with an increase in beta power at the initial stage of the virtual navigation reflect the requirement for greater attention than that needed at the begining. Additionally, after the initial stage of the virtual navigation, the observed decrease in physiological changes may reflect a reduction of attention load by adaptation, cybersickness, or by fatigue. Changes in eyeblink frequency and EEG during post-navigation show a rapid recovery to baseline levels. In most cases, the sympathetic activation was exaggerated or sustained throughout the test, and was followed by a rapid return to or below the pretest levels during the posttest recovery.

In this study, significant positive correlations were found between the Cybersickness scores and MSSQ scores, Cybersickness scores and Anxiety scores, and between Cybersickenss scores and Involvement factor scores of the immersive tendency questionnaire. There were significant negative correlations found between simulator sickness questionnaire scores and the Control factor score of the presence questionnaire. These findings were consistent with previous studies (Collins & Lentz, 1977; Kennedy et al., 1993; Lindseth & Lindseth, 1992; Money, 1970; Witmer & Singer, 1998). These results suggest the possibility that cybersickness severity can be predicted from prior susceptibility of motion sickness, level of anxiety, and level of involvement.

Previous studies showed that the occurrence of motion sickness can be characterized by an increase in gastric tachyarrhythmia, skin conductance, heart rate, and EEG delta power (Chelen et al., 1993; Cowings, Naifeh, & Toscano, 1990; Hu et al., 1991). Hu et al. (1991) studied motion sickness severity and physiological measures during repeated exposures to a rotating optokinetic drum. The development of motion sickness was

accompanied by increased tachygastria and skin conductance levels. Heart rate increased in the drum rotation period but did not predict motion sickness.

In the present paper, the Cybersickness score had a significant positive correlation with increases in gastric tachyarrhythmia, eyeblink rate, respiration rate, and heart period. Correlation between net increase in skin conductance level and cybersickness severity was positive, but not significant. The results of these two studies show consistency in the aspects of gastric tachyarrhythmia and skin conductance, but not in heart rate. We consider that the difference of results in the heart rate may partly be derived from the different experimental environments. Also, the difference may be derived from various visual stimuli and performance required in the virtual navigation. Although there may be inherent differences of symptoms and physiological responses between motion sickness and cybersickness, we can consider that they have shared processes in terms of physiology. This is supported by a report that the prior administration of anti-motion-sickness drugs could reduce cybersickness (Regan & Ramsey, 1996).

Heart period became shorter during the virtual navigation, but longer heart periods during virtual navigation were associated with more subject report of cybersickness symptoms. This seems counterintuitive in terms of sympathetic activation in motion sickness. We consider that this result is partially associated with the positive correlation of the change from baseline to the virtual navigation with the respiratory sinus arrhythmia. The respiratory sinus arrhythmia in the present study could partially reflect parasympathetic cardiac control during virtual navigation (Berntson et al., 1993). There is a need to investigate the relation between changes of heart period and cybersickness symptoms in further studies.

It is clear that physiological response levels change at the onset of navigation and when the test concludes as can be seen from Figures 1–3. Furthermore, the results from the multiple regression analysis support the conclusion that one must examine the value of physiological responses containing an autonomic variable (heart period), EEG parameters (T3 delta and beta powers), and a subjective variable (MSSQ score) as predictors of cybersickness severity. Previous studies have generally proposed autonomic variables such as heart rate, respiratory sinus arrhythmia, preejection period, skin conductance, and gastric tachyarrhythmia as predictors of motion sickness (Cowings et al., 1986; Gianaros et al., 2001; Hu et al., 1991). In this study, EEG variables, subjective variables, and autonomic variables predicted a total 46% of the variance in cybersickness severity. We have examined a number of variables to find the pivotal factor of cybersickness. In further research, the analysis of data from a larger sample of people can increase the reliability of the predictor variables.

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