Investigation of Visually Induced Motion Sickness in Dynamic 3D Contents based on Subjective Judgment, Heart Rate Variability, and Depth Gaze Behavior

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***Abstract*— Visually induced motion sickness (VIMS) is an important safety issue in stereoscopic 3D technology. Accompanying subjective judgment of VIMS with objective measurement is useful to identify not only biomedical effects of dynamic 3D contents, but also provoking scenes that induce VIMS, duration of VIMS, and user behavior during VIMS. Heart rate variability and depth gaze behavior are appropriate physiological indicators for such objective observation. However, there is no information about relationship between subjective judgment of VIMS, heart rate variability, and depth gaze behavior. In this paper, we present a novel investigation of VIMS based on simulator sickness questionnaire (SSQ), electrocardiography (ECG), and 3D gaze tracking. Statistical analysis on SSQ data shows that nausea and disorientation symptoms increase as amount of dynamic motions increases (nausea: $p<0.005$; disorientation: $p<0.05$). To reduce VIMS, SSQ and ECG data suggest that user should perform voluntary gaze fixation at one point when experiencing vertical motion (up or down) and horizontal motion (turn left and right) in dynamic 3D contents. Observation of 3D gaze tracking data reveals that users who experienced VIMS tended to have unstable depth gaze than ones who did not experience VIMS.**

I. INTRODUCTION

Rapid usage and implementation of stereoscopic 3D technology have increased expectation on more user-friendly dynamic 3D contents that considers human factors [1], [2]. An important safety issue in stereoscopic 3D technology is visually induced motion sickness (VIMS). VIMS is a condition in which viewers of dynamic 3D contents feel symptoms of nausea, dizziness, or visual fatigue during or after exposure while they are being physically still [3].

Takada [4] found that unnatural viewing mechanism in virtual environment might cause visual fatigue and VIMS. The decoupling of vergence and accommodation affected how user perceived depth information in virtual environment [16]. Since vergence provides veridical depth information [12], observing depth gaze during exposure of dynamic 3D contents is important.

Previous research works combined subjective judgment with objective measurement to observe VIMS. For example, researcher incorporated simulator sickness questionnaire (SSQ) [5] with either 2D gaze tracking [7], [11] or electrocardiography (ECG) [6], [8]. Diels *et al.* [7] and Yang *et al.* [11] used 2D gaze tracking to observe effect of VIMS on gaze behavior. However, they merely measured gaze position in horizontal and vertical direction. Furthermore, instead of viewing dynamic motions in stereoscopic movie, users watched optical flow content or alternate black-and-white vertical stripes [7], [11]. To the best knowledge of authors, there is no publication reporting investigation of VIMS based on subjective judgment, heart rate variability, and depth gaze behavior.

In this study, we used simulator sickness questionnaire (SSQ), electrocardiography (ECG), and 3D gaze tracking to demonstrate novel investigation of VIMS. We showed both low and high motion stimulus in two different types of 3D movie. We utilized SSQ as preliminary tool to investigate the occurrence of VIMS. We then analyzed ECG and 3D gaze tracking data to observe user behavior and duration of VIMS during exposure of dynamic 3D contents.

II. MATERIALS AND METHODS

A. Measurement devices

We used our 3D gaze tracking system to measure point of gaze in virtual 3D space. We designed a novel 3D gaze tracking system for Nvidia 3D Vision® glasses [18]. The average errors of our system in X, Y, and Z direction were 0.83 cm, 0.87 cm, and 1.06 cm, respectively [9], [10]. We used portable ECG system (WEB-5500; Nihon Koden Co., Tokyo) with wireless receiver and transmitter to record ECG data. We analyzed heart rate variability (HRV) to detect the occurrence of VIMS symptoms. HRV is variations between subsequence heartbeats modulated by *sympathetic* and *parasympathetic* nerves of the autonomic nervous system.

In normal condition, the harmonious mechanism of sympathetic and parasympathetic nerves to govern cardiopulmonary function is almost similar as two opposite sine waves [13]. In contrast, when a human is experiencing symptoms of VIMS or being mentally stressed, the ideal balance of sympathetic and parasympathetic nerves changes. The sympathetic nerves are generally found to be more dominant than parasympathetic nerves.

In this research, we investigated HF (high frequency) and LF (low frequency) of HRV [14]. The value of HF, LF, ratio of LF/HF, and their corresponding timestamps were calculated in real-time every 2 seconds using proprietary software of the ECG system. The data was then saved to spreadsheets for offline analysis. We put two marks in the timestamps column of ECG data, each of which informed the

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beginning and the end of the 3D contents, respectively. High sympathetic nerves activity was investigated by observing maximum and minimum point of LF/HF and HF graph when both graphs were unbalanced. Using the aforementioned information, we observed provoking scenes in 3D contents that induce VIMS.

We used SSQ questionnaire to obtain subjective judgment of VIMS. We asked each participant to fill in a SSQ form containing 16 symptoms with four points scale (0, 1, 2, and 3). We computed effect of nausea, oculomotor, and disorientation based on weight of each symptom (1 or 0) [5].

B. Preparation of 3D contents

We designed two experiment sessions. The first session showed low stimulus motions from a computer graphics (CG) movie of city walkthrough. We used the 3D Studio Max 2011 to develop and render the CG movie. The movie contained up, down, turn left, and turn right motion with moderate amount (see Table 1).

The CG movie consisted of narrow walking road with different sizes of buildings, fences, trees, and electric poles on the left and right side. We developed sensation of up and down motion by providing a scene of passing bridge in the movie. To show the movie in stereoscopic display appropriately, we separated the left and right scene camera by 6.5 cm of disparity (0.0325 unit in 3D Studio Max 2011), producing slightly different view for left and right eye. The resolution of CG movie was 1920 x 1080 pixel. The duration of the CG movie was 5 minutes.

The second session consisted of high stimulus motions from a real scenery of front seat real roller coaster taken at Great Yarmouth Pleasure Beach, United Kingdom [15]. The movie consisted of intense dynamic motions with stronger sensation of vection (see Table 1).

We added a white point on each movie by customizing the stereoscopic 3D movie player. The point was aimed as a focus point of gaze during exposure of dynamic 3D contents. The point was positioned at the center of screen with 70 cm of visual distance from user.

C. Experiment procedure

The ethics committee of School of Information and Telecommunication Engineering, Tokai University granted permission to the authors for conducting experiment. All participants were healthy, with normal or corrected eyes.

In the first session, 20 participants joined the experiment (15 male; 5 female; average of age 22.25 year old). We randomly divided the participants into two groups, each of which consisted of 10 students. We asked the first group (8 male; 2 female) to watch CG movie while fixating the gaze to a white point positioned at the center of the screen. On the other side, we asked the second group (7 male; 3 female) to watch CG movie while freely gazing at arbitrary direction on the screen.

TABLE I

COMPARISON OF DYNAMIC MOTIONS IN CG AND REAL MOVIE

Movie	Motions			
	Up	Down	Turn Left	Turn Right
CG (low stimulus)	2	2	7	8
Real (high stimulus)	13	11	7	9

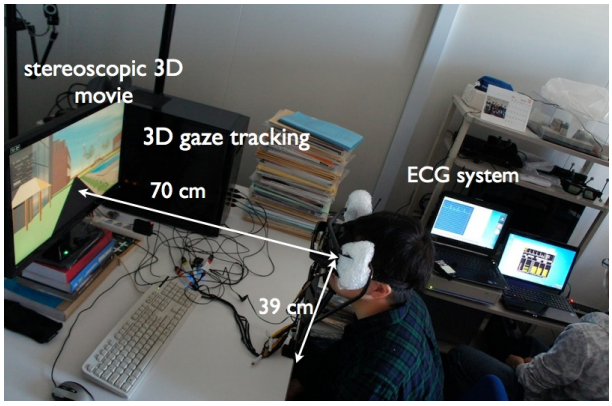

Fig. 1. Configuration of experiment devices. The stereoscopic display was positioned 70 cm from the user. The ECG system was installed behind the participant to prevent participant from seeing the ECG signal analyzer.

We positioned the participant such that the center of the screen was vertically and horizontally aligned at the middle point between both eyes. The distance between participant and screen was 70 cm. The height of eye from tabletop was 39 cm. Fig.1 shows the configuration of experiment.

The duration of experiment for each participant was about 15 minutes. In the first three minutes, we explained experiment procedure and requested the participant to sign an informed consent after agreeing all procedures. Next five minutes, we installed ECG electrodes and prepared 3D gaze tracking system to record gaze data. We then showed five-minute 3D movie to participant. We recorded ECG and 3D gaze tracking data during exposure of stereoscopic content. After the movie finished, we asked the participant to rest and answer post-experiment SSQ for about two minutes. We allocated a week of rest time between the first and the second experiment session to avoid fatigue and learning experience.

In the second session, 20 participants joined the experiment (17 male; 3 female; average of age 22.65 year old). Two naïve male students replaced two female students who could not participate in the second experiment session. To avoid any individual-basis error, we performed randomization of participants when dividing all participants into two groups. The duration and procedure of the second session is mostly similar to the first session. We asked the first group (9 male; 1 female) to fixate their gaze at a white point during roller coaster movie while the second group (8 male; 2 female) to freely gaze at arbitrary direction on the screen. Filling in SSQ questionnaire ended the experiment for each participant.

III. RESULTS AND DISCUSSION

Figure 2 shows results of SSQ score for nausea (N), oculomotor (O), disorientation (D), and total (T) component. Participants experienced minimum VIMS symptoms when they watched CG movie with fixation ($N = 1.91 \pm 3.82$,

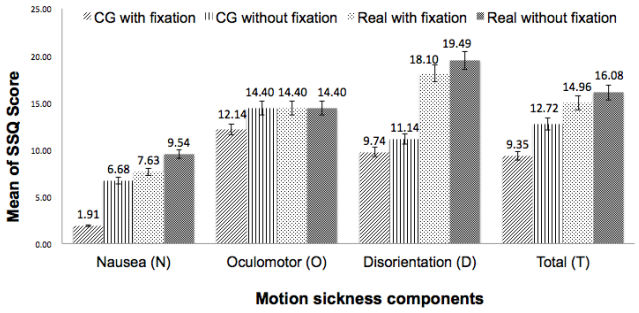

Fig. 2. Mean of SSQ score for nausea (N), oculomotor (O), disorientation (D), and total (T) component in four experimental conditions (CG movie with fixation, CG movie without fixation, real movie with fixation, and real movie without fixation).

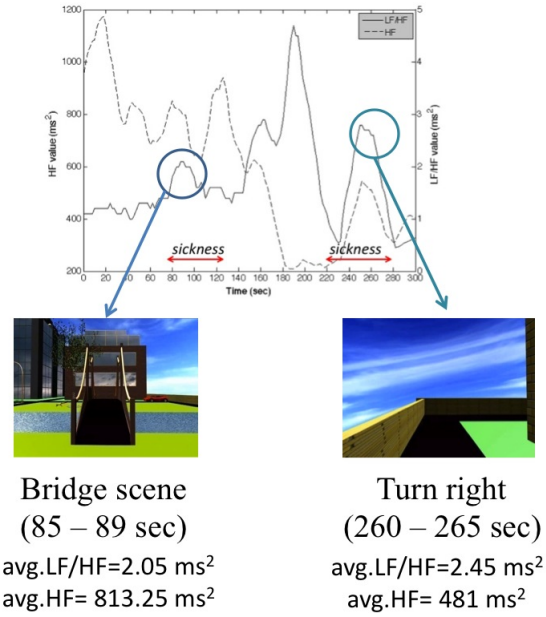

Fig. 3. Sample of an ECG data from the 3rd participant in CG movie without fixation group shows high activity of sympathetic nerves in bridge scene and turn right scene. Solid and dashed line are LF/HF and HF data, respectively. Left and right vertical axes are computed Power (ms^2) of HF and LF/HF. Horizontal axis is duration of 3D movie (sec).

$O = 12.14 \pm 13.24$, $D = 9.74 \pm 16.53$, $T = 9.35 \pm 10.21$). Particular increment of average SSQ score in N, D, and T component is observed in group of participants who watched CG movie without fixating their gaze ($N = 6.68 \pm 11.33$, $O = 14.40 \pm 12.43$, $D = 11.14 \pm 24.74$, $T = 12.72 \pm 13.4$). Similar trends were observed in group of participants who watched real roller coaster movie. We found that group of participants who fixated their gaze during experiment reported lower sickness level than group of participants without gaze fixation. Additionally, real roller coaster movie resulted higher SSQ score in N, D, and T component.

We also evaluated the results of SSQ using two-way statistical analysis of variance (ANOVA) between subjects. The two independent variables are type of movie (CG vs. real movie) and type of gaze (fixation vs. no fixation). The dependent variables are nausea, disorientation, oculomotor,

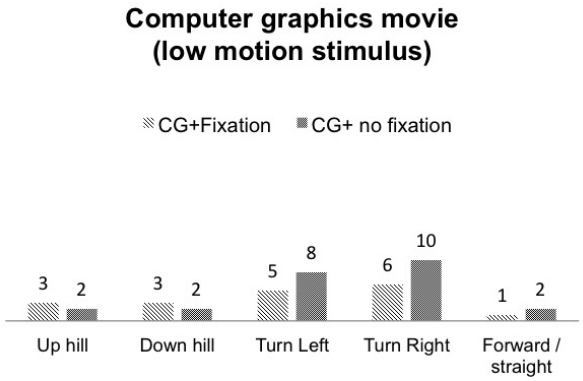

Fig. 4. Amount of dominant sympathetic nerves activity in the first experiment session (CG movie).

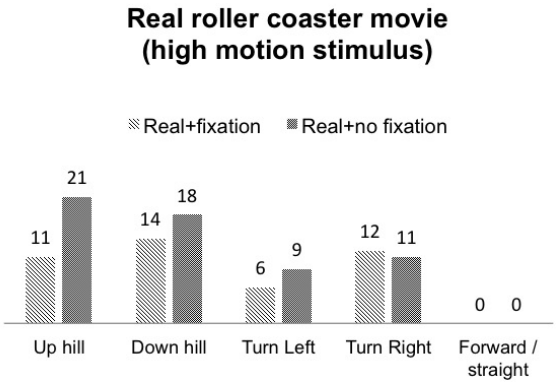

Fig. 5. Amount of dominant sympathetic nerves activity in the second experiment session (real roller coaster movie).

and total score. Statistical analysis shows that effect of different type of movie to nausea component is significant ($F(1,36) = 11.161$, $p<0.005$). Furthermore, effect of different movie to disorientation component is also significant ($F(1,36) = 5.886$, $p<0.05$). No other significant effect is found in analysis.

Figure 3 shows a sample of ECG data from the 3rd participant in CG movie without fixation group that experienced high activity of sympathetic nerve in bridge scene (avg.LF/HF = 2.05 ms^2; avg.HF = 813.25 ms^2) and turn right scene (avg.LF/HF = 2.45 ms^2; avg.HF = 481 ms^2). We computed the total occurrence of high sympathetic nerves activities from all participants. Fig.4 and Fig.5 show amount of dominant sympathetic nerves activity for CG and real roller coaster movie, respectively.

There were participants who experienced sickness when seeing long forward motion in CG movie (Fig.4). However, the effect of long forward motion is not as strong as effect of horizontal and vertical motion. We found that horizontal motion is the dominant contributing factor of VIMS in CG movie while vertical motion is the dominant contributing factor of VIMS in real roller movie (Fig.5). One possible reason is different composition of motions in those movies, as shown in Table 1. Since the roller coaster movie contains more vertical motion, VIMS is induced by vertical motion.

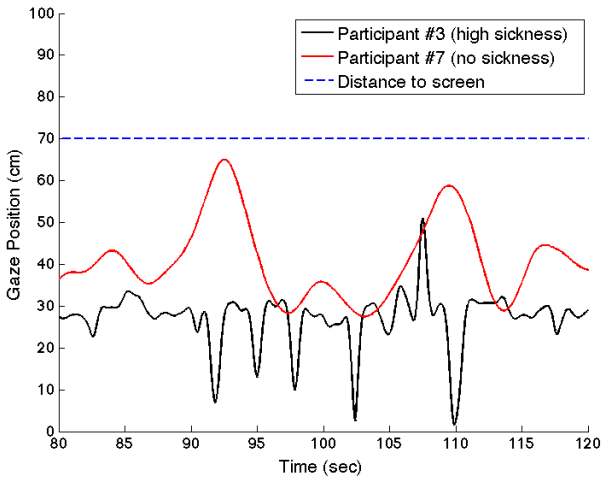

Fig. 6. Depth gaze (Z-gaze) of the 3rd and the 7th participant from CG movie without fixation group during a scene of bridge passing in 85–89 *second* (see also Fig.3).

We also found that most participants who fixated their gaze at one point experienced less dominant sympathetic nerves activity than ones without fixation. This finding confirms the results of SSQ data shown in Fig.2.

Figure 6 shows comparison of depth gaze from participants with high sickness and no sickness during a scene of bridge passing. Similar trends across group of participants were observed. We found that as participants experienced VIMS, their depth gaze oscillated more frequently than participants who did not experience VIMS. This finding may relate with the presence of intense version-vergence *optokinetic nystagmus* (OKN) induced by optical flow-like dynamic scene [17]. OKN allows participants to follow visual stimulus and reduce retinal slip. However, previous research work also found that OKN was responsible for VIMS since OKN increased velocity of eye movement [11]. In this case, gaze fixation is useful for participants with high VIMS susceptibility to reduce the velocity of eye movement. Further information and supplementary data of this research are available online: `http://bit.ly/sunu-vims`

IV. CONCLUSION

We demonstrate a novel investigation of visually induced motion sickness (VIMS) in dynamic 3D contents based on simulator sickness questionnaire (SSQ), electrocardiography (ECG), and 3D gaze tracking. SSQ was used to obtain general information of VIMS. ECG and 3D gaze tracking were used to investigate VIMS during exposure of dynamic 3D contents. We presented two types of 3D movie containing low and high dynamic motions, respectively. Statistical analysis on SSQ data shows that nausea and disorientation symptoms increases as amount of dynamic motions increases (nausea: $p<0.005$; disorientation: $p<0.05$). Analysis of ECG data shows that horizontal motion (turning left and right) and vertical motion (up and down hill) are effective contributing factors of VIMS. SSQ and ECG data suggest that user should perform voluntary gaze fixation at one point when experiencing vertical and horizontal motion in dynamic 3D contents to avoid VIMS. We also found that participants who experienced VIMS tended to have unstable depth gaze than ones who did not experience VIMS.

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