Evaluation of Differences between Real and Virtual Exercises for Preventing Cybersickness

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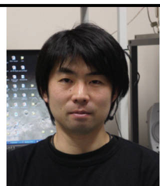

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ABSTRACT

In this paper, we showed a feasibility study for preventing cybersickness by evaluation of influences during real and virtual exercises on the autonomic nervous regulation (ANR). Studying the priority of different sensory stimuli on ANR, we first of all evaluated the ANR for the muscle contractions during cycling and for the visual stimuli by a mountain bike real video with the first-person viewpoint. Then, we tried to discuss a dynamic threshold between positive and negative sensations based on the results for real and virtual exercises. Identifying the dynamic threshold for individuals would be a key to prevent cybersickness.

Keywords

cybersickness, autonomic nervous regulation, exercise, visual stimuli, muscle activity

INTRODUCTION

Development of virtual environment (VE) applications in rehabilitation engineering [8] are expanding several types of exercises (real active exercise, real passive exercise, and virtual exercise). Enhancing a specific sensory stimulus in VE, however, sometimes evokes unpleasant sensation due to the conflict among sensory systems (sensory conflict theory) [5]. This problem is, in relation to simulator sickness and motion sickness, called cybersickness that causes an unpleasant sensation under visually-inducing illusions of self-motion. Unpleasant sensation has been assessed in terms of autonomic nervous regulation (ANR) estimated from biosignals including heart rate, blood pressure, finger pulse volume, respiration rate, skin condition, and gastric myoelectrical activity [2], [3], [16]. Regarding the future direction of VE, health and safety implications of VR have been pointed out to make recommendations [15].

We first of all evaluated the characteristics of sensory systems at the input-level and discussed the relationships between sensory characteristics and the ANR [9], [10]. For experiments in real exercise, we measured myoelectric signals and estimated a muscle force-related index and muscle fatigue-related index to be compared with the pedal torque during bicycling exercise [9], [12]. To study the influence of muscle activity on ANR, we evaluated the time-varying behavior of the respiratory sinus arrhythmia estimated from the RR interval time-series [4]. For experiments in virtual exercise, we measured the relationship between a pupil diameter and the brightness of a video image, and between an eye movement and the image motion factors. We used a mountain bike riding video images with the first-person viewpoint. The motion vectors, that are used in image data compression [6], was used for quantifying vection-inducing real video images. As a similar parameter, So *et al*. [17] proposed a metric for quantifying virtual scene movement by the spatial velocity of computer graphics images. To study the relationships between sensory characteristics and the ANR at the output-level, we analyzed measured signals by time-frequency representations, and investigated the relationship between input factors and ANR.

The ANR supports continuous exercise by controlling the cardiovascular system. It should be noted that there is a large difference in time-scale between ANR and sensory stimuli (Fig. 1), and a time delay in ANR as a combination of different responses to several types of sensory stimuli. This combination means that there could be the priority of individual sensory stimuli on the ANR. Real exercise is divided into active phases and passive phases depending on the motor control strategy. Thus, comparison of the input stimuli at active phases with the output ANR at following passive phases would be suitable for evaluating the input-output-relations with a time-delay. Discrimination of these phases was easy for real exercise because muscle activity requests strong responses of ANR, but not for virtual exercise. For virtual exercise, we therefore tried to define cybersickness intervals by referring the behavior of ANR-related indices, and presumed the candidates of input visual stimuli. Finally, assuming the priority of ANR for individual sensory stimuli during real and virtual cycling exercise, we will discuss how to prevent cybersickness.

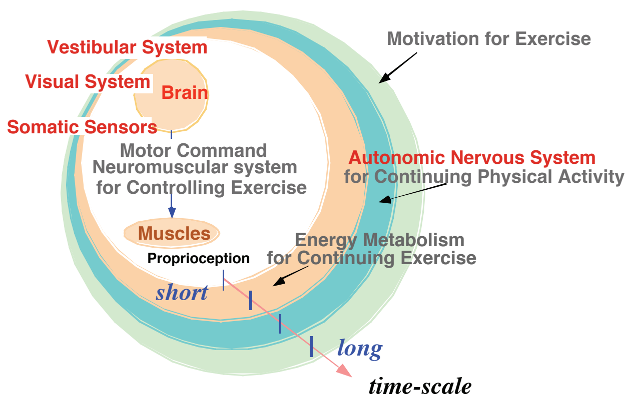

Fig. 1. Several time-scales in biosignals.

METHOD

Experiments

Subjects were informed of the risks involved in advance in our experiments. For biosignal processing, it needs a time interval over several minutes to estimate the ANR and a sampling frequency over 1000 Hz to deal with biosignals at sensory systems.

For real exercise in the field experiments [9], subjects were asked to pedal a torque-assisted bicycle at 60 rpm. The length of the circuit path was approximately 840-m and there was a steep uphill section near the middle of the path. We divided the path into three phases: before and after climbing, and climbing. An experimental set consisted of five or six consecutive trials and each trial comprised 2.5-minute cycling exercise followed by 2-minute rest. The ECG and EMG were sampled at 5000 Hz with a 12-bit resolution. To supplement the limitation of biosignals, we used a subjective index, the NASA task load index (NASA-TLX) [1], for each rest period between consecutive trials

For virtual exercise [10], subjects viewed the 18-min-long, ten sections of different sports, video image with the first-person viewpoint: for example, the video camera mounted on the handlebars of a mountain bike produced unexpected camera motion. An experimental set was composed of a 5-min rest period followed by the18-min-long video and a final 5-min rest period. The ECG, blood pressure, and respiration were measured at the sampled frequency of 1000 Hz with 12-bit resolution. As a subjective index, we compared the total scores of the Simulator

Sickness Questionnaire (SSQ) [7] before and after watching the vection-inducing video. Besides, for each video image section, a simple questionnaire (unpleasant, neutral, or pleasant) was used.

Biosignal Processing

At the level of sensory systems, the relationship between sensory stimuli and physical factors was evaluated by the system function approach or the multivariate analysis [13]. For evaluating the ANR-related indices at the output-level, the time-frequency representation of measured signalss by the wavelet transform (WT) was used [9].

For cycling exercise, we studied the relationships between a muscle force-related index and the pedal torque, or between a muscular fatigue-related index and the pedal torque during each pedaling period [9]. [12], because such indices can be related to the torque. We practically estimated the average rectified value (ARV) from ME signals as a muscle force-related index, and the mean power frequency (MPF) as a muscular fatigue-related index (Fig. 2). We estimated the correlation coefficient between ARV and the pedal torque, $\gamma_{ARV\text{-}trq}$, every 250 msec (4 Hz) with overlapping consecutive 10-sec segments, as an index to be compared with the ANR-related indices. The ANR-related indices at each phase were estimated from the RR interval by the WT. The focused frequency band was related to the respiratory sinus arrhythmia (RSA) [4], which frequency band ranged from 0.3 to 0.6 Hz during exercise. The difference in ANR was noticeable before or after climbing, compared with that during climbing. Then, we calculated the power ratio of RSA, pr_{RSA} before climbing a steep uphill, to try to separate the trials in relation to each property of ANR.

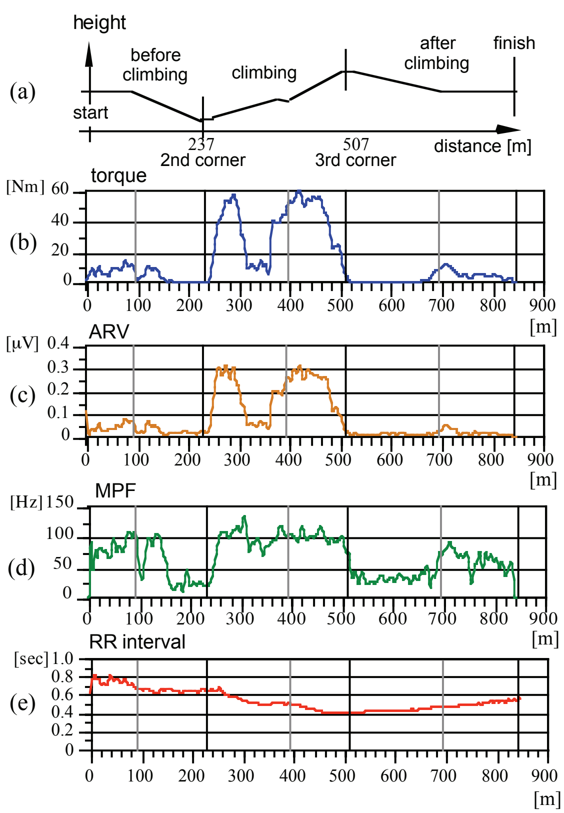

Fig. 2. For real exercise, (a) overview of the path and (b)–(c) measured signals (type-HRSA).

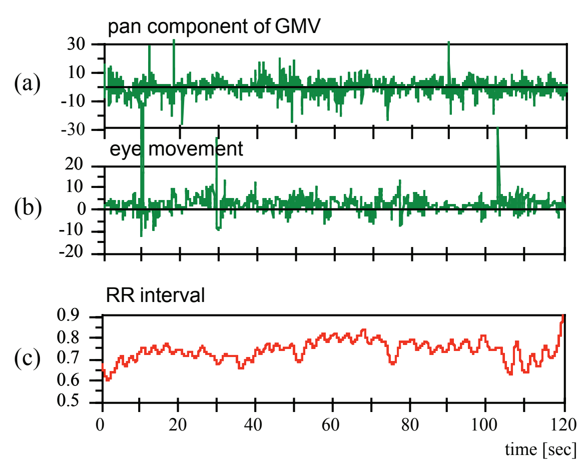

Fig. 3. Measured signals for virtual exercise.

For experiments in virtual exercise with mountain-bike riding video, we studied the relationship between a pupil diameter and the brightness of image, and between an eye movement and the image motion vectors (Fig. 3). We estimated a local motion vector (LMV) by the block matching method in each section of a screen [13]. Note that the whole screen was divided into 25 regions. Besides, a global motion vector (GMV), which represents camera work, was estimated from LMV by a bottom-up approach. Using a frame-by-frame sliding window with a 1-sec interval, we estimated the time-series of the correlation coefficients, γ, between three GMV components (zoom, pan, and tilt) and each LMV components (up/down and right/left) at 25 regions of a screen. Since the frame rate was 30 frames/sec, we uniformly resampled interpolated RR interval time-series at the frequency of 30 Hz. In extraction of ANR-related indices, the limited frequency rages are 0.04–0.15 Hz for blood pressure and RR interval (Mayer wave (MW)-related signal), and 0.16–0.45 Hz for respiration and RR interval (RSA-related signal) [4]. Those correspond to the low-frequency (LF) and high-frequency (HF) power components of ANR-related indices. Then, we obtained the time-series of the ANR-related indices every frame with a 10-sec interval.

After estimating the averaged LF and HF power components during each image section for individual subjects, we determined the cybersickness intervals based on the following conditions [11], [13]: the LF power component is greater than the 120% of averaged LF power component, LF120, and the HF power component is less than the 80% of averaged HF power component, HF80. In addition to the cybersickness intervals, we presumed the triggered points that could emerge unpleasant sensation, tracing the time-series of the LF power component followed by a cybersickness interval backwards in time and locating a triggered point as a local minimum of the power.

RESULTS

Real Exercise

For healthy young eight male and five female subjects (21–24 yrs. old), we separated 103 trials into two groups based on pr_{RSA} before climbing [9]. In practice, the results showed that the trials exhibiting type-HRSA (high RSA ratio before climbing) demonstrated a temporary decrease in pr_{RSA} during climbing; it then recovered, especially during the following rest period [12]. The trials exhibiting type-LRSA (low RSA ratio before climbing) or with assist off demonstrated a temporary decrease in pr_{RSA} starting before climbing; it then recovered gradually toward the following rest period. Consequently, the average pr_{RSA} differed significantly between types-HRSA and -LRSA for every period, and between assist on and off before climbing (Fig. 4).

Figure 5 showed the scatter graphs between $\gamma_{ARV\text{-}trq}$ during climbing and pr_{RSA} after climbing in relation to the two groups. According to $\gamma_{ARV\text{-}trq}$, type-HRSA demonstrated a higher value than type-LRSA. Actually, almost all the samples with high $\gamma_{ARV\text{-}trq}$ over 0.6 concentrated in the region with pr_{RSA} over 25%. Note that there was no overlap region if pr_{RSA} before climbing was used.

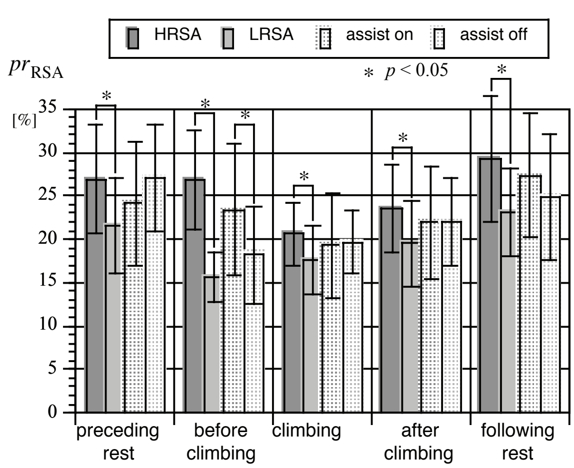

Fig. 4. RSA-related power ratio, pr_{RSA}, for HRSA and LRSA and for assist on and off, for three phases and during rest periods before and after.

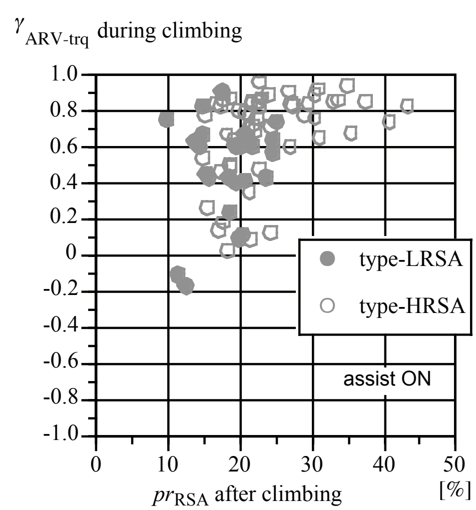

Fig. 5. For real exercise, scatter graphs between $\gamma_{ARV\text{-}trq}$ during climbing and pr_{RSA} after climbing.

Figure 6 shows the results for NASA-TLX, a subjective index. Significant differences occurred in physical demand, temporary demand, effort, and frustration between type-HRSA and type-LRSA and between assist on and off. That is, each was higher for type-LRSA or assist off than for type-HRSA or assist on.

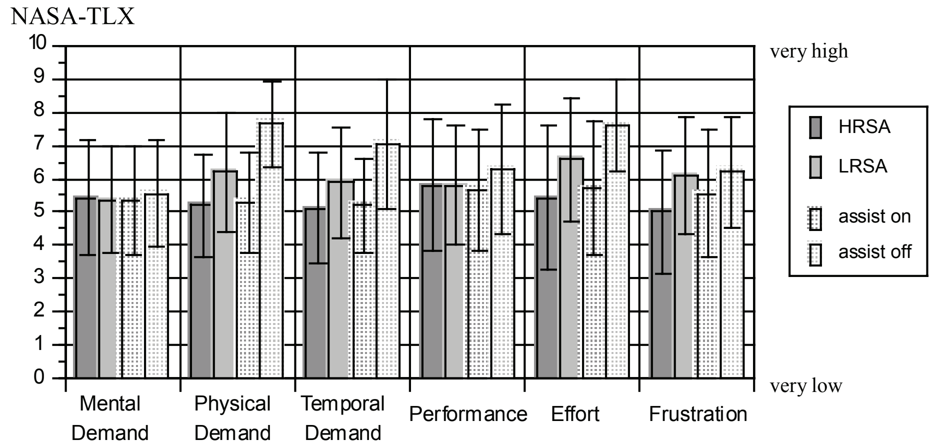

Fig. 6. Scores of NASA-TLX for HRSA and LRSA and for assist on and off.

Virtual Exercise

For healthy young 22 male and three female subjects (22.4 ± 1.0 yrs. old) participated in the experiments of virtual exercise. Using a frame-by-frame sliding window with a 1-sec interval, we estimated the time-series of the correlation coefficients, γ, between three GMV components (zoom, pan, and tilt) and each LMV components (up/down and right/left) at 25 regions of a screen. In the mountain bike section $|\gamma| > 0.8$ was located at the center and distant views for both the pan-(right/left) components and the tilt-(up/down) components, whereas $|\gamma|$ was low at the near view (**Fig. 7**) [13], [14]. Moreover, the intervals with high $|\gamma|$ were relatively long around 0–10 sec, 40–65 sec, and 90–105 sec. **Figure 8** shows the 36 trigger points for 25 subjects at each 10-s segment. According to the trigger points, the cybersickness intervals were around 61–70 s and 91–100 s segments.

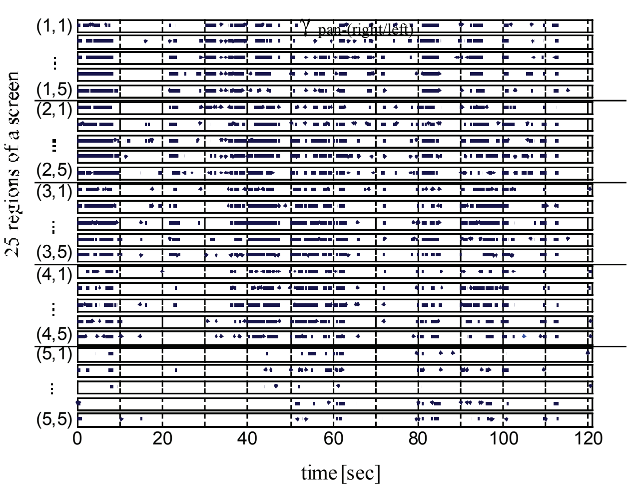

Fig. 7. Intervals with $|\gamma_{\text{pan-(right/left)}}| > 0.8$ with respect to time from top-left (1, 1) at distant view to bottom-right (5, 5) at near view.

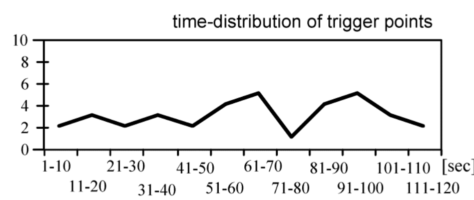

Fig. 8. Time-distribution of trigger points for the mountain bike section.

Based on the total score in the SSQ, we selected the mountain bike section as a typical cybersickness-inducing video image and the bike race section as a weaker-cybersickness video image. The difference of the total score increased for 8 of sampled 11 subjects. This means that subjects felt uncomfortable due to the vection-inducing video image. Among image sections the mountain bike section showed the highest number of subjects with unpleasant sensation for the simple questionnaire and the highest number of trigger points normalized by the elapsed time (Fig. 9). The image of mountain bike section caused typical cybersickness for almost all the subjects and the image of bobsleigh section did not always cause cybersickness.

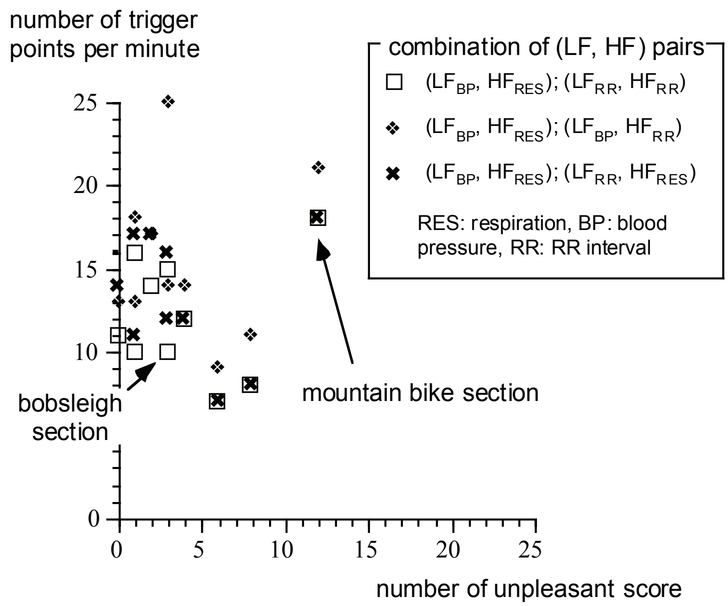

Fig. 9. Scatter graph between the number of subjects with unpleasant sensation and the number of trigger points per minute estimated from biosignals.

DISCUSSION

Preventing cybersickness is a key point for applying the virtual reality to the variety of potential fields, such as rehabilitation training and telesurgery, for a long time use. Unpleasant sensation has been evaluated by the subjective questionnaires and/or the autonomic nervous activity related objective indices. The autonomic nervous regulates the cardiovascular system that is continuously disturbed by the external and internal factors. Demands for the ANR would be evoked by the external trigger and enlarged by the internal factors. Regarding the external factors, the demands evoked by muscle contractions for real exercise is stronger than those evoked by visual stimuli with the first-person viewpoint for virtual exercise.   As we demonstrated, the external factors are now able to be measured as objective data. The internal factors are composed by the substantial characteristic and the acquired characteristic in the growth process. Muscle contractions are mainly related to the substantial characteristics, whereas visual stimuli are related to the acquired characteristic. Thus the demand by visual stimuli could be enlarged by the acquired characteristic, even though the physical intensity of external trigger is weak for a vision system. Thus subjective evaluation is still required to supplement the limited information of objective data.

There are two types of approaches for preventing unpleasant sensation triggered by external triggers: blocking external triggers and regulating autonomic nervous disorder. A simple approach for blocking external triggers for virtual exercise is closing the eyes. For regulating autonomic nervous disorder, the behavior of ANR for several kinds of external stimuli should be evaluated in terms of the capacity for recovering the conditions of the cardiovascular system. That is, it should be studied whether or not some external stimuli can suppress autonomic disorder evoked by visual stimuli.

There might be a dynamic threshold between positive and negative sensations even for the same stimuli, depending on the different conditions of ANR. For example, even though the same path for cycling exercise, a subject felt refreshment when the demand for cardiovascular system was relieved smoothly afterwards, but felt heavy when it took a longer time for recover than he or she expected. For virtual exercise, similarly, a subject felt unpleasant sensation when it took a long time for regulating autonomic nervous disorder. Thus, it needs to develop an evaluation process for determining a dynamic threshold between positive and negative sensations. Comparison of dynamic thresholds for several types of external stimuli would be helpful for designing how to regulate autonomic nervous disorder.

During a series of repetitive exercise, the function of ANR is to support continuous exercise by controlling the cardiovascular system. During real exercise, the muscle sympathetic nerve activity activated by strong muscle contractions properly requests autonomic responses. That is, the high demand for ANR occurs to preserve continuous real exercise. In Fig. 5, trials were separated by the ANR-related index, pr_{RSA}, before climbing, and those in type-LRSA demonstrated the low correlation of $\gamma_{ARV\text{-}trq}$. This might correspond to the mismatch between muscle activity and the pedal torque. The mismatch could enlarge muscular fatigue and then strongly request ANR after climbing. Moreover, the physical demand, temporal demand, effort, and frustration of the NASA-TLX (Fig. 6), a subjective index representing internal factors, showed the similar tendency as those by pr_{RSA}. Therefore, grouping by pr_{RSA} before climbing seems reasonable for evaluating the dynamic threshold, but pr_{RSA} after climbing should also be assessed in terms of the capacity of ANR.

According to Figs. 8 and 9, visual stimuli under virtual exercise with the first-person view point were weaker than those during real exercise for the ANR. Those included relatively large individual differences. Defining the cybersickness interval determined by the ANR-related conditions, we obtained the specific frequency components of the image brightness and the image motion vectors that could often disturb ANR [14]. However, the disturbance of ANR does not always link to unpleasant sensation (Fig. 9). For unpleasant scores below 5, the correlation was negative: there might be trigger points that cause some sensation, but not cybersickness. Further experiments are needed to completely assess the cybersickness intervals and trigger points in terms of different types of ANR-related indices. Then, the evaluation process for determining the dynamic threshold would be clarified.

CONCLUSION

For preventing cybersickness, we showed the feasibility study on the influence of sensory stimuli on the autonomic nervous regulation (ANR) for real and virtual exercise by presenting several approaches and results. Physical signals of external stimuli and biosignals as reactions at sensory systems are now available. For real cycling, we measured vehicle data, ECG, and EMG. For virtual cycling, the mountain-bike riding video with the first-person viewpoint, we measured video image data, vision-related biosignals, and ANR-related biosignals. The relationships between physical signals and biosignals were able to be investigated by signal processing and multivariate analysis. However, subjective indices were still required because ANR seemed to be affected both external factors and internal factors; internal factors are hard to be measured quantitatively. Accordingly, objective and subjective data should be finally combined for designing prevention of cybersickness for individuals.

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