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Quantifying Visually Induced Motion Sickness (VIMS) During Stereoscopic 3D Viewing Using Temporal VIMS Rating

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Abstract. *Visually induced motion sickness (VIMS) is evoked by conflicting motion sensory signals within the brain. Use of the simulator sickness questionnaire (SSQ) or postural stability measures to quantify one's VIMS experience only measures the changes between pre- and post-experiment. The motion sickness susceptibility questionnaire (MSSQ) is widely used to measure individual's sensitivity to motion sickness, but its applicability to VIMS has not been proven. We are introducing a novel VIMS susceptibility measure by combining measures of the subject's "sensitivity" and "endurance" to VIMS. The proposed VIMS susceptibility measure was tested for various VIMS inducing conditions, and demonstrated its effectiveness by conducting both between-subjects and within-subject comparisons for different VIMS conditions.*

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INTRODUCTION

When viewing the contents of stereoscopic 3D (S3D) displays, observers often complain of various symptoms of discomfort, such as light-headedness, dizziness, queasiness, and nausea. Such symptoms are similar to those of motion sickness experienced in cars or boats. When they are mainly induced by visual motions, these symptoms are referred to as visually induced motion sickness (VIMS).

The mechanisms behind VIMS invocation are not well understood. They may include conflicts in perceived self-motion (vection) between two or more sensory systems (i.e., visual–vestibular systems),[1,2] or within a single sensory system (i.e., depth/space distortion as in S3D).[3,4]

In our previous study,[5] multiple wearable devices were tested to identify potential physiological markers of VIMS onset (i.e., EEG, BP, HR) induced by virtual driving in a simulator. Although some physiological changes were measured between before and after the onset of VIMS, it was difficult to conclude that the differences found were caused by the VIMS onset alone, or by the physical interactions of driving. However, it was found that the subjective reporting of the VIMS level during the course of the experiment showed a unique pattern for each subject, but we did not have a clear way to analyze this data.

In this study, we employed a more controllable, stationary experimental framework (i.e., passive contents viewing) to focus on the effects of S3D depth distortion, which has been proposed as a possible cause of VIMS experienced in S3D.[3] Both subjective and objective (physiological) measurements of VIMS were collected in three viewing conditions: 2D, S3D, and S3D with distortion (S3DD).

For the subjective VIMS measures, the simulator sickness questionnaire (SSQ)[6] was conducted before and after the experimental session. The subjective scoring of VIMS level was also collected during the experimental session. A similar temporal scoring method was previously used to measure the effects of peripheral visual field size

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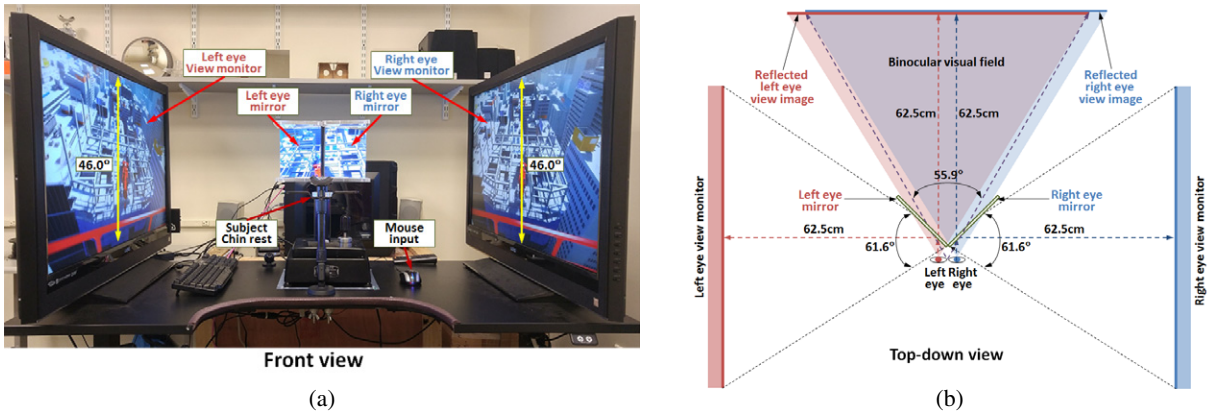

Figure 1. (a) Front view picture of the experimental setup. A Wheatstone stereoscope was composed of two mirrors that can present the left and right eye views on corresponding two 42″ monitors. A custom video player was developed to play S3D videos. (b) Top view schematic of the experimental setup. When the subject's head was positioned close to the mirrors, the total binocular field of view became 67.4°, supporting an effective overlapping S3D field of view of 55.9°.

on virtual reality (VR) sickness.[7] For the objective measure, postural stability was measured. We excluded the previously tested physiological measures because they were not found to be sensitive enough to distinguish slight VIMS changes among the different viewing conditions.

METHODS

Subjects

After the informed consent process was completed, initial screening tests were conducted to determine whether the subjects' binocular visual acuity, stereo depth perception, stereopsis, and motor-balance control met the enrollment criteria.

Subjects with (1) visual acuity worse than 20/25, (2) no stereopsis, as determined by the Frisby stereotest,[8] (3) stereoacuity worse than 60 sec of arc, as measured by the Randot stereoacuity test[9] at 60 cm distance, or (4) failure in the Romberg balance test[10] were excluded from the study.

The motion sickness susceptibility questionnaire (MSSQ)[11] was also administered, and subjects who were highly susceptible (total score >25.9, over 90th percentile in population) or hardly susceptible (total score <7, below 30th percentile in population) to motion sickness were excluded from the study for safety and efficacy, respectively. Note that during the pilot testing of the experiment, subjects who scored less than the 30th percentile in the MSSQ showed almost no VIMS change during the experiment.

Apparatus

A custom built Wheatstone stereoscope (Figure 1(a)) was used to display video stimuli in 2D and S3D. The virtual (reflected) screens were located 65.5 cm away from the subjects, providing a binocular field of view of 67.4° × 46.0° (overlapping S3D field of view of 55.9° × 46.0°), as shown in Fig. 1(b). A custom video player software was developed to present the S3D contents on the two monitors with additional distortions (explained below) using the OpenGL shader. This experimental setup allows us to display 2D/S3D contents without the confounding effects of other optical distortions as found in head mounted displays (HMDs).

Video Clips and Viewing Conditions

Fifteen S3D video clips containing highly active motion scenes were downloaded from YouTube (e.g., clips of virtual roller coaster rides or first-person shooter (FPS) game playing), which were known to induce VIMS. The video clips were 1920 × 1080 pixels at 60 fps in side-by-side format. Each video clip was edited to last 3 minutes.

During the experiments, the video clips were presented in three display conditions: 2D, S3D, and S3D with additional distortion (S3DD). For 2D presentation, the left eye view of the S3D video clips was presented to both monitors. For S3D presentation, the left and right eye views were presented to the corresponding monitors to convey stereoscopic depth. For S3DD, a shader-based 2D pincushion distortion was applied to the left and right eye views, simulating the overcorrection of the high power lens distortions in common HMDs. We developed a custom video player to present the side-by-side video clips on two monitors with mirroring, and be able to collect VIMS responses from subjects before and after the video clip presentation.

Experimental Procedure

Before each session, subjects completed the SSQ[6] to measure pre-experiment VIMS. Then, postural stability was measured using a Wii balance board (Nintendo, Kyoto, Japan). During the stability measurement, subjects were asked to stand still on the balance board for 1 minute with feet together and eyes closed. The spatial coordinates of the center of pressure (CoP) on the board were logged, and later analyzed. Note that the use of the Wii balance board as a CoP analysis tool has been thoroughly validated by Clark et al.[12]

The subject was then seated at the Wheatstone stereoscope (Fig. 1) to watch a series of video clips. The subjective VIMS levels were rated on a five level scale from 0 (No VIMS) to 4 (Very severe VIMS). Before and after watching each

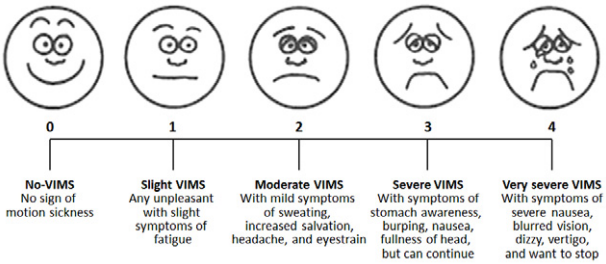

Figure 2. The onscreen VIMS level rating instructions. Subjects were asked to rate their current VIMS level on a scale from 0 (no VIMS) to 4 (very severe VIMS). The VIMS level was measured before and after each video clip viewing for the series of video clips (every 3 minutes).

video clip, they were presented with onscreen instructions similar to the Wong-Baker FACES pain rating scale,[13] as shown in Figure 2. The subjects could terminate the video watching when they reached VIMS level 4, or sooner if they could no longer endure VIMS. Fifteen video clips (total of 45 min length) were prepared.

Once the subject completed the video clip viewing task, the subject's postural stability was measured again. Then, the subject was asked to complete the post-experiment SSQ.

Each subject finished the entire experimental procedure three times in three display conditions (2D, S3D, and S3DD). In order to reduce the effect of VIMS from one session to the next, a period of at least 48 hours of rest was scheduled between each session. The order of the video clips and display conditions were counter-balanced among the subjects.

Analysis of SSQ, and Posture Stability

Two-way repeated measures ANOVAs were performed on the SSQ scores on stimuli exposure (before and after) and display conditions (2D, S3D and S3DD). Three symptom-wise sub-scores regarding nausea, oculomotor, and disorientation, as well as a combined total score[6] were computed from the SSQ responses. The log odds of dropping,[14] which is an estimate of a participants' dropout probability on given stimulus exposure, was also computed from the subject's SSQ responses. Note that the log odd of dropping ranges from 0 to ∞, where the values greater or less than 1 correspond to dropout probabilities above and below 0.5, respectively.

Each subject's posture stability before and after video stimulus exposure was estimated in three ways: (1) the area of an ellipse containing the CoP data with 95% confidence,[15,16] (2) spatial variability of the CoP,[17] and (3) velocity variability of the CoP shifts.[18] Note that the first and last 5 seconds of the CoP data from the 1 minute CoP measure were excluded from the analysis to avoid abrupt changes immediately before and after getting on and off the balance board. A two-way repeated measure ANOVA was applied to the computed posture stability values.

Analysis of VIMS Level Rating

The subjective VIMS level ratings during the stimulus exposure were used to measure the VIMS susceptibility of each subject. The VIMS susceptibility is computed as a function of the VIMS level ratings and endurance time (i.e., the duration of VIMS exposure until the subject terminated the experiment).

Figure 3 shows two examples of measured VIMS level ratings. As seen, the VIMS onset time (e.g. begin to experience VIMS) increase rate, and endurance time can substantially differ among subjects, and among display conditions.

For example, visual observations of Fig. 3 indicate that subject S2 is more susceptible to VIMS than subject S1 because S2 showed shorter VIMS onset time, higher increase rate, and shorter endurance time.

For S2, the VIMS onset time and endurance time were the same and only the VIMS increase rates were different across the display conditions. Therefore, the VIMS susceptibility of S2 in three display conditions can be easily ordered as S3DD > S3D > 2D.

For subject S1, it is relatively clear that subject S1 was less susceptible to VIMS in 2D than in the S3D or S3DD conditions because of longer VIMS onset time, lower increase rate, and longer endurance time in the 2D condition. However, since the VIMS level rating curves for the S3D and S3DD conditions crossed with each other (i.e., under S3DD, the VIMS onset took longer but the VIMS increase rate was higher and endurance time was shorter, where those factors were shorter, lower and shorter under S3D, respectively), it is hard to determine under which display condition S1 is more susceptible to VIMS.

To quantify the VIMS susceptibility of each subject in each display condition, we first time-normalized the VIMS level ratings, as shown in Figure 4, and then computed the area under the curves (AuC), similar to the receiver operator characteristic (ROC) coefficient computation,[19] to define each subject's sensitivity to VIMS. Note that the AuC combines the VIMS onset time and increase rate to describe one's VIMS sensitivity. Finally, each subject's VIMS sensitivity (AuC) was divided by the endurance time to incorporate VIMS endurance time factor.

In our study setup, the area under the time-normalized VIMS level rating curve can be computed as following:

$$A_{\mathrm{AUC}} = \left(\frac{\frac{x_0}{r}+\frac{x_1}{r}}{2}\right)\frac{1}{n} + \left(\frac{\frac{x_1}{r}+\frac{x_2}{r}}{2}\right)\frac{1}{n} + \cdots + \left(\frac{\frac{x_{n-1}}{r}+\frac{x_n}{r}}{2}\right)\frac{1}{n} \tag{1}$$

$$= \frac{1}{nr}\left(\frac{x_0+x_n}{2} + \sum_{i=1}^{n-1} x_i\right), \tag{2}$$

where x_i is the VIMS rating after the each video clip viewing, r is the maximum value on the VIMS rating (i.e., 4) and n is the number of video clips watched.

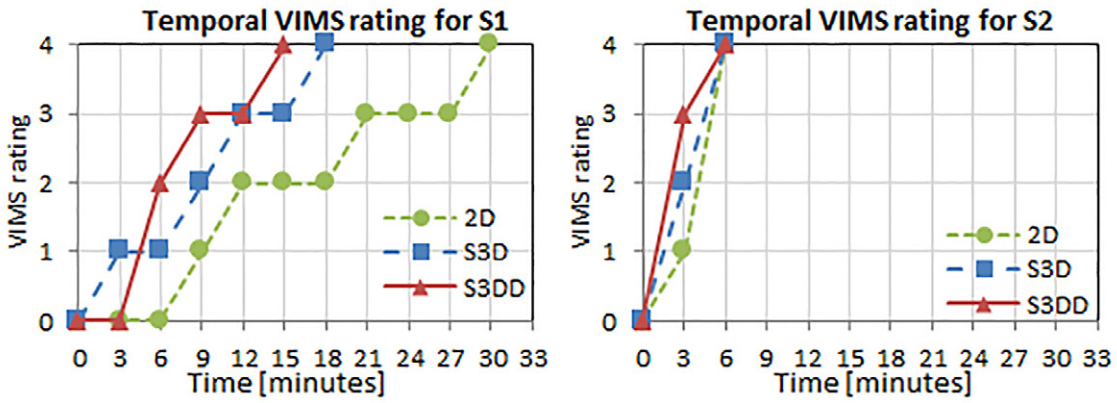

Figure 3. Examples of VIMS level ratings for high (left) and low (right) MSSQ scored subjects, where the MSSQ scores were 19.28 and 9.5, respectively. The VIMS onset time, increase rate, and endurance time are different among display conditions and between the subjects. S1 stopped watching the videos at 15, 18 and 30 minutes for 2D, S3D, and S3DD, while S2 stopped at 6 minutes for all conditions. Note that in visual observation, in contrast to what the MSSQ score suggested, the subject S1 seems less susceptible to VIMS than S2. The subject S2's VIMS susceptibilities under various display conditions can be ordered as (S3DD > S3D > 2D). However, for subject S1, although the VIMS susceptibility in 2D display condition is lower than other display conditions, it is hard to tell whether S1 is more VIMS susceptible under S3DD than under S3D, because the VIMS onset time is shorter and the VIMS increase rate is lower under S3D, while they are longer and higher under S3DD, respectively.

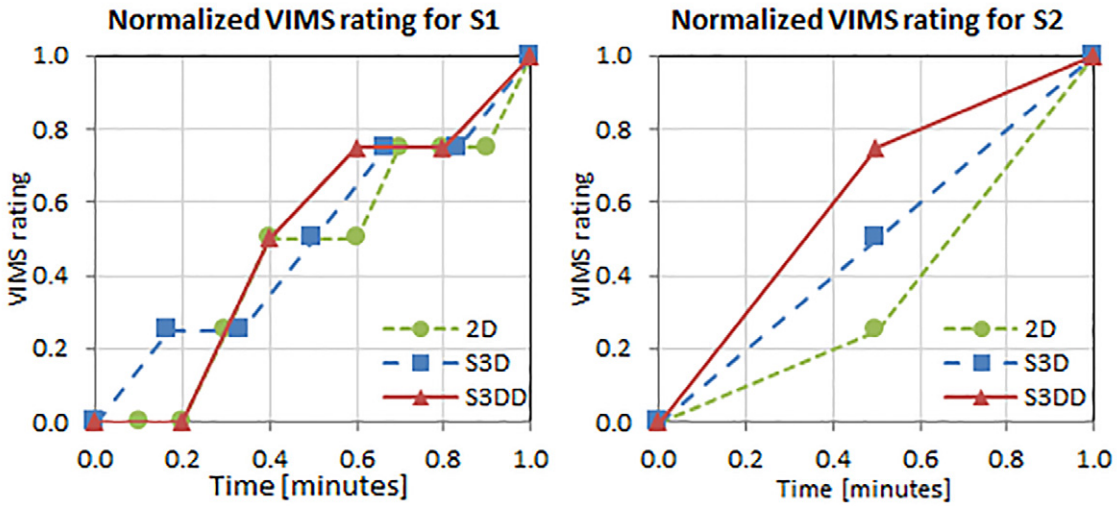

Figure 4. Time-normalized VIMS level ratings for the two subjects, shown in Fig. 3. The area under the curve (AuC) represents the VIMS sensitivity of a subject. The VIMS susceptibility of a subject can be computed by dividing the AuC by endurance time.

The VIMS susceptibility can be computed by dividing the VIMS sensitivity (AuC) by the ratio of endurance time to the maximum exposure time because the endurance time is inversely proportional to the VIMS tolerance. The final VIMS susceptibility can be computed as

$$S = \frac{A_{\mathrm{AuC}}}{n/N} = \frac{N}{n^2 r}\left(\frac{x_0 + x_n}{2} + \sum_{i=1}^{n-1} x_i\right), \qquad (3)$$

where N is the total number of video clips prepared by the experimenter.

Figure 5 shows the results of AuCs for normalized exposure time, our VIMS susceptibility measure, and the relative discomfort score (RDS) used by Fernandes & Feiner.[7] Note that the RDS computation assumed that the last VIMS rating (i.e., the score when subject terminated the experiment) repeated to the end of the experiment even if the subjects gave up prematurely.

As seen (Fig. 5(a)), the AuC computation alone does not fully represent one's VIMS susceptibility, because it ignores the effect of the VIMS endurance time. The RDS (Fig. 5(c)) orders subject's discomfort sensitivity correctly, but the differentiations between the subjects and among the display conditions were relatively weak compared to the proposed VIMS susceptibility measure (Fig. 5(b)). If the experiment was designed to last longer, the sensitivity differences measured by the RDA will be diminished (especially for the subjects that dropped out of the experiment early) because the assumed "repeated" rating portion will take the majority of the computation. Our proposed VIMS susceptibility measure (Fig. 5(b)) shows more distinct separations among display conditions and between subjects

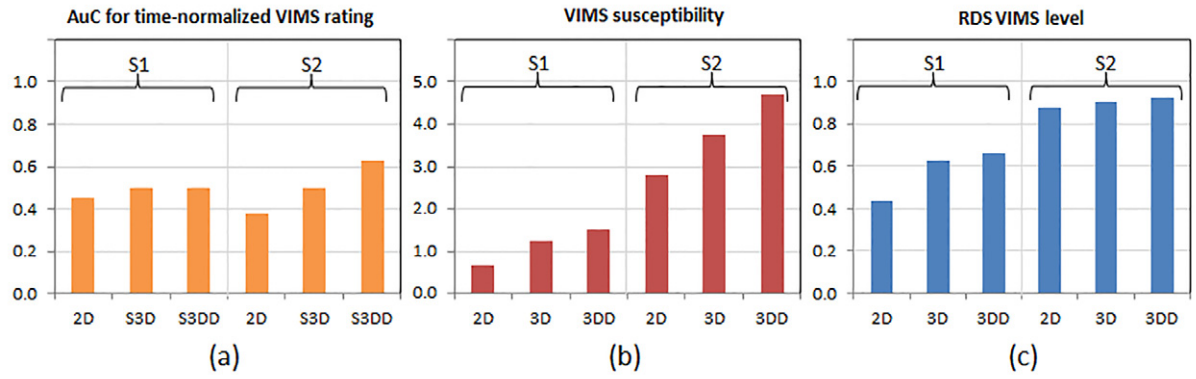

Figure 5. Computed AuCs, VIMS susceptibility, and the relative discomfort score (RDS) of subjects shown in Fig. 3. A higher value of VIMS susceptibility means that a subject is more susceptible to VIMS. Note that the RDS assumes the last VIMS rating to be maintained to the end of the experiment, even if the subject terminated the experiment early, which makes the measure less sensitive to early termination, as shown in the RDS plot for S2.

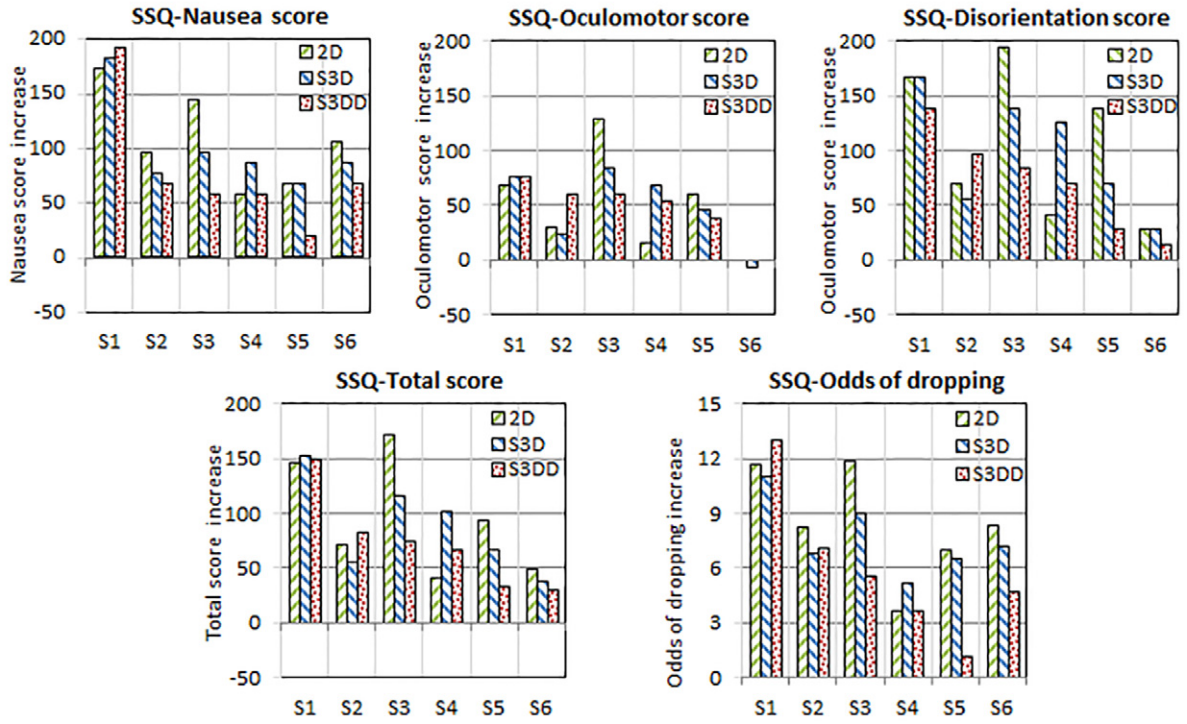

Figure 6. Differences of various SSQ scores between before and after exposure to the 2D, S3D, and S3DD display conditions. Almost all data shows positive differences, indicating the increase of these scores after watching video clips (except SSQ-Oculomotor score for S6). No significant effect of display condition was found.

because it incorporates both the VIMS sensitivity and endurance time.

A single-factor ANOVA was applied to each subject's VIMS susceptibility for display conditions, and the correlations with other VIMS measures, i.e., SSQ, MSSQ, posture stability, were computed for the final analysis.

RESULTS

Twenty subjects were recruited for the study. Two subjects were excluded due to high motion sickness susceptibility and ten subjects were excluded due to low motion sickness susceptibility during the screening using the MSSQ. Two subjects dropped out of the study due to VIMS. Therefore, total of six subjects (three males and three females, 33.7 ± 11.3 years old) finished the study and were included in analysis.

Pre- and Post-SSQ Data

Figure 6 shows the SSQ score differences measured before and after the exposure to the video clips. Two-factor ANOVAs were applied to the nausea, oculomotor, disorientation, and total scores, as well as the estimated log odds of dropping between measured timing (before/after) and display conditions (2D/S3D/S3DD).

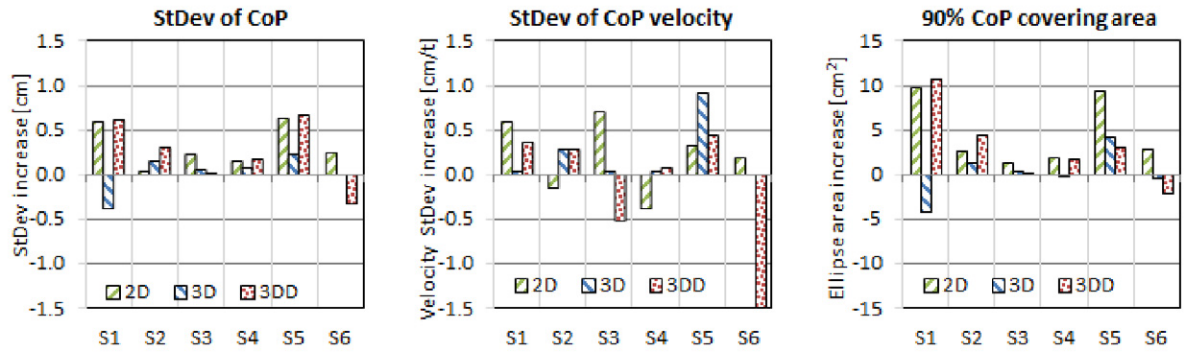

Figure 7. Differences of various posture stability measures before and after exposure to the 2D, S3D, and S3DD display conditions. Marginally significant increases in the ellipse area and spatial variability of CoPs were found after exposure to the video clips.

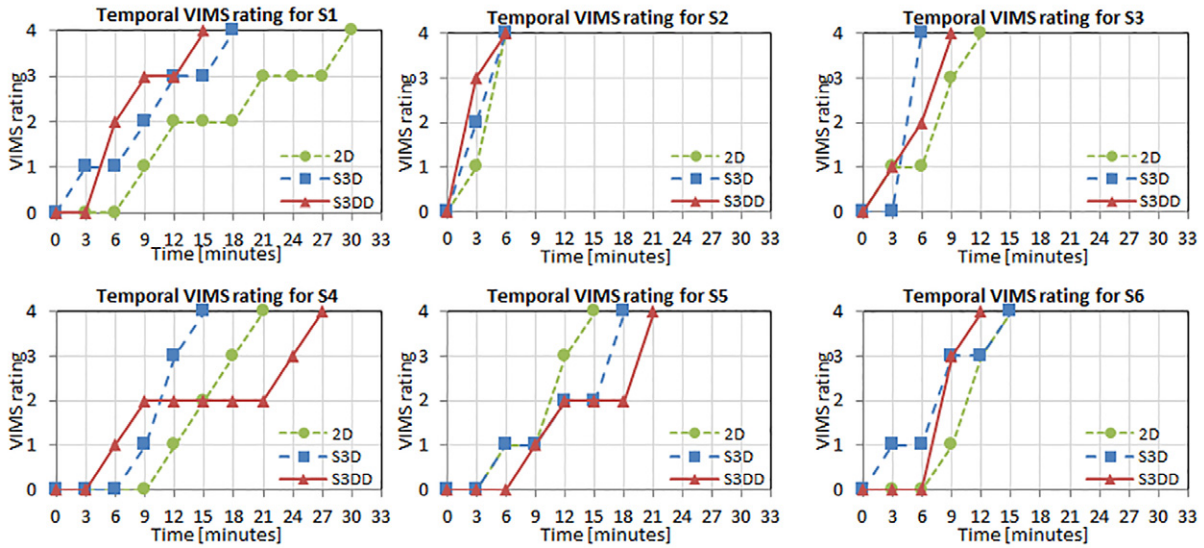

Figure 8. Each plot shows each subject's VIMS level ratings during the video stimuli exposure in 2D, S3D, and S3DD.

Significant main effects of stimuli exposure (before/after) were found in all SSQ scores (all $Fs(35, 1) > 33.08$, $ps < 0.01$), where all scores increased after exposure. No significant main effects of display conditions (2D/3D/3DD) were found (all $Fs(35, 2) < 0.96$, $ps > 0.40$). No interaction between stimuli exposure and display condition was found (all $Fs(30, 2) < 0.62$, $ps > 0.36$).

Pre- and Post-Posture Stability Data

Figure 7 shows the posture stability differences measured before and after exposure to the video clips. Two-factor ANOVAs were applied to the spatial variability, velocity variability, and ellipse area containing CoPs. Marginally significant main effects of stimuli exposure (before/after) were found in the ellipse area ($F(35, 1) = 3.3, p = 0.08$), and in the CoP spatial variability ($F(35, 1) = 3.62$, $p = 0.07$), where the increased eclipse area and spatial variability indicated the reduced posture stability after video exposure. However no significant main effect of exposure was found in the CoP velocity variability ($F(35, 1) = 0.20$, $p = 0.65$). No significant main effect of display conditions was found on all measures (all $Fs(35, 2) < 0.17$, $ps > 0.85$). No significant interaction was found (all $Fs(30, 2) < 1.14$, $ps > 0.33$).

VIMS Level Rating and VIMS Susceptibility

Figure 8 shows the VIMS level rating of each subject in each display condition. All participants started at VIMS level 0 and reached VIMS level 4 (the highest VIMS level) in less than 30 minutes in all display conditions.

As seen, the estimation of one's VIMS susceptibility under a given display condition based on visual observation is hard to achieve because the VIMS response and endurance time varied greatly among subjects, and even for the same subject, it varied a lot among display conditions.

Figure 9 shows the results of our VIMS susceptibility measure for each subject in each of the three display conditions (Fig. 9 left). Here, each subject's VIMS level ratings were represented with a single value, allowing us to compare the effects of display conditions and differences among subjects.

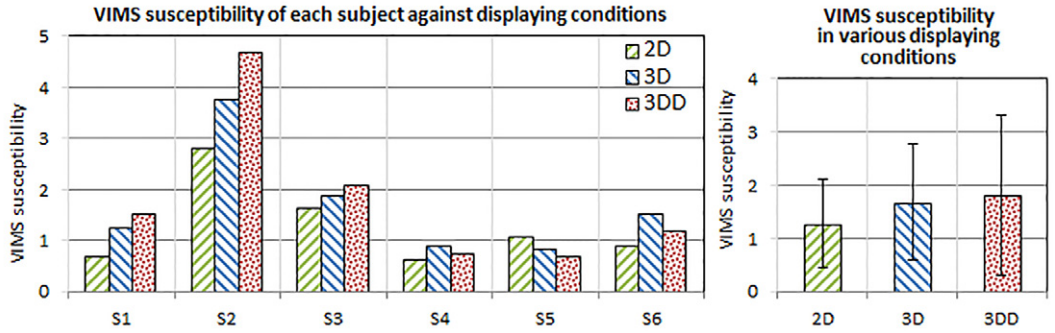

Figure 9. Plots of each subject's VIMS susceptibility under various display conditions (left) and the means and standard deviations among display conditions (right). The results show that the individual variability of VIMS susceptibility is very large. It also shows that due to the strong motions (first-person view) contained in the video clips, the subjects were susceptible to VIMS even in the 2D display condition. However, they were more susceptible to VIMS in the 3D and 3DD viewing conditions than in the 2D viewing condition.

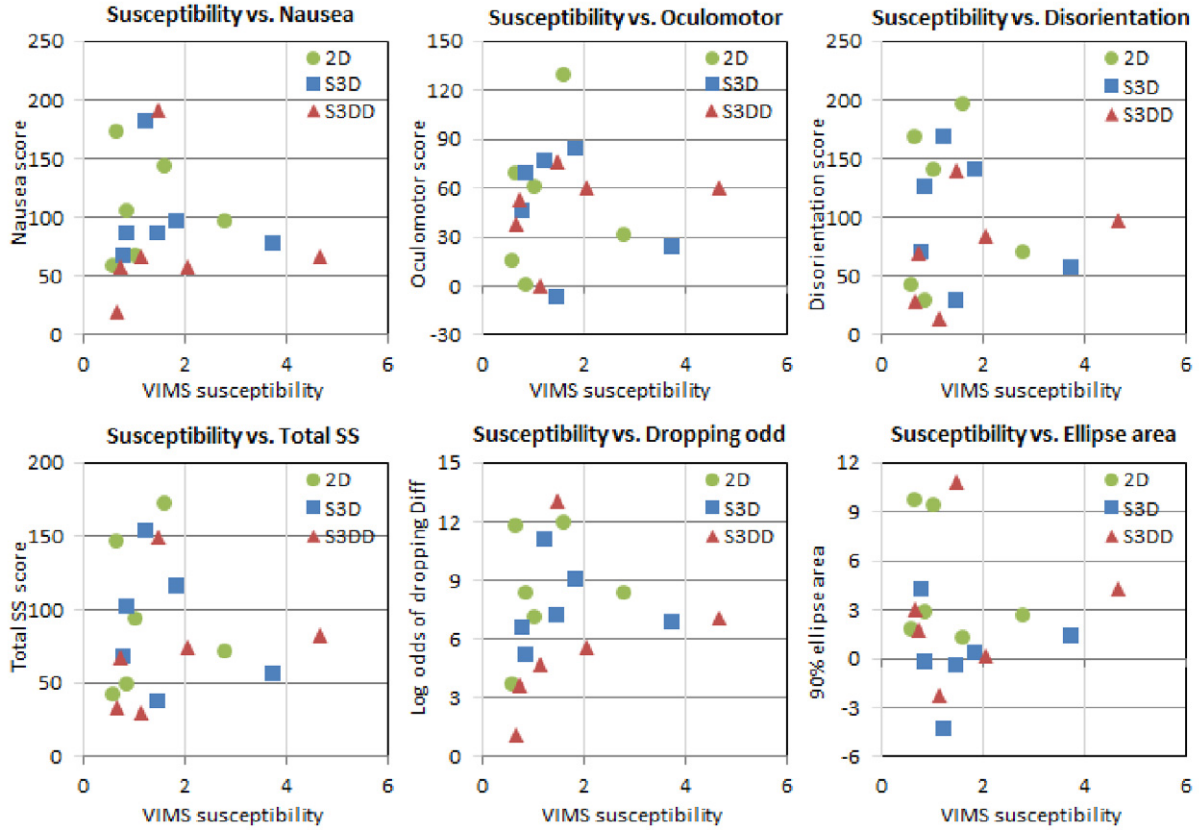

Figure 10. Correlation plots for each subject's VIMS susceptibility and other VIMS measures under various display conditions. Note that the increments of the other VIMS measures (difference before and after experiments) were compared to the subject's VIMS susceptibility. No significant correlation was found for any comparison.

A single-factor (display condition) ANOVA was applied to the measured VIMS susceptibility. A significant main effect of subjects was found ($F(17, 5) = 24.05$, $p < 0.01$), indicating a large between-subjects variation. A marginally significant effect of display condition (within subject) was also found ($F(17, 5) = 2.91$, $p = 0.09$), where the means and standard deviations of the VIMS susceptibilities for 2D, S3D, and S3DD are 1.28 ± 0.70, 1.68 ± 1.17, and 1.81 ± 2.25, respectively (Figure 10 right). A set of post hoc tests (pair-wise t-test) was applied among display conditions (2D versus S3D, 2D versus S3DD, and S3D versus S3DD), and found significant increase of VIMS susceptibility between 2D versus S3D ($t(5) = 2.50$, $p = 0.03$), marginally significant increase between 2D versus S3DD ($t(5) = 1.70$, $p = 0.08$), and no significant increase between S3D versus S3DD ($t(5) = 0.68$, $p = 0.26$).

VIMS Susceptibility to Other VIMS Measures

To find out whether there is correlation between VIMS susceptibility and other VIMS measures, Pearson correlation coefficients were computed between VIMS susceptibility and

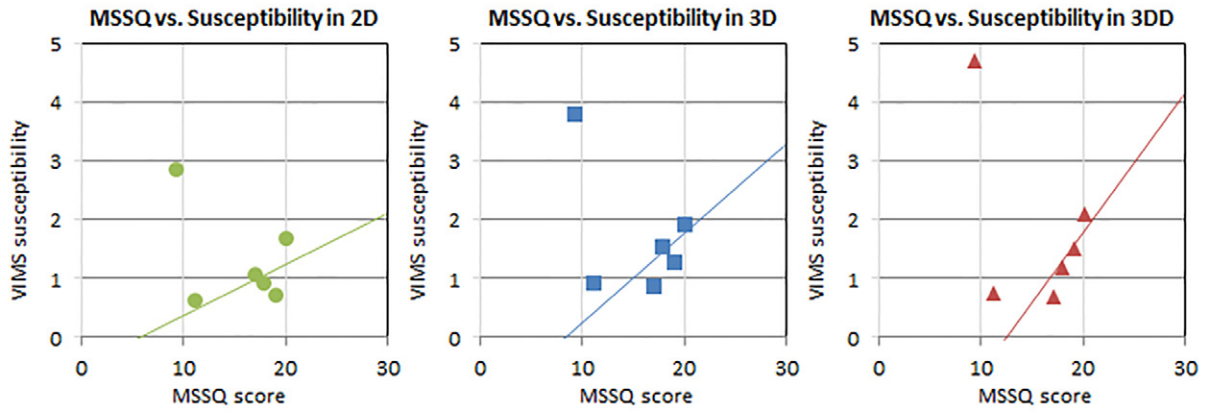

Figure 11. Correlation plots for each subject's VIMS susceptibility and MSSQ scores under various display conditions. The lines in each plot represent the linear regression of the data sets excluding one extreme subject's data (located at upper left corner).

SSQ based score changes (before and after experiments), as well as VIMS susceptibility and posture stability changes. However, no significant correlation was found (all Corrs $<$ 0.07, $ps > 0.59$). Fig. 10 shows the correlation plots between the factors.

VIMS Susceptibility to MSSQ

Finally, the Pearson correlation coefficients were computed between the VIMS susceptibility and the MSSQ scores used for the subject screening. Although some correlations were found, where the correlation coefficients increased as the display conditions changed from 2D, to S3D, and S3DD (Corr2D $= 0.61$, Corr3D $= 0.68$ and Corr3DD $= 0.74$), due to the small sample size, p-values for those correlations were not significant ($p2D = 0.23$, $p3D = 0.20$ and $p3DD = 0.15$). Figure 11 shows the correlations between those susceptibility measures.

CONCLUSION

Unlike other conventional VIMS measures, which only consider the overall symptomatic changes between pre- and post-measurements, the proposed VIMS susceptibility has face validity, as it can directly quantify each subject's VIMS experienced (in terms of sensitivity and endurance) throughout the experiment under given VIMS inducing conditions. Therefore, the VIMS susceptibility provides a better way to conduct within-subject comparisons. For example, if a particular display configuration increases subjects' VIMS susceptibility, this configuration should be avoided because this indicates that people become more susceptible to VIMS under the display configuration. Note that the VIMS susceptibility also naturally supports the between-subjects comparisons because the VIMS susceptibility is based on the ROC-like sensitivity computation over normalized time which is then weighted by normalized endurance time.

Our data showed that (1) the SSQ can be a potential candidate for the VIMS marker as indicated by significant main effects of exposure (before/after) on all scores. However, the SSQ failed to distinguish the VIMS experienced among display conditions (i.e., no significant main effect of display condition), which has been known to make a difference; (2) The posture stability measure also showed a similar trend as the SSQ measures, where it could distinguish VIMS changes between before and after the exposure, but did not show a difference among display conditions; (3) The proposed VIMS susceptibility measure showed clear existence of VIMS, since it is a direct measure of subjects' experience of VIMS. The VIMS susceptibility measure was able to distinguish the VIMS experienced under 2D and S3D display conditions (within-subject comparison). It also showed a large between-subjects variation on given VIMS conditions (i.e., highly significant main effect of subjects); (4) Poor correlations between the VIMS susceptibility and other measures indicate that the conventional VIMS measures, which are indirect symptomatic measures, did not correctly represent how much VIMS each subject experienced; (5) The proposed VIMS susceptibility showed a marginal correlation with the MSSQ results. However, the MSSQ could not predict one particular subject who received the lowest MSSQ score (still within the subject inclusion criteria), but performed worst in actual VIMS experiments. This is due to the fact that the design of the MSSQ largely depends on the past motion sickness experiences induced by strong physical vestibular stimulations (e.g., amusement park ride or mode of transportation), which are only remotely related to current S3D or VR experiences, where the motion sickness is strongly driven by visual stimulations.

Still, our VIMS susceptibility was not able to clearly show the effect of additional distortions applied to the S3D display condition (3DD). This may be because the pincushion distortions introduced to each eye's views ended up either breaking binocular fusion in the periphery, which reduced the overall S3D depth motions, or compensating for the peripheral depth distortion indicated by Hwang & Peli.[3] Unfortunately, we could not pinpoint a single cause at this moment because no information on capturing or rendering configurations of the S3D video clips was available.

Although the VIMS susceptibility measure showed better insight of a subject's VIMS experience under the

experimental condition and among the subjects, further study concerning the repeatability and transferability should be followed, so that we can check whether the VIMS susceptibility for a subject is consistent throughout the similar stimulus exposures, or can be used to predict the VIMS susceptibility of subjects when they are exposed to different kinds of VIMS inducing stimuli.

Once the VIMS susceptibility measure is fully validated, it can be used as a quality measure for the pre-produced visual contents regarding VIMS, and a quantitative measure for testing the effectiveness of VIMS prevention techniques.

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REFERENCES

[1] J. Reason, "Motion sickness: some theoretical and practical considerations," Appl. Ergon. **9**, 163–167 (1978).

[2] R. S. Kennedy, J. Drexler, and R. C. Kennedy, "Research in visually induced motion sickness," Appl. Ergon. **41**, 494–503 (2010).

[3] A. D. Hwang and E. Peli, "Instability of the perceived world while watching 3D stereoscopic imagery: a likely source of motion sickness symptoms," i-Perception **5**, 515–535 (2014).

[4] J. Kim, "An overview of depth distortion in stereoscopic 3D displays," J. Inf. Disp. **16**, 89–97 (2015).

[5] R. Liu, E. Peli, and A. D. Hwang, "Measuring visually induced motion sickness using wearable devices," *IS&T Electronic Imaging: Human Vision and Electronic Imaging 2017* (IS&T, Springfield, VA, 2017), pp. 218–223.

[6] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness," Int. J. Aviat. Psychol. **3**, 203–220 (1993).

[7] A. S. Fernandes and S. K. Feiner, "Combating vr sickness through subtle dynamic field-of-view modification," *IEEE Symposium on 3D User Interfaces (3DUI)* (IEEE, Piscataway, NJ, 2016).

[8] J. Rosner and G. D. Clift, "The validity of the Frisby stereotest as a measure of precise stereoacuity," J. Am. Optometric Association **55**, 505–506 (1984).

[9] J. A. Alexander, "A new clinical test of stereopsis," Clin. Exp. Optom. **62**, 191–193 (1979).

[10] W. T. Grant, "The Romberg test, a graphic method of recording disturbances of equilibrium," Bull. Los Angeles Neurol. Soc. **8**, 25–30 (1941).

[11] J. F. Golding, "Predicting individual differences in motion sickness susceptibility by questionnaire," Personal. Individ. Differ. **41**, 237–248 (2006).

[12] R. A. Clark, A. L. Bryant, Y. Pua, P. Mccrory, K. Bennell, and M. Hunt, "Validity and reliability of the Nintendo Wii balance board for assessment of standing balance," Gait Posture **31**, 307–310 (2010).

[13] D. L. Wong, M. Hockenberry-Eaton, D. Wilson, M. L. Winkelstein, and P. Schwartz, "Wong–Baker faces pain rating scale," Home Health Focus **2**, 62 (1996).

[14] S. A. Balk, M. A. Bertola, and V. W. Inman, "Simulator sickness questionnaire: twenty years later," *Proc. 7th Int'l. Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (Public Policy Center, University of Iowa, 2013), pp. 257–263.

[15] T. E. Prieto, J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust, "Measures of postural steadiness: differences between healthy young and elderly adults," IEEE Trans. Biomed. Eng. **43**, 956–966 (1996).

[16] R. J. Doyle, E. T. Hsiao-Wecksler, B. G. Ragan, and K. S. Rosengren, "Generalizability of center of pressure measures of quiet standing," Gait Posture **25**, 166–171 (2007).

[17] F. Kinoshita, M. Takada, M. Miyao, and H. Takada, "Expression of balance function after exposure to stereoscopic video clips," *IEEE Int'l. Conf. on Computer Science & Education (ICCSE)* (IEEE, Piscataway, NJ, 2016).

[18] K. Yoshikawa, F. Kinoshita, K. Miyashita, A. Sugiura, T. Kojima, H. Takada, and M. Miyao, "Effects of two-minute stereoscopic viewing on human balance function," *Int'l. Conf. on Universal Access in Human-Computer Interaction* (Springer International Publishing, 2015).

[19] J. A. Hanley and B. J. Mcneil, "The meaning and use of the area under a receiver operating characteristic (ROC) curve," Radiology **143**, 29–36 (1982).