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Effect of Respiratory Modulation on Relationship between Heart Rate Variability and Motion Sickness

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***Abstract*—This study investigates the interplay among heart rate variability (HRV), respiration, and the severity of motion sickness (MS) in a realistic passive driving task. Although HRV is a commonly used metrically in physiological research or even believed to be a direct measure of sympathovagal activities, the results of MS-effected HRV remain mixed across studies. The goal of this study is to find the source of these contradicting results of HRV associated with MS. Experimental results of this study showed that the group trend of the low-frequency (LF) component and the LF/HF ratio increased and high-frequency (HF) component decreased significantly as self-reported MS level increased (p<0.001), consistent with a perception-driven autonomic response of the cardiovascular system. However, in one of the subjects, the relationship was reversed when individuals intentionally adjust themselves (deep breathing) to relieve the discomfort of MS during the experiments. It appears that the correlations between HRV and MS level were higher when individuals made fewer adjustments (the number of deep breathing) during the passive driving experiments.**

I. Introduction

MOTION sickness (MS) is considered as a consequence of conflicts in perceptions originated from the visual, vestibular and proprioceptive systems [1]. Experimental MS is commonly induced in virtual reality (VR) environments [2] or by a rotating drum with or without optokinetic stimulation [3].

The MS symptoms are associated with perturbed sympathovagal activities [4]. Physiologically, HRV is a measure of the interplay of autonomic, humoral, and intrinsic influences on heart rate [5]. Thus previous studies have examined the relationship between MS symptom and sympathovagal activities by heart rate variability (HRV) [4, 6]. The studies that examined the relationship between the severity of MS and the automatic nervous system (ANS) typically compared averaged HRV before and during experimental motion exposure over a period and demonstrated that the development of motion sickness was accompanied by an increase in sympathetic activity and a decrease in parasympathetic activity [6]. Gianaros *et al*., [4] temporally correlated MS with fluctuations in HRV and demonstrated that parasympathetic activity decreased as severity of MS increased.

However, other studies indicated that there was no linear correlation between MS and HRV [7, 8]. Yet, other studies suggested that the relationship between HRV and sympathovagal activities could be influenced by subjects' active adjustments [9, 10]. For instance, HRV within the high-frequency band, as known as respiratory sinus arrhythmia (RSA), was considered as an index of cardiac parasympathetic tone [11]. However, Jerath *et al.*, [10] have shown that deep and/or slow breathing could increase the parasympathetic tone and decrease sympathetic activity. That is, the relationship between RSA and cardiac parasympathetic tone could be influenced by respiration.

This study hypothesizes that the source of inconsistent results of MS-effected HRV in the previous studies was that the subjects adjusted their breathing to relieve the MS symptoms during experiments, which altered the relationship between HRV and sympathovagal activities. To validate this hypothesis, this study uses a high temporal resolution and minimally intrusive apparatus to simultaneously measure the severity of MS, HRV and respiration rate to investigate the interplay among these parameters.

II. Methods

A. Subject

Five volunteers with normal or corrected-to-normal vision were paid to participate in this MS experiment. For accurate evaluation of HRV, subjects were instructed not to imbibe alcoholic or caffeinated drinks, or to participate in strenuous exercise a day prior to the experiments. Experiment protocol was approved by the Institutional Review Broad of Taipei Veterans General Hospital, Taiwan. Subjects were informed of the experimental procedure and written consent was obtained from each subject prior to the experiment

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B. Experimental setup

Experiments were performed in a dynamic Virtual-Reality (VR) environment comprising a 360º VR scene (Fig. 1A) and a real vehicle mounted on a motion platform with 6 degrees of freedom (Fig. 1B) [12]. Such dynamic VR environments provided a combination of visual, vestibular and proprioceptional sensations for inducing MS. To provide better protection to the subjects in the experiments, a video camera was set up in the immersive VR driving simulator to monitor subject's conditions.

Before data collection, all subjects were required to view the VR scenes for > 10 minutes until they had fully adapted to the VR environment. During each experiment, a subject sat alone and passively viewed the driving scenery as a passenger in the driving simulator. Each MS experiment had three consecutive phases without interruption (Fig. 1D): 10-min straight road as baseline (baseline session), 40-min long winding road for inducing MS (MS-induction session), and, finally, 15-min straight road for recovery (recovery session).

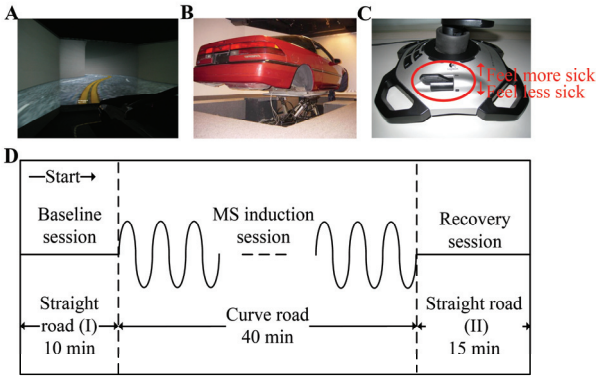

Fig. 1. The immersive VR-based dynamic-motion driving environment and a schematic diagram of an MS experimental paradigm.

C. Data acquisition

1) Behavior data: During the experiment, subjects continuously reported their MS levels using a slide-type switch on a commercially available joystick as shown in Fig. 1C. The position of the switch reflected the severity of MS continuously – for example, subjects could report their MS level by tuning the switch into upper or lower positions when they felt more or less sick. There is no immediate feedback to the subjects to show subject's MS level, but they were informed that the highest position of the switch represented severe nausea. Switch positions were digitized with a sampling rate of 60 Hz and 16-bit vertical resolution (0-65535) using emulation software. When the experiment began, the emulation software started sending trigger signals to the signal-acquisition system to synchronize MS levels, respiration, electrocardiograms (ECG) signals and riding events.

After finishing the experiment, each subject was required to fill a MS questionnaire [13] to recall the levels of MS during the experiment. In the questionnaire, the subjects used 6 levels (0 – 5) to report their symptoms of MS (with 0=no MS, 1=stomach awareness, 2=stomach discomfort, 3=slight nausea, 4=moderate, 5=severe nausea).

In the video camera, all subjects' motions can be observed clearly. The numbers of deep breathing were assessed by visual monitoring the ascending of the subject's clavicle and deep inhaling.

*2) Respiration data***:** Respiration data were acquired by respiratory effort sensory (BRAEBON respiratory effort sensory 2 foot double buckle effort belt), which uses piezoelectric technology to assess respiration and connects directly to amplified (NuAmps, Compumedics Ltd., VIC, Australia).

3) ECG data: Electrocardiogram signals were acquired by two electrodes in a modified leads II configuration [14]. The positive and negative leads were placed on the left arcus costalis and right clavicle, respectively. The ECG signals and respiration signal were amplified and recorded at a sampling rate of 500 Hz, and notch filtered at 60 Hz.

D. Data analysis

1) Behavior data: The digitized MS levels were rescaled into 6 levels (0–5) according to each subject's MS questionnaire. First, the digitized MS levels (0–65535) were divided by its maximum value, and then multiplied by individual subject's maximum MS value reported in the questionnaire (0–5). This normalized MS levels were then smoothed using a 5-min moving window overlapped by 4.5 min (the same window criterion as used in analyzing HRV, respiration rate). Fig. 2A shows a typical smoothed MS time series.

*2) Respiration data***:** The respiration rate measures the number of breaths taken per minute [15]. The respiration rate was calculated according to the method developed by [16]. The respiration rate was then smoothed using a 5-min moving window overlapped by 4.5 min (the same window criterion as used in analyzing MS level, HRV) (Fig. 2B).

3) ECG data: The HRV was analyzed according to the modified procedures developed by [17]. Briefly, the (QRS) peaks were first identified in the digital ECG signals using spike-detection algorithms. The QRS rejection procedure was then utilized to remove the irregular QRS complex resulting from noise or un-related behavioral responses.

The R-R intervals outside 0.5–1.3 sec (or mean±3 SD) were eliminated from further analysis. The validated R-R values were subsequently re-sampled and interpolated at the rate of 250 Hz to accomplish the continuity in time domain**.** The tachogram was analyzed by fast Fourier transform (FFT) with a 5-min Hamming window overlapped by 4.5 min (the same window criterion as used in analyzing MS level, respiration rate). This study focused on three frequency bands: the VLF (0.003–0.04 Hz), LF (0.04–0.15 Hz), and HF (0.15–0.4 Hz). The powers of the LF and HF were normalized by total power minus the power of the VLF, that is, NLF = LF / (total power − VLF) * 100% and NHF = HF /

(total power − VLF) × 100%, where total power = LF + HF + VLF. The natural logarithmic transformation was applied on the LF/HF ratio, that is, LF/HF ratio = log (LF/HF). The time series of the NLF, NHF, and LF/HF ratio were then time averaged (Matlab Curve Fitting Toolbox, function "smooth" with a moving setting of 25) (Fig. 2C).

To assess the changes in HRV (NHF, NLF and LF/HF ratio) under different levels of MS, this study defined the periods of low- and high-MS levels. The high-MS level window was defined as the period during which a subject's MS rating was 75 – 100 % of maximum MS (shaded areas in Figs. 2). The low-MS level window was defined as the period with the same length as the high-MS level window, but low-MS level window started from the beginning of the baseline session. Fig. 3 shows the averaged HRVs and respiration rate as a function of MS level for each of the five subjects.

4) Statistical analyses: To quantitatively assess the changes in HRVs and respiration rate under different MS levels across subjects, the individual subject's HRVs and respiration rate were first normalized into z-scores with respect to the mean and standard deviation of variables during the low-MS level period. Then, the normalized HRVs and respiration rate of 5 subjects were divided into two (low- and high-MS level) groups. Wilcoxon rank sum test was then used to assess the statistical significance of the differences of the normalized HRVs and respiration rate at different MS levels.

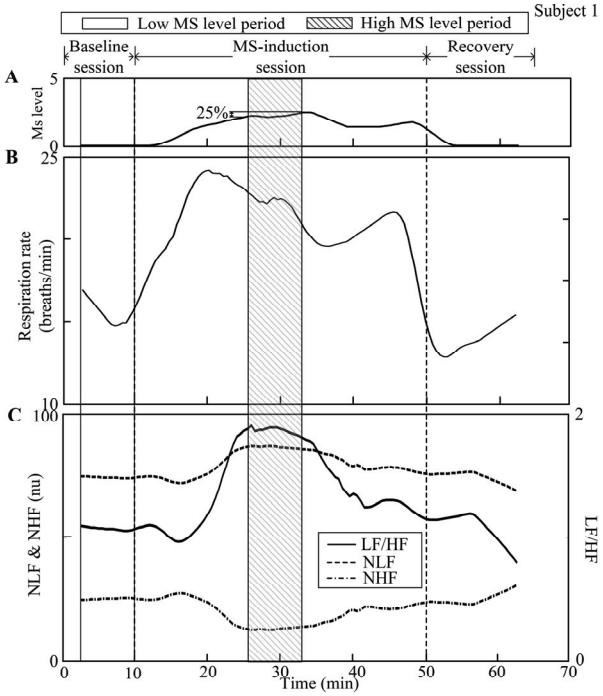

Fig. 2. Changes in (A) MS level, (B) respiration rate and (C) HRV during the driving experiment.

III. RESULTS

Fig. 2 shows the changes in the HRVs (smoothed NLF, NHF and LF/HF ratio), respiration rate and MS levels over the entire experiment for a sample subject (subject 2).

The study first assessed the statistical difference of MS level, HRVs and respiration rate between low- and high-MS level groups across subjects. The group trends showed that MS level, NLF, LF/HF ratio and respiration rate increased and NHF decreased during high-MS level group, compared to those during low-MS level group (p<0.001). Fig. 3 shows the mean of MS levels, HRVs and respiration rate under low- and high-MS level periods for each of the 5 subjects. Most subjects (n = 4) consisted with the group trends. One subjects had opposite HRV responses to those of the 'typical' subjects (n=4) during the high-MS level period. Specifically, the atypical subject had decreased mean NLF and LF/HF ratio, and increased mean NHF values during the high-MS level period. This subject had the lowest respiration rate than the typical subjects during the experiment (Fig. 3E, bottom trace)

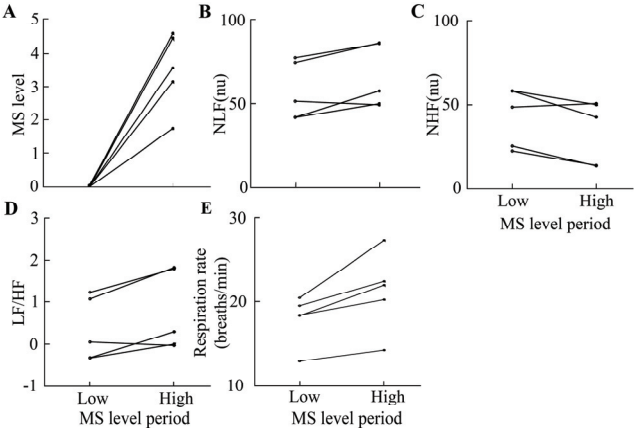

Fig. 3. Averaged (A) MS level, (B) NLF, (C) NHF, (D) LF/HF ratio and (E) respiration rate during low- and high-MS level periods across 5 subjects.

Next, this study utilized the spearman rank correlation coefficients to quantitatively assess the correlations between changes in HRV (NLF, NHF and LF/HF ratio) and self-reported MS levels. Table I shows the correlation coefficients between the MS levels and NLF and the number of deep breathing which was observed from the video recordings. In general, the NLF and LF/HF ratio were positively correlated with the MS level, while NHF was negatively correlated with the MS level.

TABLE I The spearman rank correlation coefficient

The number of subject	S1	S2	S3	S4	S5
Correlation coefficient between MS and NLF	0.8	0.6	0.5	0.4	-0.6
The number of deep breathing	29	50	60	56	69

IV. DISCUSSIONS

This study explores the interplay among HRV, respiration, and severity of MS during a realistic passive driving task. Results of this study showed that HRVs derived from the recorded ECG signals during low-MS level period differed

from the ones during high-MS level period for most of the subjects, consistent with previous HRV studies noted that exposure to motion sickness stimulation would increase cardiac sympathetic while decrease cardiac parasympathetic activities [4, 6, 13]. However, one subject (atypical) had autonomic responses opposite to those of the majority of the subjects (n=4) during MS exposure. Close inspection of his video recording found atypical deep breathing throughout the experiment. He also confirmed that he felt sickness immediately after the beginning of the experiment and constantly adjusted himself to relieve the sick feeling.

Results of a Spearman's rank correlation coefficient analysis showed that the correlations between changes in MS level and NLF were related to number of deep breathing (self adjustment) as, in general, the higher numbers of deep breathing, the lower correlations between NLF and severity of MS. The atypical subject has the highest number of deep breathing and an opposite (negative) correlation between severity of MS and NLF, compared to typical subjects.

NHF has been thought as a measure of the vagal action of the heart, whereas NLF has been linked to sympathetic action of the heart [11]. However, such a classification may sometimes fail, for example when the respiration is irregular or very slow or the respiration rate overlaps with the LF band [9, 10]. In other words, HRV could be considerably influenced by respiration. Our results were consistent with the reports suggesting that the irregular respiration may affect the relation between HRV and sympathovagal activities when the conscious subjects actively change their respiration depth or rate [9, 10] and then affect the relation between MS and sympathovagal activities, as reflected in HRV. Therefore, one needs to take into account or control the respiration rate when she or he wants to assess the relationship between HRV and MS severity.

V. Conclusion

This study showed that MS would increase sympathetic activities and decrease parasympathetic, as indexed by HRV. However, this relationship could be altered by irregular respiration due to subject's adjustment to relieve the discomfort of MS. In general, this pilot study on 5 subjects suggested that the correlation between HRV and MS level inversely correlated with the number of deep breathing (self-adjustments) made by subjects.

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