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Heart Rate Variability and Motion Sickness During Forklift Simulator Driving

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The goal of the study was to determine the effect of a 1-h hour long forklift truck virtual simulator driving on the mechanism of autonomic heart rate (HR) regulation in operators. The participants were divided into 2 subgroups: subjects with no definite inclination to motion sickness (group A) and subjects with a definite inclination to motion sickness (group B). Holter monitoring of electrocardiogram (ECG) signal was carried out in all subjects during the virtual simulator driving. For 12 consecutive epochs of ECG signal, HR variability analysis was conducted in time and frequency domains. In subjects with a definite inclination to motion sickness after ~30 min of the driving, changes in parameter values were found indicating an increase in sympathetic and parasympathetic activity with parasympathetic dominance.

motion sickness   heart rate variability   spectral analysis   forklift truck virtual simulator

1. INTRODUCTION

Driving simulators is a safe training alternative for drivers-operators in acquiring driving skills and appropriate behavior in dangerous situations. However, some subjects undergoing VE (virtual environment) simulator training experience unwanted side effects such as motion sickness, like symptoms called simulator sickness (SS). SS symptoms include, e.g., dizziness, nausea, eyestrain, feelings or warmth, headache, disorientation, and fatigue [1].

Rotation the body about its vertical axis and tilting the head slightly out of the axis of that rotation is a laboratory stimulus applied in aviation to evoke motion sickness [2, 3, 4, 5]. Such motion conditions generate Coriolis effects. Coriolis test evokes nausea, likewise motion of a real vehicle, e.g., boat, airplane or car while swerving or braking rapidly [2]. The test allows to identify individuals with an inclination to motion sickness and to determine the degree of intensity of subjective sensation indicating motion sickness. In aviation, it has been assumed that optokinetic nausea is similar to nausea experienced under real flight conditions [5].

Recognition of subjects who may experience VE SS is important as discomfort resulting from this sickness may affect task performance during simulated driving and evaluation of training effectiveness [6]. Determining the time of exposure to simulator environment virtual with no physiological responses and VE SS, which may affect the quality

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of task performance is essential for planning a correct and effective training.

The goal of the study was to verify whether there is any relation between the inclination to motion sickness in forklift truck VE simulator operators revealed by Coriolis test and the changes observed in autonomic cardiovascular control mechanisms in subjects undergoing training on forklift truck VE simulators. The hypothesis that heart rate variability (HRV) parameters indicate a different response of the sympathetic and parasympathetic components of autonomic heart control to VE simulator training in subjects with no or slight inclination to motion sickness and in subjects with apparent symptoms of motion sickness was verified. Additionally, an attempt was made to determine the time of autonomic nervous system (ANS) response development, manifested by significant changes in HRV parameters, from the moment of beginning of the forklift truck VE simulator test.

2. MATERIALS AND METHODS

2.1. Subjects

The sample comprised 24 healthy volunteers aged 20–26 years (mean age = 22.9) with normal vision, and not on any current medication. The study was a randomized controlled trial.

The participants were divided into two groups according to the degree of inclination to motion sickness. The degree was evaluated based on the test carried out at the Military Institute of Aviation Medicine. The test was performed in the seated position on the electronically controlled chair (Micromedical Technologies, USA). During a 2-min chair rotation with the speed of 120°/s the subject performed alternant head movements from the right to the left shoulder in the rhythm imposed by metronome sound. During the test the subjects were observed for changes in face skin color and accumulation of chaotic head movements. Then, the subjects' subjective sensations, indicating the intensity of motion sickness, were recorded. The symptoms associated with the Coriolis test [2] were graded using the following criteria: 0 degree—no complaints, or apparent symptoms of motion sickness; 1st degree—worse well-being, slight pallor; 2nd degree—general weakness, discomfort in the abdominal cavity, nauseogenicity, excessive diaphoresis, salivation; 3rd degree—general malaise, rapid pallor, acute nausea, cold sweat, vomiting (test interrupted).

Next, the subjects were divided into two groups. Group A consisted of 11 subjects without an disposed to motion sickness (0 and 1st degree). Group B included 13 subjects with an definite inclination to motion sickness (2nd and 3rd degree).

2.2. Experimental Setup

The study was carried out in an air-conditioned room having parameters assuring thermal comfort, using forklift VE truck simulator carrying loads in a virtual industrial building. The VE simulator is part of the equipment of the Laboratory of Mechanical Hazards at the Central Institute for Labor Protection – National Labour Institute (CIOP-PIB). Ethical approval was granted by CIOP-PIB's Ethics Committee.

Figure 1 presents the forklift truck VE simulator (left) used in experiments and the VE simulator cockpit in the VE (right). The cockpit construction and the arrangement of control elements resemble these of one of the forklift trucks manufactured by a European company.

During the experiment a head mounted display (HMD) Visette 45 SXGA (Virtual Realities, USA) was used with field of view (FOV) ±45° diagonal, color depth 24 Bits, contrast ratio >200:1. The resolution was 1024 × 768. The subjects driving forklift truck were immersed in a VE using the aforementioned HMD, enabling stereoscopic vision of the environment and stereophonic reception of sound.

The correctness of location constancy for essential points in the VE of the VE simulator was checked by recording data concerning the subject's head location, using a magnetic sensor mounted in the HMD, and the detector mounted behind the operator. The uncertainty of position according to the manufacturer's tracking system data was 0.019 m. The sensor was calibrated according to the manufacturer's recommendations by static measurements in the

Figure 1. Forklift truck VE simulator used in experiments (left). VE simulator cockpit in a virtual environment (right). *Notes.* Speed—speed of the forklift truck virtual environment (VE) simulator moving in a VE (km/h); height—height of fork position (m) (the fork supports the load in the VE simulator); tilt—inclination of the mast of the simulated forklift truck (°); errors—number of errors (e.g., collision between the simulated forklift truck and elements of infrastructure) made by the operator during driving, recorded by the VE simulator acquisition system.

Figure 2. Picking the load in the virtual environment to carry it along the route determined in the virtual environment to its destination.

points with known geometric coordinates. No significant changes in time were recorded.

All the operators carried loads of 0.5 m and 1 m in height on identical EUR 1.2 m × 0.8 m pallets. Each forklift truck VE simulator operator picked the load in a defined place in the VE (e.g., the place in Figure 2) and drove it along a defined route to its destination. The instructor was present close to the driver providing support, or giving advice when needed.

2.3. ECG Signal Recording and Analysis—the Defined Parameters

Electrocardiogram (ECG) signal was recorded using Holter's method, enabling to obtain record noninvasively, without interfering the simulator driver in his/her duty performance. The Medilog Optima apparatus (Oxford Medical Systems, UK) was used, meeting the requirements in terms of quality and HRV analysis, determined by the European Society of Cardiology and North American Society of Pacing and Electrophysiology. The record was analyzed using a stationary system of analysis. The ECG signal was recorded in beat-to-beat mode using Medilog Oxford recorders series MR45. The ECG signal was recorded on a magnetic tape. HRV analysis was carried out using Medilog Optima system program. For the analysis, R-R interval sequences, free of ventricular and supraventricular pacing were selected. HRV parameters were determined in the time and frequency domains from the linearly sampled tachograph. Power spectrum was determined by means of Fast Fourier Transformation FFT [7].

For each sequence of RR intervals, four parameters, describing HRV were determined. For time analysis, the mRR (ms) parameter, being the arithmetic mean of all sinus rhythm RR intervals, was selected.

In the frequency domain, HRV was described using power spectrum values in the low frequency (LF) band (0.04–0.15 Hz) and high frequency (HF) band (0.15–0.40 Hz), in ms^2, and the LF/HF ratio. The HRV defining parameters were determined for 12 consecutive 5-min epochs of the ECG record, from the moment of beginning the virtual simulator driving to the end of driving.

2.4. Statistical Analysis

Nonparametric tests were used. These were Friedman ANOVA tests. The analysis also served the evaluation of the differences in HRV parameter values during the hour-long simulated lifting truck driving, separately in two groups of subjects: not disposed (group A) and definitely disposed (group B) to motion sickness as confirmed by the Coriolis test. For the comparison of the values obtained in two different moments of the simulator test, the pair sequence Wilcoxon's test was applied; $p = .05$ was considered statistically significant.

3. RESULTS

Figures 3–4 present the mean values (*SD*) of mRR, LF, HF and LF/HF parameters, determined for 12 consecutive epochs of the ECG signal, recorded during the hour long lifting truck simulator test.

In group A, including subjects disposed to 0- or 1st-degree motion sickness, the Friedman ANOVA test did not reveal significant differences for any of the studied parameters (mRR, LF, HF and LF/HF). In group B, including subjects disposed to motion sickness of the 2nd or 3rd degree, significant differences were observed in the mRR (χ^2 (13.11) = 47.209, $p < .0001$) and LF (χ^2 (13,11) = 23.503, $p < .024$) parameters. In this group, the analysis of difference in the values of parameters determined for the first half of the simulator test (from the very start to 30 min) showed significant differences only in the values of mRR (χ^2 (13,5) = 11.740, $p < .0038$). During the second half of the simulator test (30–60 min), significant differences were noted for mRR (χ^2 (13.5) = 26.344, $p < .0001$) the LF/HF ratio (χ^2 (13.5) = 16.033, $p < .007$).

In group-A subjects, the hour-long forklift truck VE simulator test did not result in any changes in autonomic HR regulation. Conversely, in group-B participants, a gradual increase in RR was observed. During the first 5 min, the mean mRR value was 813 ms (*SD* 75 ms) while during the last 5 min it was 899 ms (*SD* 98 ms) (Wilcoxon test $p < .006$). In group B, after ~30 min of the simulator test, a decrease in LF/HF ratio was observed. During the 35th–40th minute it was 5.435 (*SD* 2.03) and during the last 5 min of the test it was 3.635 (*SD* 1.907) and was significantly lower at $p < .001$ (Figures 3–4).

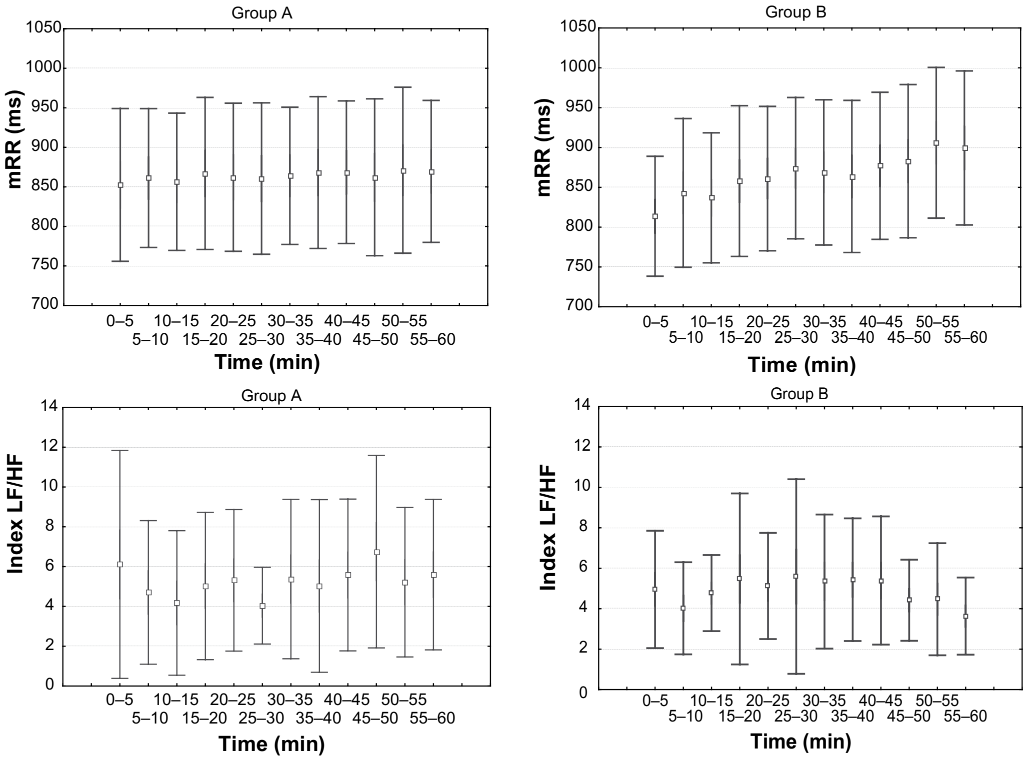

Figure 3. Changes in the length of RR intervals (*M* ± *SD*) and low frequency/high frequency (LF/HF) ratio values, obtained during consecutive 5-min epochs of ECG record of the hour-long forklift truck virtual environment simulator driving *Notes.* Group A—subjects disposed to 0- or 1st-degree motion sickness, Group B—subjects disposed to 2nd- or 3rd-degree motion sickness.

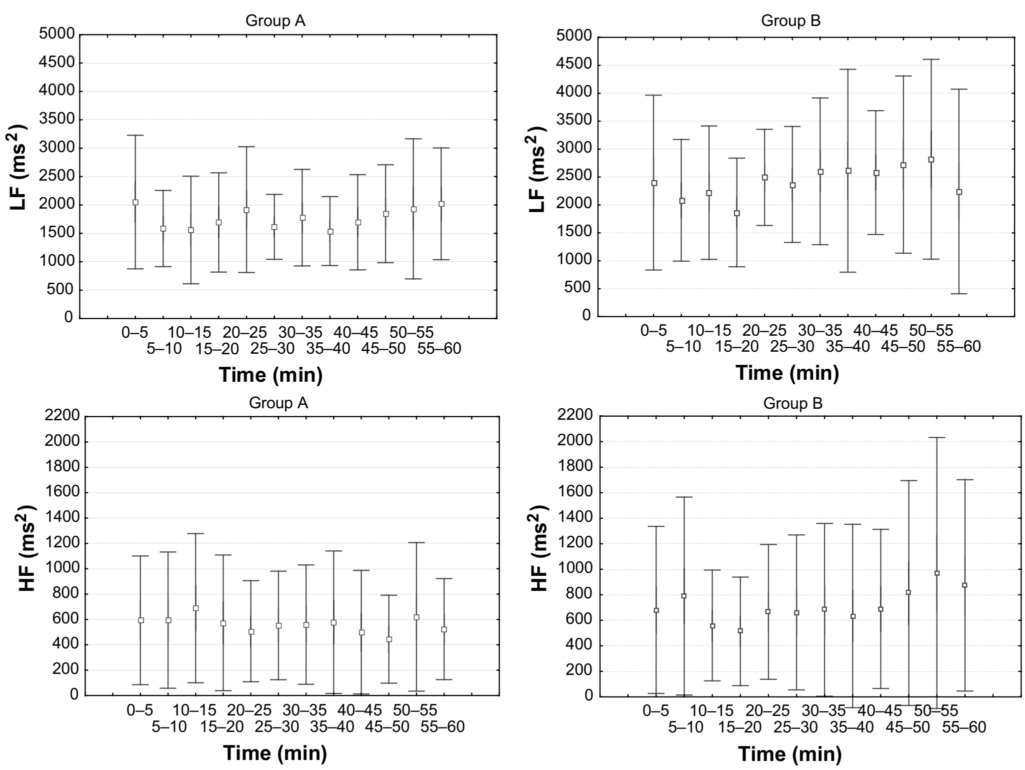

Figure 4. Spectrum power (*M* ± *SD*) in the low and high frequency bands, obtained during consecutive 5-min epochs of ECG record of the hour-long forklift truck virtual environment simulator driving *Notes.* Group A—subjects disposed to 0- or 1st-degree motion sickness, Group B—subjects disposed to 2nd- or 3rd-degree motion sickness.

4. DISCUSSION

It is assumed that various manipulations within the performed task, involving, e.g., change of task requirements, evoke different responses from autonomic HR control [8]. HR may increase under the following circumstances:

- sympathetic activation is not combined with parasympathetic activation;
- sympathetic activation exceeds parasympathetic activation;
- parasympathetic inhibition exceeds sympathetic inhibition.

According to Backs, Lenneman, Wetzel, et al. this physiological evaluation is a valuable research method, assessing workload in, e.g., drivers [8]. According to Berntson, Cacioppo and Quigley, interpretation of HR changes may be facilitated by determining the relation between the kind or degree of psychophysical load during a defined task performance and the type of autonomic control mode psychophysiological mapping [9].

Backs describes two important limitations of using HR values to define workload [10]. Firstly, HR does not necessarily change with changing task requirements, even with apparent response from the ANS, manifested by changes in spectrum power in LF band (sympathetic activity) or HF band (parasympathetic activity). Secondly, the observed changes in HR may result from multiple patterns of responses from the nervous system.

The decrease in LF/HF ratio values manifesting autonomic balance and observed after ~30 min from the beginning of the test in group B with disposed to 2nd- and 3rd-degree motion sickness confirmed by Coriolis test may indicate a decrease in sympathetic predominance as related to the parasympathetic system. This explains the increase in RR interval length, observed in this group after ~30 min from the beginning of the simulator test.

The test was planned so as the scope of tasks performed, involving forklift truck VE simulator operations was similar for all the participants. The examiner, however, did not have any influence on the time and way of task performance. The participants committed various errors. If they realized this, the lapses might influence their emotions, translating into physiological responses including HR. We may assume that the incidental nature of these episodes did not affect the direction of changes in mean parameter values, determined during consecutive 5-min epochs, but may have affected the increase in data dispersion.

The occurrence of VE SS symptoms and the degree of response intensification may be connected with the extent of immersion in virtual reality and thus, with the type of simulator [11, 12, 13, 14]. HMD provides a relatively deep immersion in VE, however, it is somehow inconvenient for the user. The examiners tried to minimize this inconvenience. The HMD was mounted on each operator's head in a way allowing to minimize the stress exerted on head and neck muscles, with no additional load resulting from electric wire tension. We may assume that the discomfort level was similar in each participant of the experiment.

As the HMD did not require adjustment of the positioning of monitors at each subject's eye level, only the subjects, who did not require sight correction (did not wear glasses or contact lenses), took part in the experiment. During the test, all the participants were asked if the vision was good. Since no one reported any problems, it was assumed that the sight load was not too high.

It was noted that after the hour-long VE simulator training, the participant's subjective sensations did not always indicate good tolerance to the VE conditions of the forklift truck simulator exposure. The symptoms indicating VE SS were noted also in the participants without the disposition to motion sickness, confirmed by Coriolis test. The literature pertaining to simulator studies reports that proneness to SS may be increased by such factors as fatigue, sleep loss, acute stress, gastric ailments or meal consumption immediately prior to the test [15, 16, 17, 18, 19, 20, 21]. All the participants had been informed about such a possibility before the study was conducted. However, it was impossible to control their behavior several hours prior to the study. Thus, the division into subgroups was guided only by the objectively confirmed inclination to motion sickness, not by the symptoms observed following the hour long simulator test, which might suggest simulator sickness development.

5. CONCLUSIONS

In the participants not disposed to motion sickness, the hour-long forklift truck VE simulator driving did not result in significant differences in HRV parameter values. The participants disposed to motion sickness experienced HR slowing manifested by the increase in RR intervals and a significant decrease in sympathovagal balance coefficient after ~30 min of immersion in VE. The changes in spectrum power values observed in these subjects in LF and HF frequency bands were statistically insignificant, but indicated a simultaneous increase in sympathetic and parasympathetic ANS activity with a significant decrease in the former.

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