

Identifying physiological correlates of cybersickness using heartbeat-evoked potential analysis

Virtual Reality

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1. Supplementary Methods

1.1 Electrocardiogram (ECG)

Using BIOPAC's AcqKnowledge 4.2 software, we derived three indices for an individual's ECG signal: heart rate, heart period, and heart rate variability (HRV). We used the "Find Rate" function in the software to analyze the heart rate and the heart period. Peaks were detected on the basis of the positive trend in the ECG signals, and noise rejection was adjusted to 1% to 10% of the peak according to the individual ECG waveform. The peak interval window for the heart rate ranged from a minimum of 40 beats per minute (bpm) to a maximum of 180 bpm, whereas that of the heart period ranged between 333 ms and 1500 ms.

For the HRV analysis, we performed the "Heart Rate Variability" function in the software. Time-series ECG signals were converted into the frequency domain for four bands: very low frequency band (0–0.04 Hz), low-frequency band (0.04–0.15 Hz), high-frequency band (0.15–0.40 Hz), and very high frequency band (0.40–3.0 Hz). The value of the HRV (also referred to as the "sympathetic-vagal balance" in the software) was calculated from the ratio of by LF/HF. We performed a 2×3 repeated measures analysis of variance (rmANOVA) with the orientation (upright vs. inverted) and repetition (day 1 vs. day 2 vs. day 3) as the factors.

1.2 Eye gaze trajectories

FOVE HMD (FOVE, Inc., Tokyo, Japan) was used to track eye movements during the VR experience. The tracking data were recorded at 70 frames per second, and the resolution of the display was 2560×1440 pixels. To investigate the pattern of gaze trajectories during each experimental condition, we computed the deviation of the eye gaze from the center point of the VR content. Following the method of Chang et al. (2021), we preprocessed the eye-tracking data and then calculated the average distance between the eye gaze and the center position during the entire virtual ride, which is named as mean deviation. As the deviation increased, we

assumed that the gaze trajectories tended to be off-center. However, when the deviation was near zero, the participants tended to stare at the center point. By calculating the mean deviation of each experimental condition, we were able to examine the change in the participants' gaze trajectories under certain VR conditions.

Owing to the malfunction of the eye tracking, part of the data of two participants failed to record (subject 5: day 1; subject 7: day 3). Because the rmANOVA ignored the missing data from the entire dataset, we analyzed eye movements from 18 participants in total.

1.3 Statistical analysis for the order effect

We tested the order effect on the subjective measures (i.e., SSQ, FMS, levels of reality, predictability, and immersion) to determine whether the participant's subjective experience was affected by the order of the ride rather than by the orientation of the VR content. Because the participants experienced four iterative VR rides during each visit, we investigated whether they reported higher SSQ scores in the last ride owing to the cumulative discomfort. A 3×4 rmANOVA with the repetition (day 1 vs. day 2 vs. day 3) and order (1st ride vs. 2nd ride vs. 3rd ride vs. 4th ride) as the factors was conducted.

2. Supplementary Figures

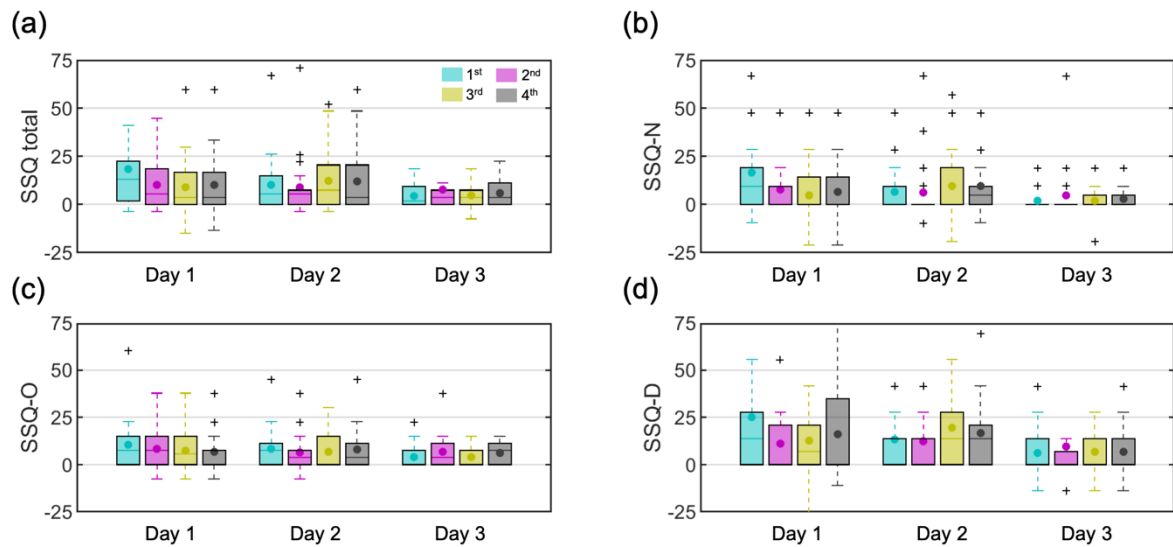


Fig. S1: Box-and-whisker plots of the SSQ scores (a) SSQ total, (b) SSQ nausea (SSQ-N), (c) SSQ oculomotor (SSQ-O), (d) SSQ disorientation (SSQ-D). The CMYK color of each bar represents the order of ride (i.e., cyan: 1st, magenta: 2nd, yellow: 3rd, black: 4th ride). A dot and horizontal line in the box represent the mean and median of each experimental condition, respectively. The black cross indicates outliers. The results indicated that there were no significant differences in the level of each SSQ score between each VR ride. That is, the participants did not report increased discomfort according to the order.

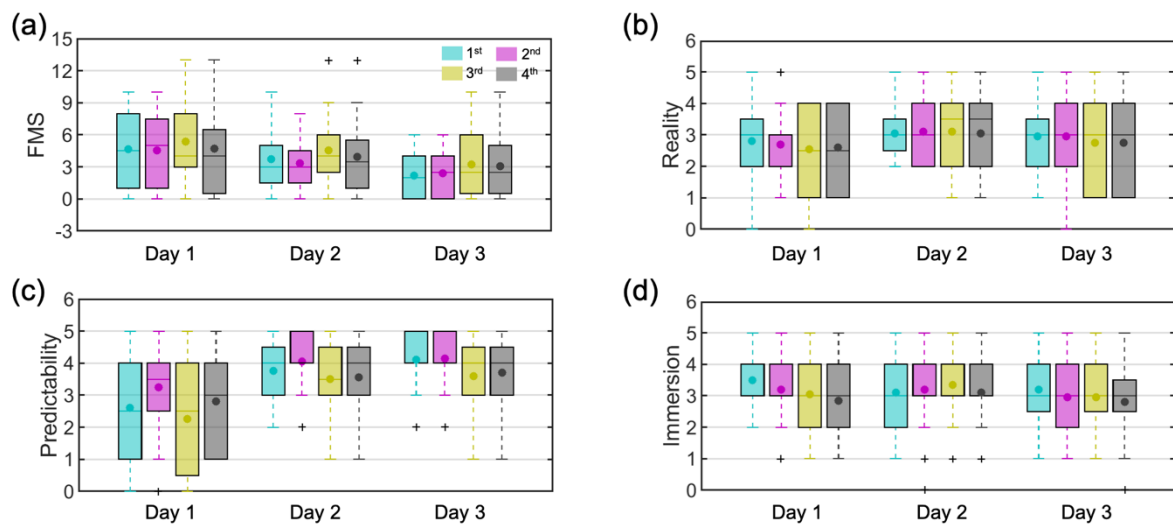


Fig. S2: Box-and-whisker plots of the FMS and each verbal report (a) FMS, (b) Reality, (c) Predictability, (d) Immersion. The CMYK color of each bar represents the order of ride (i.e., cyan: 1st, magenta: 2nd, yellow: 3rd, black: 4th ride). A dot and horizontal line in the box represent the mean and median of each experimental condition, respectively. The results indicated no significant differences between each VR ride for all measures.

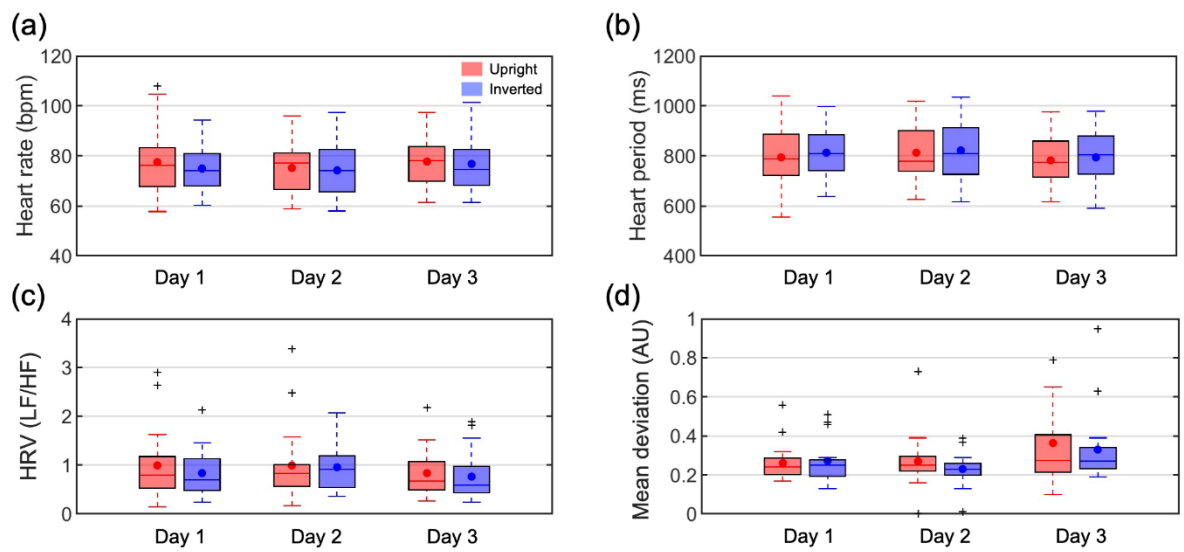


Fig. S3: Box-and-whisker plots of ECG-related indices and eye trajectories (a) Heart rate, (b) Heart period, (c) HRV, (d) Mean deviation of eye trajectories. The red box represents an upright condition, while the blue one represents an inverted condition. A dot and horizontal line in the box represent the mean and median of each experimental condition, respectively. The black cross indicates outliers. Participants did not show any statistical differences between conditions for each index.

3. Supplementary Table

Table S1: The statistical results of the HEP amplitude for four different temporal range. We made a temporal shift before and after 20 ms from the target time window (shift 0). The F and t values of each time window indicated similar results, showing that the statistical significance of the HEP amplitude did not depend on the specific measurement window (* $p < 0.05$, ** $p < 0.025$, *** $p < 0.001$).

	shift 0 (300–448 ms)	shift 1 (280–468 ms)	shift 2 (280–448 ms)	shift 3 (300–468 ms)
<i>F</i> test				
site	40.029***	27.509***	27.826***	37.860***
orientation	1.927	1.900	1.946	1.878
repetition	1.527	2.268	2.222	1.643
site × orientation	5.323*	5.322*	4.894*	5.791*
site × repetition	0.218	0.204	0.258	0.192
orientation × repetition	0.347	0.166	0.236	0.266
site × orientation × repetition	0.577	0.443	0.546	0.464
<i>t</i> test				
fronto-central	-2.495**	-2.542**	-2.444**	-2.596**
parietal	1.834	1.806	1.728	1.917

4. Supplementary Discussion

For the ECG signal, we did not find any significant differences between the experimental conditions among the three indices (i.e., heart rate, heart period, and HRV). Though the heart rate indicated a tendency showing an increased bpm in the upright condition compared to the inverted condition, it did not reach a significance level ($p = 0.079$). Previous studies revealed that participants showed higher bpm as they experienced severe cybersickness with longer VR interaction (Dennison et al., 2016; Gavgani et al., 2017). Considering that participants reported higher cybersickness in the upright condition, this stressful situation might induce transiently increased heartbeats.

We did not observe a repetition effect on any of the ECG-related indices. In the study of Gavgani et al. (2017), the participants' heart rate significantly changed with the ride time (e.g., before the ride vs. the first or last minute of the ride), but no differences were observed between the days of the experiment (e.g., day 1 vs. day 2 vs. day 3). Several methods, such as meditation, deep breathing, and exercise, have been widely introduced to change the cardiovascular activity, which takes several weeks to months to show any significant difference (Bahrke and Morgan, 1978; Cipryan and Litschmannova, 2013). Rather, cardiac changes over days may indicate serious health problems (Quer et al., 2020). Therefore, according to homeostasis perspectives, it is likely that we failed to find a repetition effect on the ECG indices.

The eye trajectories of the participants did not indicate any statistical differences between the experimental conditions. Though the participants' eyes tended to show more deviated gaze behavior from the center during the repetition, the difference did not reach a significance level ($p = 0.061$). Given that previous research found a negative correlation between the total SSQ score and the degree of deviation from the center (Chang et al., 2021), the present result might support the link between eye trajectories and cybersickness. That is, increased eye deviation behavior might reflect the reduced subjective discomfort due to the repetition. Further studies are required to clarify the relationship between the participants' eye movement and their level of cybersickness.

References

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