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Preventing Drowsiness by Heartbeat-Synchronized Vibration

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Abstract—**The purpose of this study is to develop a stimulation, which has an active physiological influence to prevent severe driver drowsiness while driving. This paper presents a heartbeat-synchronized vibration, which is the rhythmic pulsation of a motor with each beat of the heart, as an effective means to ease drivers' slight deprivation of oxygen with the appearance of cardiorespiratory coordination. The effects of this stimulation were confirmed by the results of an experiment done in cooperation with 15 subjects. The results showed that cardiorespiratory coordination appeared under the stimulation and it played an active influence on the oxygen supply to the body. We conclude that the vibratory stimulation has an active influence to prevent drowsiness. It might be effective to prevent severe drowsiness while driving.**

Index Terms—**Drowsiness, heartbeat, respiration, vibration, synchronization, cardiorespiratory coordination.**

I. Introduction

DROWSINESS is one of the major contributors to car accidents. The National Highway Traffic Safety Administration (NHTSA) estimated that about 100,000 drowsy related crashes happen each year. Those crashes result in approximately 1,500 fatalities and 71,000 nonfatal injuries. The annual monetary loss is estimated to be about $12.5 billion [1]. Another report showed that 54% of drivers (105 million) experienced drowsy driving at least once in the past year, and 28% (54 million) did so at least once per month [2]. Drowsy driving is more likely to occur when drivers lack sleep and are fatigued, or when they are driving around the peak times for crashes to occur (2:00 a.m., 6:00 a.m., and 4:00 p.m.) [3]. To prevent the drowsy related crashes or near misses, the best way is to get adequate sleep, take a break or a nap constantly, and avoid driving at times when one would normally be asleep. However, these precautions cannot be practiced without drivers' awareness about drowsiness risks. Even if they are aware of it, such steps are not always practicable in every driving situation. Therefore, mechanical methods that ease drivers' drowsiness are needed to improve safe driving.

Many automobile companies and institutions have been studying ways to awake drowsy drivers. Audible or text alarms [4][5], vibratory stimulation by seat belts [6] or steering [7] are used to rouse drivers. These methods are practical when drivers are in severe drowsy situations such as closing their eyes or nodding off. However, this is already too late. We need a method that prevents such driver drowsiness. The point of easing drowsiness is to supply enough oxygen to the brain. It is because drowsiness involves decreased of prefrontal activities [8].

The purpose of this study is to develop a stimulation, which has an active physiologic influence to ease drowsiness and prevent severe driver drowsiness. In this paper, we confirmed that the heartbeat-synchronized vibration is effective to ease drivers' slight deprivation of oxygen during drowsiness by enhancing cardiorespiratory coordination. The coordination has two types, respiratory sinus arrhythmia (RSA) and cardiorespiratory phase synchronization (CRPS). RSA is the phenomenon by which heart rate increases during inspiration and decreases during expiration. When RSA appears in heart rate variability, efficiency of pulmonary gas exchange improves [9]. CRPS is a coupling of respiration and cardiac rhythm, and is considered to be different from RSA [10]. RSA is the modulation of cardiac timing by pulmonary afferents activities. Unlike CRPS is thought to be a modulation of inspiratory timing by hemodynamic afferents activities [11]. Galletly et al. reported that when CRPS is concerted with RSA, it may optimize the performance of the thoracic pump and helps matching of cardiac filling [12].

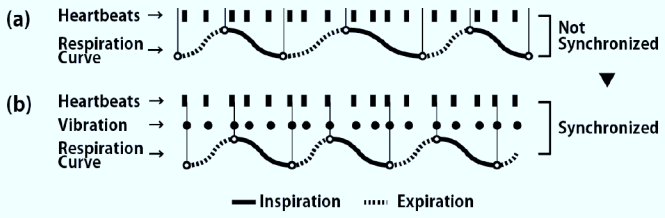

Figure 1. Changes of breath timing by heartbeat-synchronized vibration. (a) without vibration. (b) with vibration.

Our idea is to induce the CRPS by controlling timing of breath using heartbeat-synchronized vibration to ease the drowsiness. As Figure 1 shows, the pulsations serve as an indicator of timing of inspirations and expirations to make it synchronize with heartbeats. We verified the effect of this stimulation in this paper.

II. Methods

The experiment was done in cooperation with 15 subjects (6 males, 9 females, age: 20.9 ± 1.6) who provided written informed consent. The subjects drove an hour with a driving simulator. A highway tunnel was selected as a driving scene to make the subjects drowsy and to reduce influences of landscape changes. A plasma display (TH-50PHD6,

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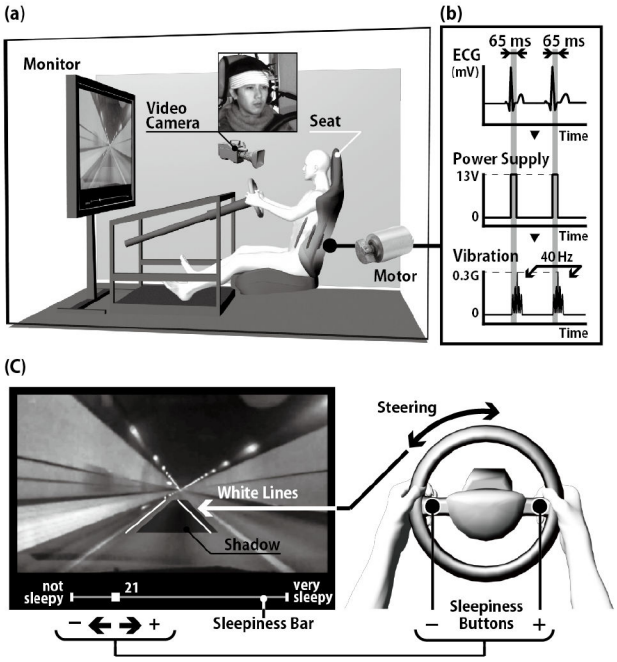

Figure 2. Environment and equipment of the experiment. (a) Driving simulator. (b) Heartbeat-synchronized vibration. (c) Tracking task and the subjective sleepiness level indication.

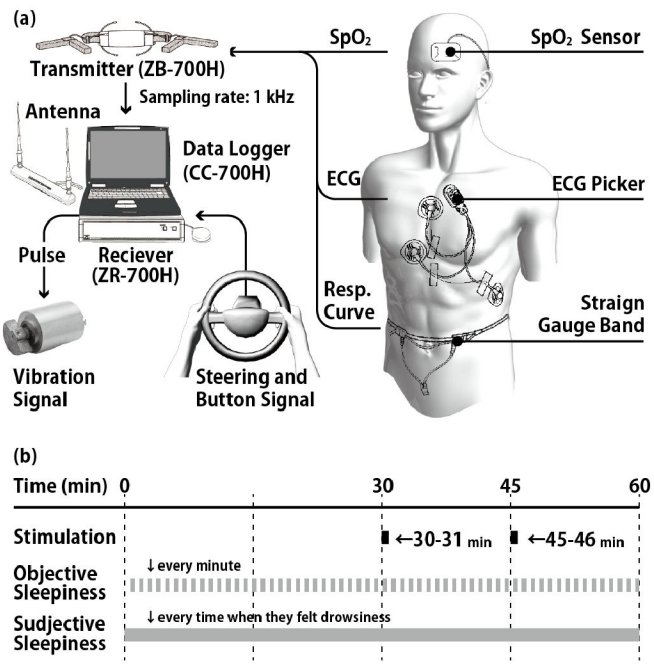

Figure 3. Devices and protocol used in experiments. (a) Bio-signal sensors and I/O devices. (b) Protocol of experiment.

Panasonic) was used for the screen and the subjects kept their head 2 meters away from the display. The vibratory stimulation was given to the subjects at 30 and 45 minutes from the beginning for 1 minute duration at each occasion (Figure 3(b)). The subjects kept driving without the stimulation in the first 30 minutes to become drowsy and tired. The second stimulation was given after the interval of 15 minutes from the first stimulation in order to avoid influences of the first one. In order to investigate the involuntary breath changes by the stimulation, no instructions were given to the subjects to control their breath timing while the stimulations were given to them. The stimulation was given to the subjects from a motor attached on the seat back frame. The motor vibrated every time a R-wave appeared on the electrocardiogram (ECG) (Figure 2(b)). The motor was vibrated for 65 milliseconds on each pulsation for strength and frequency of the vibration 0.4 G and 40 hertz, respectively. This amount was settled to reduce the negative impression of the vibration [13].

The subjects were assigned to steer the wheel to keep the white lines on the edges of the shadow projected on the screen to simulate driving (Figure 2(c)). The shadow repeated moving right to left at a frequency of 0.1 hertz.

Three points of effects on the stimulation were verified. The first point was the appearance of CRPS and RSA by the stimulation. The second point was the increase of oxygen supply to the body. The third point was the decrease of drowsiness. These points were verified by indices of ECG and respiration curves, oxygen saturation (SpO_2), and objective and subjective sleepiness levels, respectively. ECG, respiration curve, and SpO_2 were recorded through the telemeter system (WEB-7000, Nihon Kohden) with 1 kilohertz sampling frequency. ECG was obtained from electrodes attached to the chest and respiration was from a strain gauge bandaged at the abdominal region of the subjects. SpO_2 was measured by two frequencies of light (red and infrared) from a pulse oximeter attached on the left forehead. These bio-signals were transmitted to the receiver (ZR-700H, Nihon Kohden) and were recorded into the data logger (CC-700H, HP) (Figure 3(a)).

The subjective sleepiness levels were obtained via buttons on a steering wheel (Figure 2(c)). Subjects marked the sleepiness levels on the bar shown on the bottom of the screen by pressing the buttons every time when they felt sleepiness changes (Figure 3(b)). Sleepiness was graded according to 100 levels and was recorded by the data logger through the receiver. Objective sleepiness levels were evaluated every minute (Figure 3(b)) by two observers monitoring the face of the subject captured by a video camera (Figure 2(a)). We used the evaluation method, which developed by the New Energy and industrial technology Development Organization (NEDO) [14]. Sleepiness was graded according to 5 levels.

III. Analysis

Three bio-signal indices and two sleepiness indices were obtained for the analysis of the three effects mentioned above. A synchrogram was used for the quantification of CRPS. It is a visualization tool that helps to observe the phase synchronization between two oscillators [15]. The frequency domain method was used for the quantification of RSA. We estimated high-frequency (HF) component (0.15 - 0.40 hertz) magnitude from the spectrum of R-R intervals (RRI). SpO_2

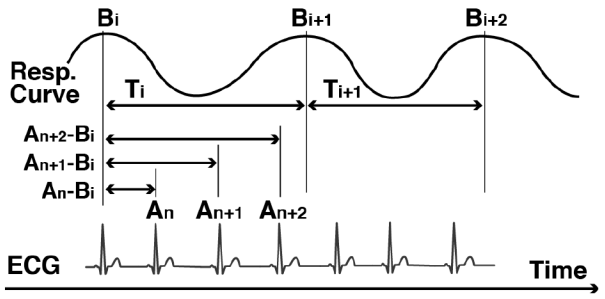

Figure 4. Calculation of a phase difference between respiration and heartbeats.

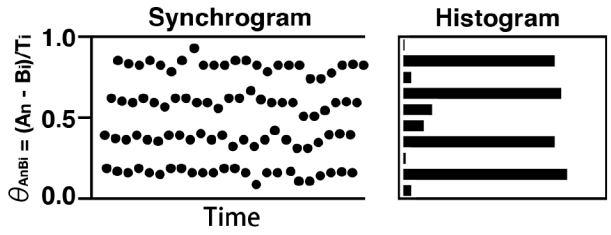

Figure 5. Histogram of a synchrogram.

was used for the reference of oxygen supply into the body. Objective and subjective sleepiness levels were used for indices of drowsiness. Calculations of these indices are shown.

A. Synchrogram of respiration curve and heartbeats

The synchrogram was obtained by calculating a phase difference between oscillator A and B during every cycle of oscillator B. For the detection of CRPS, the respiration curve was defined as oscillator B and the subject's heartbeat as oscillator A (Figure 4). The analysis of inspiration was done within the corresponding heartbeats. When there is a peak between B_i to B_{i+1} in an oscillator B cycle (T_i), the interval of B_i to A_n is A_n-B_i. In the condition of $B_i < A_n < B_{i+1}$, the phase difference between these two rhythms ($\theta_{An,Bi}$) is defined as $\theta_{An,Bi} = (A_n - B_i) / T_i$. When the two rhythms are synchronized, specific phase differences appear on the synchrogram and it can be seen as stripe patterns (Figure 5). The histogram is used for quantifying this synchronization. It characterizes the amount of phase difference in each bin, dividing a cycle into equal amounts of N. For example, when the two rhythms are synchronizing in a ratio of 4 to 1, 4 peaks appear on the histogram. We used the standard deviation to quantify the histogram obtained from the phase differences (formula (1)). When no peaks have been seen on the histogram, σ becomes smaller.

$$\sigma = \sqrt{\frac{1}{k}\sum_{i=1}^{k}(F(i) - F_{avg})^2} \quad (1)$$

The range of $\theta_{An,Bi}$ is divided into same interval of bins and σ was calculated for 50 continuous heartbeats per minute. F(i) is the distribution frequency of each bin (i), and F_{avg} is the average. The increase of σ stands for the appearance of strong CRPS on subjects' heart-rate variability.

B. High frequency (HF) component

The common technique for detecting RSA is the frequency domain method, which estimates HF component (0.15 - 0.40 hertz) magnitude from RRI spectrum. The autoregressive model was used for the calculation of the power density spectrum. HF was calculated every minute from interpolated RRI series.

C. Oxygen saturation (SpO_2)

SpO_2 is the percentage of oxygen saturation, which is the hemoglobin in the blood that is saturated with oxygen. It is an indicator of oxygen transportation in the body and indicates a higher percentage when sufficient oxygen is supplied to the body. SpO_2 time series, which digitized in 1 kilohertz, were averaged every minute.

D. Objective and subjective sleepiness levels

Subjective sleepiness levels obtained via buttons on a steering wheel, were graded according to 100 levels. The higher levels indicate stronger drowsiness. The average sleepiness level was calculated every minute. Objective sleepiness was graded according to 5 levels by 2 observers every minute. Those 2 observer levels were averaged for the analysis.

IV. Results

Figure 6(a)(b) show the time series of a subject's respiration curve and RRI, respectively. The grayed parts are the time between 30 to 31 minutes when the stimulation is given to the subject. Both grayed parts were fluctuating

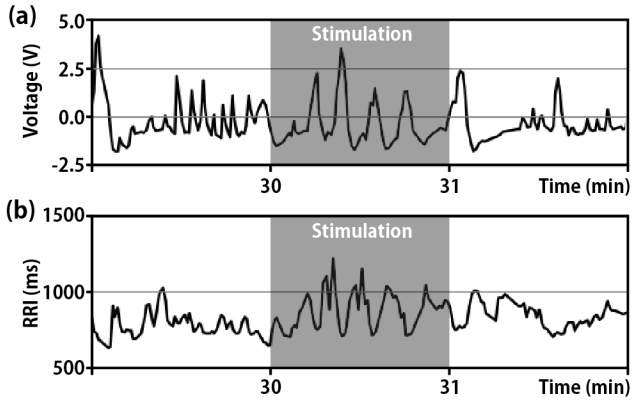

Figure 6. Fluctuations of a respiration curve and RRI. (a) Respiration curve. (b) RRI

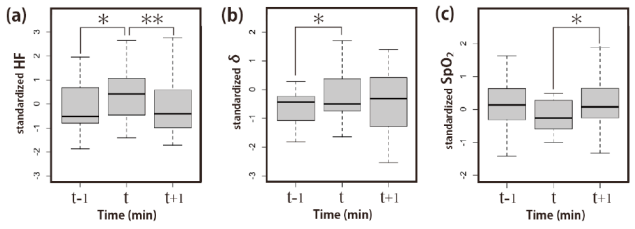

Figure 7. Standardized HF, δ, and SpO_2 before, during, and after the stimulation. (t=30,45) (a) standardized HF (b) standardized δ (c) standardized SpO_2. (Asterisks stand for *p*-values: * $p<0.05$, ** $p<0.01$)

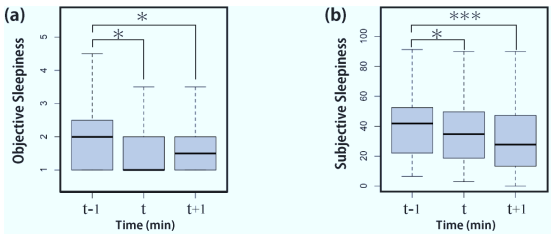

Figure 8. Sleepiness levels before, during, and after the stimulation. (t=30,45) (a) Objective sleepiness levels (b) Subjective sleepiness levels. (Asterisks stand for *p*-values: * p<0.05, **p<0.01 , ***p<0.001)

similarly compered to the other parts. At the inspiration in the gray part, voltage of the respiration curve rose by decrease of strain gauge resistance and RRI decreased by increase of heartbeats. The opposite fluctuation is seen at the expiration. This synchronic fluctuation is the coordination of cardiorespiratory, especially RSA, and it is considered to appear by stimulation. To quantify this, HF and standard deviation of histograms obtained from synchrograms are used. A *t*-test was used for the comparisons between the groups of before (t=29, 44) and during (t=30, 45) the stimulation was given to the subjects. As Figure 7 show, HF and σ got significantly higher while the vibratory stimulation was given to the subjects. This result indicates that CRPS and RSA appeared due to the stimulation. After these two appearances, a significant increase of SpO_2 was observed. Improvement of gas exchanges by the CRPS and the RSA might have caused this increasing of SpO2 with slight delays. Moreover, there were significant decreases in both objective and subjective sleepiness levels by the stimulation (Figure 8). These results imply that the CRPS and the RSA caused by the stimulation had an active influence on the oxygen supply to the body and eased the subjects' drowsiness.

V. Discussion and Conclusion

This study proposes that the heartbeat-synchronized vibration has an effect of easing drivers' slight deprivation of oxygen during the drowsiness induced by cardiorespiratory coordination. The effect of this stimulation was confirmed by the results of the experiment done in cooperation with 15 subjects. As the results show, HF and σ showed a significant increase when the vibratory stimulation was given to them. After the stimulation was given to the subjects, there were significant increase in SpO_2 and decrease both in the objective and subjective sleepiness levels. These results insisted that CRPS and RSA appeared by the vibratory stimulation and it played an active influence on the oxygen supply to the body, which eased subjects' drowsiness. We suppose that the CRPS appeared by the breath timing changes due to the stimulation and it enhanced the RSA. The rhythmic pulsations of the motor with each heartbeat served as an indicator of inspirations and expirations to make it synchronize with the heartbeats. We conclude that the stimulation has an active physiologic influence to possibly ease severe driver drowsiness.

However, the induction of breath timing by the stimulation is not clarified. We need to investigate how the stimulation served as an indicator of inspirations and expirations to make it synchronize with the heartbeats. Also an alternation of patterns and strength of the stimulation might affect the results. We should increase the number of subjects to clarify these matters in our further studies.

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