Controlled Mechanical Vibration Applied to Driver's Right Heel to Sustain Alertness: Effects on Cardiovascular Behavior

Takehiro Yamakoshi[a, §], Kenta Matsumura[a], Peter Rolfe[b, c]

[a]*School of Mechanical Engineering, College of Science and Engineering, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan*

[b]*Department of Automatic Measurement and Control, Harbin Institute of Technology, 92 West Dazhi Street, Nan Gang District, Harbin 150001, China*

[c]*Oxford BioHorizons Ltd., 31-33 Albion Place, Maidstone, Kent ME14 5DZ, UK*

Email addresses:

TY: takey@staff.kanazawa-u.ac.jp

KM: kenta16moon@se.kanazawa-u.ac.jp

PR: PeterRolfe@aol.com

§ Corresponding author:

Takehiro Yamakoshi, PhD, Postdoctoral Fellow

School of Mechanical Engineering, College of Science and Engineering

Kanazawa University

Kakuma-machi, Kanazawa, Ishikawa 920-1192

Japan

Tel: +81-(0)76-234-4739

Fax: +81-(0)76-234-4737

E-mail: takey@staff.kanazawa-u.ac.jp

ABSTRACT

Vehicle-related countermeasures to sustain driver's alertness might improve traffic safety. The purpose of this study was to investigate the effects of somatosensory 20 Hz mechanical vibration, applied to driver's right heel during prolonged, simulated, monotonous driving, on their cardiovascular hemodynamic behavior. In 12 healthy young male volunteers, during 90-min periods of simulated monotonous driving, we compared cardiovascular variables during application of 20 Hz mechanical vibration with 1.5 Hz as a control and with no vibration. The parameters recorded were indices of key cardiovascular hemodynamic phenomena, *i.e.*, blood pressure as an indicator of stress, cardiac output, and total peripheral-vascular resistance. The principle results were that all conditions increased the mean blood pressure, and elicited a vascular-dominant reaction pattern typically observed in monotonous driving tasks. However, mean blood pressure and total peripheral-vascular resistance during the monotonous task were significantly decreased in those receiving the 20 Hz vibration as compared with 1.5 Hz and with no vibration. The observed differences indicate the cardiovascular system being more relieved from monotonous driving stress with the 20 Hz vibration. The major conclusion is that applying 20 Hz mechanical vibration to the right heel during long-distance driving in non-sleepy drivers could facilitate more physiologically appropriate status for vehicle operation and could be a potential vehicular countermeasure technology. (210 words)

Keywords: foot; hemodynamics; sleep countermeasures; vibratory stimulus; vehicle accidents.

1. Introduction

In the industrialized nations, driver sleepiness and fatigue have been reported to be major causes of serious traffic accidents, leading to major injuries or death (Horne and Reyner, 1995; McCartt et al., 1996; Philip et al., 2001; Sagberg, 1999). It has been reported that falling asleep while driving accounts for approximately 20% of all motor vehicle accidents on motorways and other monotonous roads (Horne and Reyner, 1995). To prevent this type of sleep-related traffic accident, drivers usually take countermeasures themselves against sleepiness before driving, such as taking a short (<15 min) nap, and/or during driving, such as opening a window, increasing the radio volume, drinking hot or cold caffeinated beverages, getting out to stretch and/or exercise, changing drivers, eating, and singing or talking to themselves or passengers (Asaoka et al., 2012; Horne and Reyner, 1999; Oron-Gilad and Shinar, 2000; Royal, 2003). In fact, research studies have shown that some of these simple driver-related actions or combined actions are effective at warding off sleepiness during prolonged driving (Horne and Reyner, 2001; Mets et al., 2011; Philip et al., 2006; Yamakoshi et al., 2013). However, there is a case to be made for countermeasures that do not require conscious participation by the driver. This approach would involve installing in the road or vehicle technology that functions automatically without hampering the driver's own actions and without interfering with the correct operation of the vehicle. Efforts are already being made to explore and develop such technological solutions in order to reduce the incidence of, or prevent, fatigue-/sleep-related vehicle accidents (Balkin et al., 2011).

In relation to road-related countermeasures, the best known and most widely used interventions are edge or center line rumble techniques (Anund et al., 2008) which can alert drivers by causing audio-tactile vibrations, as the vehicle tires pass over them. Other research studies have shown that roadside visual stimulation including various non-standard (*i.e.*, interesting) message signs for drivers have an impact on driving fatigue, which may promote alertness in drivers and reduce the likelihood of fatigue-/sleep-related accidents (Merat and Jamson, 2013; Thiffault and Bergeron, 2003).

Regarding vehicle-related emerging countermeasures, three examples are, firstly, a system to increase the fraction of the inspired oxygen available to the driver as a stimulus, which has been reported to increase driver activation state (Yamakoshi et al., 2005), secondly, state-of-the-art lane change support systems (Ren et al., 2010; Tideman et al., 2010) and, thirdly, cooperative vehicle-to-vehicle and/or infrastructure-to-vehicle communication systems (Ammoun and Nashashibi, 2010; Farah et al., 2012; Sepulcre et al., 2013).

Alertness, which is closely related to vigilance, fatigue, arousal, and sleepiness, is strongly associated with brain activity and to its control of cardiovascular hemodynamic activity (Lang et al., 1997; Yamakoshi et al., 2009b). There are different brain waves, as recorded in the electroencephalogram (EEG), associated with alertness (beta-frequency range; 16–24 Hz) and sleep (delta/theta-frequency range; 1.5–4 Hz). Accumulated evidence shows that it is possible to stimulate brain activity in those ranges by auditory (Karino et al., 2006; Lane et al., 1998), visual (Herrmann, 2001), and somatosensory vibration (Tobimatsu et al., 1999) stimuli with the same frequencies. Thus, the key to enhancing alertness is not simply the application of a stimulus, but recognizing how to attune the action of the stimulus by observing its effect on brain waves.

Driving is essentially a repetitive cycle of perceptions, judgments and operations. Therefore, it is undesirable to apply stimuli that interfere with these actions while driving. Taking this into consideration, vibratory stimuli could be prime candidates for influencing driver's alertness. Interestingly, it has been reported that drowsiness worsens when the vibrations of a moving vehicle are mainly in the low-frequency range (1–2 Hz) (Kimura et al., 2008). This frequency range is consistent with that of the delta brain wave in the EEG (usually associated with the deepest stages of sleep), which may have implications for the effect of applying vibration stimuli to the driver.

There are two kinds of vibrations that humans can perceive—amplitude modulated mechanical vibration and electrically-induced vibration. The latter is an uncomfortable stimulation for humans (Snyder, 1992). Furthermore, it has been reported that the hand and foot areas are effective sites for application of vibratory stimuli because of the abundance of sensory receptors in these areas, and the EEG is synchronized with the vibratory frequency applied to these sites (Tobimatsu et al., 2000). Therefore, taking these factors into consideration, mechanical vibration in the beta-frequency range (approximately 20 Hz) applied to the right heel (the side with the acceleration pedal) might be an appropriate strategy for enhancing the driver's performance and, if proven to have a physiological basis, could have potential as a countermeasure technology for achieving safer driving.

The cardiovascular hemodynamic (*i.e.*, blood pressure, cardiac output, and total peripheral-vascular resistance) reactivity is known to reflect clearly and sensitively the state of alertness or stress or driver's activation (Lang et al., 1997; Yamakoshi et al., 2009b). Blood pressure in particular is a key parameter for reflecting the driver's stress. It has been shown that, during simulated monotonous driving, the blood pressure gradually increases. We have conjectured that this is in accordance with the acceleration of sympathetic activity, due to the demanding mental workload resulting from the effort to remain alert to ‘keep an eye on surroundings’ and to ‘shake off inevitable drowsiness’ (Yamakoshi et al., 2009b). It is therefore considered that the vibration has some influence on this behavior. In the present study we therefore focused on its reactivity to the vibratory stimulus, assessed during an experiment using a driving simulator. An experimental paradigm was developed in which 1.5 Hz vibration, as control, or 20 Hz vibration was applied to the right heel, during 90 min of monotonous driving. In a third condition, the same subjects drove for 90 min without receiving any test vibration. Based on the previous findings described above, we hypothesized that, compared with the control vibration or no vibration, 20 Hz vibration would have a significant effect on cardiovascular hemodynamic behavior.

2. Materials and methods

This study was a double-blind, controlled, crossover trial with a three-stage, within-subjects design. The study safeguards and protocols were approved by the ethics commission of the Faculty of Medicine of Kanazawa University, and the study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. All subjects agreed to take part in the study voluntarily and signed an informed consent statement before participating.

2.1 Subjects

To minimize inter-individual variability, a total of 12 healthy undergraduate male volunteer students, with a mean age of 21.7 ± 0.8 years, participated in the study. The sample size n = 12 was determined arbitrarily so that it should be multiples of the number of counterbalancing orders within the same age and gender group. The subjects were regular drivers (more than 5,000 km/year), had been in the possession of a driver's license for at least one year, were non-smokers, and had regular sleeping hours. The Japanese version of the Epworth sleepiness scale was applied to assess general levels of daytime sleepiness (Takegami et al., 2009). Subjects who's scores exceeded 10 were excluded from the study, and all participants abstained from alcohol consumption at least 24 h before the start of the test day.

2.2 Experimental design

The study comprised one training day and three test days for each subject. On the training day, participants were screened and familiarized with the test procedures using a driving simulator, which is described below. Participants were assigned at random to a protocol in which each of the following conditions including a 2- or 3-day reversal period were applied in the order shown in Table 1: 1) 20 Hz mechanical vibration applied to the right heel (*20Hz*); 2) 1.5 Hz mechanical vibration applied to the right heel as control (*1.5Hz*); and 3) no vibration applied (*0Hz*). The order of the conditions was counterbalanced across subjects.

On each of the test days, after checking all of the above-mentioned criteria, the three stages of the experiment were performed with subjects sitting in a quiet, temperature-controlled, driving simulator in the following order: (a) sensors were attached in the appropriate positions, which took at least 15 min; (b) subjects were given a rest period of 15 min; and (c) a simulated monotonous driving period was conducted for 90 min. Each test was performed over a 120-min period. In order to simulate an actual monotonous driving situation, each subject was previously informed that they had to continue driving safely as though they were actually driving, that they should maintain a speed of 80–120 km/h, and that they should drive within a specified lane. Test sessions were performed either in the morning (10:00–12:00 AM) or in the afternoon (13:00–15:00 PM) in a balanced manner. Each subject started each test day at the same time.

2.3 Test vibrations

Test vibrations were 20 Hz or 1.5 Hz mechanical vibration (control vibration), administered to the bare foot throughout the driving period. As mentioned above, the reason for the selection of 1.5 Hz vibration as control is that the frequency is consistent with the delta brain wave of the EEG (usually associated with the deepest stages of sleep), and the frequency contains that of the moving vehicle vibration. As shown in Fig. 1, each vibration was made by amplitude modulation according to Tobimatsu et al.'s method (Tobimatsu et al., 1999) using the Portable VISIC® System (Acouve Laboratory Inc., Tokyo, Japan). The carrier frequency was fixed at 128 Hz. The treatment code was revealed by a third person at Kanazawa University after the study was completed and data were analyzed.

2.4 Measurement quantities and apparatus

Driving tests were performed using a driving simulator, which had previously been constructed at Kanazawa University and validated in terms of usefulness as a simulator (Yamakoshi et al., 2009a; Yamakoshi et al., 2009b). The simulator consists of an adjustable car seat, steering wheel, gear lever, clutch, brake, and accelerator pedals for vehicle control. The system generates realistic monotonous roadway scenery, which is projected on a 1219 × 1626-mm screen, placed 1.3 m in front of the midpoint between the driver's eyes. The screen provided the driver with a 65° horizontal field of view. Auditory feedback, including the sound of an engine, is provided by speakers. In addition, the road condition is transmitted through the steering wheel by mechanical vibration where appropriate.

We measured the following cardiovascular variables during the experiment: systolic, mean, and diastolic blood pressure (SBP, MBP, and DBP, respectively) in the proximal phalanx of the left index finger; cardiac output (CO); and total peripheral-vascular resistance (TPR; = *MBP/CO*). These variables were all acquired on a beat-by-beat basis. The BP and CO monitoring systems were developed as experimental instruments and have been described fully elsewhere (Ito et al., 1976; Yamakoshi, 2004; Yamakoshi et al., 1980). The BP system, utilizing the volume-compensation principle (Yamakoshi et al., 1980), is capable of measuring instantaneous BP in the finger, and the admittance cardiograph (Ito et al., 1976) provides an instantaneous indication of CO. Concerning blood pressure, we used MBP as a representative value in the present analysis.

Driving performance was measured by a single-axis inclinometer (FAS-A®, Microstrain Inc., Williston, VT, USA) attached to the center of the steering wheel. We adopted the steering wheel reversal rate (SRR) (McLean and Hoffmann, 1975) as an index of driving performance. SRR is defined as the number, per minute, of changes in steering wheel reversals larger than a certain angular value referred to as the gap size. In order to facilitate the determination of the reversals, the steering wheel angle signal is low-pass filtered (cut off frequency 2 Hz was applied in this study), which eliminates noise in the signal. An extrema detection algorithm developed by us is employed to find minimum and maximum values in the signal. When the angle between two neighbouring extrema points is greater than the gap size, a reversal is counted. Typically, gap sizes between a half and ten degrees are arbitrarily selected (MacDonald and Hoffmann, 1980). In this study, a 3 degrees threshold was used. Increased SRR indicates that the steering task has become more difficult.

In this experiment, the level of sleepiness, as estimated from the verbal answers to a questionnaire read to subjects by an investigator at 10-min intervals during the driving task, was also measured. Subjects reported their perceived sleepiness on a 9-level scale from Level-1 (very alert) to Level-9 (very sleepy, an effort to stay awake, fighting sleep); this is referred to as the Japanese version of the Karolinska sleepiness scale (KSS-J) (Kaida et al., 2006).

In addition, the contact force and pressure to the right heel were measured in a driving position after the experiment using a digital platform scale (FG-150KBM, A&D Co. Ltd., Tokyo, Japan: Resolution 20 g, weighing capacity 150 kg) and a digital pressure gauge (PG-200-102GH-P, Copal Electronics Corp., Tokyo, Japan: Pressure range 0–98 kPa), respectively.

2.5 Data reduction and analyses

The data for each condition (*20Hz*, *1.5Hz*, and *0Hz*) and period (0–30, 30–60, and 60–90 min) were compared statistically by means of two-way repeated-measures analysis of variance (ANOVAs). The Greenhouse-Geisser correction was applied to the degree of freedom where appropriate. Bonferroni tests for post hoc comparison, and the standardized mean differences of Cohen’s *d* (Cohen, 1992) for the effect size were used. To exclude individual differences in the absolute value, the delta change (Δ) in reactivity was calculated by subtracting averaged rest period (5-min) values from each value during the experiment, and then these values were averaged over 30 min. Statistical analyses and extrema detection for SRR were performed using IBM SPSS Statistics 19.0 for MacOS (IBM Inc., Tokyo, Japan) and/or Microsoft Excel for Mac 2011.

3. Results

Summarized results of the condition (*20Hz*, *1.5Hz*, and *0Hz*) in each of the three periods (0–30, 30–60, and 60–90 min) in terms of cardiovascular variables and SRR, and KSS-J are shown in Figs. 2 and 3, respectively. The results of a series of separate ANOVAs are summarized in Table 2. In addition, the effect sizes (Cohen's *d*s) between conditions (*0Hz vs. 1.5Hz*, *0Hz vs. 20Hz*, and *1.5Hz vs. 20Hz*) against the periods for each variable are summarized in Table 3 and 4.

3.1 Mean blood pressure: MBP

The interaction between condition and period was significant. There was a significant main effect of period. MBP gradually increased over time especially in *1.5Hz* and *0Hz*. Among the conditions, post-hoc tests were significant for *20Hz vs. 1.5Hz* ($p < 0.05$) for the last 60–90 period, and MBP tended to be smaller for *20Hz* than for *0Hz* for the last 60–90 period, but this trend did not reach a significance level of 5% (*20Hz vs. 1.5Hz*, $p = 0.08$); 20 Hz vibration decreased MBP significantly more than the 1.5 Hz vibration, and tended to decrease MBP more than 'no vibration' condition in the last period.

3.2 Cardiac output: CO

We observed no significant interaction between condition and period, and no significant main effect of either condition or period. In terms of the effect size, CO has low potential for a Type II error. All conditions did not measurably affect CO.

3.3 Total peripheral-vascular resistance: TPR

The interaction between condition and period was significant. There was a significant main effect of both condition and period. TPR gradually increased over time in *1.5Hz* and *0Hz*. Among the conditions, post-hoc tests were significant for *20Hz vs. 1.5Hz* ($p < 0.01$) and *20Hz vs. 0Hz* ($p < 0.05$) for the last 60–90 period; 20 Hz vibration decreased TPR significantly more than the other two conditions in the last period.

3.4 Steering wheel reversal rate: SRR

We observed no significant interaction between condition and period, and no significant main effect of either condition or period. In terms of the effect size, SRR has small or medium potential for a Type II error in some combinations (*e.g.*, *1.5Hz vs. 20Hz* at 30-60 min). All conditions did not measurably affect SRR.

3.5 Japanese version of the Karolinska sleepiness scale: KSS-J

We observed no significant interaction between condition and period. However, it should be noted that KSS-J has a high potential for a Type II error in the interaction, because the effect sizes of Cohen's *d* are small at the first period and large at the later periods of the experiment between *20Hz* and two controls and η_P^2 is relatively large (= 0.13). We observed a significant main effect of both condition and period. KSS-J gradually increased over time in all conditions. Among the conditions, post hoc tests were significant for *20Hz vs. 1.5Hz* ($p < 0.001$) and *20Hz vs. 0Hz* ($p < 0.001$) for the whole period; 20 Hz vibration decreased the perceived sleepiness, as assessed by the KSS-J, significantly more than the other two conditions.

3.6 Contact force and pressure to the right heel

The mean contact intensity and mean pressure to the right heel were 36.86 ± 10.45 N (Newton) and 21.03 ± 4.43 kPa, respectively.

4. Discussion

In previous studies, the effects of vibratory stimulation to the hand and foot area were assessed in terms of somatosensory evoked potentials in a laboratory environment (Snyder, 1992; Tobimatsu et al., 2000). The purpose of the present study was to examine the cardiovascular hemodynamic effects of 20 Hz mechanical vibration applied to the right heel during long-distance driving. To this end, we conducted a laboratory experiment using simulated monotonous driving, and measured key hemodynamic parameters under double-blind counter-balanced crossover experimental conditions. As hypothesized, the findings clearly indicated that 20 Hz mechanical vibration applied to the right heel significantly changed cardiovascular variables towards normal physiological conditions as compared with the control vibration or no vibration. These results suggest that 20 Hz mechanical vibration applied to the right heel positively affects individuals undertaking prolonged driving and may improve physiological status in this situation.

BP is generally known as the final output of the cardiovascular system through the circulatory regulation system, and is known for reflecting human stresses. According to the simplified circulatory regulation model (deBoer et al., 1987; Yamakoshi et al., 2013), BP is fed back by the heart and/or the peripheral vessels through the autonomic nervous system so as to maintain the BP at a desired level. In this model, the heart modifies CO and the peripheral vessels modify TPR. The controlled BP is therefore calculated as "$BP = CO \times TPR$". As described above, if BP is elevated, the mechanism responsible could be described as having two patterns. One is *via* an increase in cardiac function (the cardiac-dominant reaction pattern; the rise in BP is mainly due to increased CO). The other is *via* an increase in vascular function (the vascular-dominant reaction pattern; the rise in BP is mainly due to increased TPR). Typically, the former is observed in active coping (coping exerted under the presence of response-reinforcement contingency; it enables individuals to work on a stressful task in a successful manner). The latter is observed in passive coping (coping exerted under the absence of response-reinforcement contingency; it forces individuals to tolerate only passively) (Obrist, 1981; Sawada et al., 2002). As shown in Fig. 2, MBP gradually increased in all groups with time because of the stress associated with monotonous driving, particularly the effort involved in fighting against drowsiness and the hard mental workload of monotonous driving itself (Warm et al., 2008; Yamakoshi et al., 2009b), and the underlying mechanism of MBP elevation appeared to be the same in each group. That is, all conditions exhibited the vascular-dominant reaction pattern, as indicated by the rise in TPR, which means that vasoconstriction occurred. In fact, this passive coping is a distinctive response in monotonous driving situations (Yamakoshi et al., 2013; Yamakoshi et al., 2009a; Yamakoshi et al., 2009b). However, compared with the two controls, MBP and TPR elevation is inhibited in *20Hz*. This could be because the 20 Hz mechanical vibration applied to the right heel had a positive physiological effect (possibly relaxation effect) on the body during prolonged, simulated, monotonous driving. Because the cardiovascular hemodynamic reactivity is known to reflect clearly and sensitively the state of driver's alertness (Lang et al., 1997; Yamakoshi et al., 2009b), in this study we did not focus on brain waves (EEG) or blinking duration as a conventional measure, or eye movements which has attracted a lot of attention recently as a predictor of driver's alertness (Ahlstrom et al., 2013; Di Stasi et al., 2012); however, it will be interesting to explore the reactivity of these during the driving scenario used here in further studies.

Subjective sleepiness, as assessed by the KSS-J, showed a significant tendency to be higher in the two control conditions as compared with *20Hz* (see Fig. 3). Meanwhile, the SRR as a possible indicator of driver performance showed the effectiveness of *20Hz* relative to the two control conditions, which did not differ significantly from each other in this study. This is at odds with the positive results of cardiovascular hemodynamic reactivity. We can think of three reasons for this result. Firstly, the monotonous driving time, *i.e.*, a 90-min monotonous driving task, given to the non-sleepy subjects in this study is relatively short. Simulated monotonous driving tasks in other studies exceeded 120-min, and the relevant performance parameters were statistically significant (Horne and Reyner, 2001; Mets et al., 2011). It should therefore be examined in the long-distance scenario and/or using sleepy subjects in further studies. Secondly, the reliability of the performance index applied in this study, SRR, for monotonous driving may not be adequate. It has been reported that there are other indices of driving performance from the vehicle system (Liu et al., 2009); the standard deviation of lane (lateral) position as lateral control ability, the speed deviation calculated as the difference in speed of the vehicle from the posted speed limit and the speed variability calculated as the standard deviation of speed deviation as longitudinal control ability, and the off-road incidents calculated as the number of times that the simulated vehicle left the road. As we could not apply all of these indices in the present experimental setup, all alternatives for measuring a driver's performance will need to be explored. Thirdly, the statistical power for the arbitrarily obtained sample size (n = 12) in this study, is not sufficient. Thus, in future research, adopting a more appropriate sample size, including a variety of subjects, will be needed to clarify this behavioral statistical result. However, we might at least emphasize that our physiological and subjective positive results were more than being merely safe, because in this study there were not active efforts by the driver's themselves to stay awake (*e.g.*, listening to music, having caffeinated beverages, and so on).

It is pertinent here to consider the matter of whether or not a method based on heel vibration would be acceptable to potential users, such as the long-distance driver, and there are several aspects that will require closer examination in the future. Firstly, if it is eventually concluded that the physiological basis of a vibratory stimulus is proven, almost certainly following further extensive studies, then a practical system would need to be engineered. Such a system would need to be convenient, unencumbering and comfortable for the user as well as being, reliable, and of appropriate cost. Acceptance by potential users could then be more realistically assessed with a fully operational system. This assessment would need to explore operational system characteristics, such as the relationship between time duration, timing, and intensity of the applied vibration as well as the subjective perceptions by users. These important practical aspects need to be investigated fully in future studies.

There are some limitations in our study. Firstly, the tests were conducted in a driving simulator environment. The development of sleepiness and the experience of monotony may differ between simulated and actual driving. The absence of actual risk and vehicle vibrations in the driving simulator also differs from on-the-road driving experience. The effect of applying 20 Hz mechanical vibration to the right heel on driving performance should therefore preferably be replicated in real driving situations. Secondly, with a mean age of 21.7 years, the population of only male drivers was relatively young. It will be important to examine the effects of 20 Hz mechanical vibration in women, and in older and more experienced drivers including long-distance drivers in order to be able to generalize our results to a broader and more representative driving population. Thirdly, we used morning and afternoon periods to carry out the tests and these times may not be representative for the circumstances of some drivers, for example, long-distance truck drivers. Further study will be needed using sleepy subjects or during the night and early morning hours. Finally, we applied the vibrations throughout the simulated driving period in this first study. However, the time duration of the applied vibration is likely to be relevant due to the possible occurrence of desensitization. This methodological aspect together with the practical aspects mentioned above, needs to be investigated fully in future studies.

5. Conclusions

As compared with the controls, applying 20 Hz mechanical vibration to the right heel significantly decreased the mean blood pressure, MBP, known for reflecting the stress, total peripheral-vascular resistance, TPR, and subjective sleepiness elevations in simulated monotonous driving situations. These results suggest that 20 Hz mechanical vibration applied to the right heel of non-sleepy drivers during prolonged driving could help to reduce the hard mental workload of monotonous driving, possibly leading to an appropriate driving status or sustaining driver's alertness. This could form the basis of a potential emerging technology with which to achieve safer driving.

Acknowledgements

The authors would like to give special thanks to Prof. Ken-ichi Yamakoshi and Prof. Shinobu Tanaka, Kanazawa University, for their helpful comments on this work, and Mr. Yujiro Goto and Mr. Shota Hanaki, Kanazawa University, for their technical assistance in conducting the experiment.

References

Ahlstrom, C., Nyström, M., Holmqvist, K., Fors, C., Sandberg, D., Anund, A., Kecklund, G., Åkerstedt, T., 2013. Fit-for-duty test for estimation of drivers' sleepiness level: Eye movements improve the sleep/wake predictor. *Transport. Res. C Emerg. Technol.* 26, 20-32. doi: 10.1016/j.trc.2012.07.008

Ammoun, S., Nashashibi, F., 2010. Design and efficiency measurement of cooperative driver assistance system based on wireless communication devices. *Transport. Res. C Emerg. Technol.* 18(3), 408-428. doi: 10.1016/j.trc.2010.02.004

Anund, A., Kecklund, G., Vadeby, A., Hjalmdahl, M., Akerstedt, T., 2008. The alerting effect of hitting a rumble strip--a simulator study with sleepy drivers. *Accid. Anal. Prev.* 40(6), 1970-1976. doi: 10.1016/j.aap.2008.08.017

Asaoka, S., Abe, T., Komada, Y., Inoue, Y., 2012. The factors associated with preferences for napping and drinking coffee as countermeasures for sleepiness at the wheel among Japanese drivers. *Sleep Med.* 13(4), 354-361. doi: 10.1016/j.sleep.2011.07.020

Balkin, T.J., Horrey, W.J., Graeber, R.C., Czeisler, C.A., Dinges, D.F., 2011. The challenges and opportunities of technological approaches to fatigue management. *Accid. Anal. Prev.* 43(2), 565-572. doi: 10.1016/j.aap.2009.12.006

Cohen, J., 1992. A power primer. *Psychol. Bull.* 112(1), 155-159. doi: 10.1037/0033-2909.112.1.155

deBoer, R.W., Karemaker, J.M., Strackee, J., 1987. Hemodynamic fluctuations and baroreflex sensitivity in humans: a beat-to-beat model. *Am. J. Physiol.* 253(3 Pt 2), H680-689.

Di Stasi, L.L., Renner, R., Catena, A., Cañas, J.J., Velichkovsky, B.M., 2012. Towards a driver fatigue test based on the saccadic main sequence: A partial validation by subjective report data. *Transport. Res. C Emerg. Technol.* 21(1), 122-133. doi: 10.1016/j.trc.2011.07.002

Farah, H., Koutsopoulos, H.N., Saifuzzaman, M., Kölbl, R., Fuchs, S., Bankosegger, D., 2012. Evaluation of the effect of cooperative infrastructure-to-vehicle systems on driver behavior. *Transport. Res. C Emerg. Technol.* 21(1), 42-56. doi: 10.1016/j.trc.2011.08.006

Herrmann, C.S., 2001. Human EEG responses to 1-100 Hz flicker: resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Exp. Brain Res.* 137(3-4), 346-353. doi: 10.1007/S002210100682

Horne, J., Reyner, L., 1999. Vehicle accidents related to sleep: a review. *Occup. Environ. Med.* 56(5), 289-294. doi: 10.1136/oem.56.5.289

Horne, J.A., Reyner, L.A., 1995. Sleep related vehicle accidents. *BMJ* 310(6979), 565-567. doi: 10.1136/bmj.310.6979.565

Horne, J.A., Reyner, L.A., 2001. Beneficial effects of an "energy drink" given to sleepy drivers. *Amino Acids* 20(1), 83-89. doi: 10.1007/s007260170068

Ito, H., Yamakoshi, K., Togawa, T., 1976. Transthoracic admittance plethysmograph for measuring cardiac output. *J. Appl. Physiol.* 40(3), 451-454.

Kaida, K., Takahashi, M., Akerstedt, T., Nakata, A., Otsuka, Y., Haratani, T., Fukasawa, K., 2006. Validation of the Karolinska sleepiness scale against performance and EEG variables. *Clin. Neurophysiol.* 117(7), 1574-1581. doi: 10.1016/j.clinph.2006.03.011

Karino, S., Yumoto, M., Itoh, K., Uno, A., Yamakawa, K., Sekimoto, S., Kaga, K., 2006. Neuromagnetic responses to binaural beat in human cerebral cortex. *J. Neurophysiol.* 96(4), 1927-1938. doi: 10.1152/jn.00859.2005

Kimura, H., Endo, M., Koseki, M., Inou, N., 2008. [Sleep-inducing factors in mechanical environment]. *Transactions of the Japan Society of Mechanical Engineers Series C* 74(740), 806-813.

Lane, J.D., Kasian, S.J., Owens, J.E., Marsh, G.R., 1998. Binaural auditory beats affect vigilance performance and mood. *Physiol. Behav.* 63(2), 249-252. doi: 10.1016/S0031-9384(97)00436-8

Lang, P.J., Bradley, M.M., Cuthbert, B.N., 1997. Motivated attention: Affect, activation, and action, in: Lang, P.J., Simons, R.F., Balaban, M.T. (Eds.), *Attention and orienting: Sensory and motivational processes*. Lawrence Erlbaum, Hilldale, NJ, pp. 97-135.

Liu, C.C., Hosking, S.G., Lenné, M.G., 2009. Predicting driver drowsiness using vehicle measures: recent insights and future challenges. *J. Safety Res.* 40(4), 239-245. doi: 10.1016/j.jsr.2009.04.005

MacDonald, W.A., Hoffmann, E.R., 1980. Review of relationships between steering wheel reversal rate and driving task demand. *Hum. Factors* 22(6), 733-739. doi: 10.1177/001872088002200609

McCartt, A.T., Ribner, S.A., Pack, A.I., Hammer, M.C., 1996. The scope and nature of the drowsy driving problem in New York State. *Accid. Anal. Prev.* 28(4), 511-517. doi: 10.1016/0001-4575(96)00021-8

McLean, J.R., Hoffmann, E.R., 1975. Steering reversals as a measure of driver performance and steering task difficulty. *Hum. Factors* 17(3), 248-256.

Merat, N., Jamson, A.H., 2013. The effect of three low-cost engineering treatments on driver fatigue: A driving simulator study. *Accid. Anal. Prev.* 50, 8-15. doi: 10.1016/j.aap.2012.09.017

Mets, M.A., Ketzer, S., Blom, C., van Gerven, M.H., van Willigenburg, G.M., Olivier, B., Verster, J.C., 2011. Positive effects of Red Bull® Energy Drink on driving performance during prolonged driving. *Psychopharmacology (Berl).* 214(3), 737-745. doi: 10.1007/s00213-010-2078-2

Obrist, P.A., 1981. *Cardiovascular psychophysiology: A perspective*. Plenum, New York.

Oron-Gilad, T., Shinar, D., 2000. Driver fatigue among military truck drivers. *Transport. Res. F Traf. Psychol. Behav.* 3(4), 195-209. doi: 10.1016/S1369-8478(01)00004-3

Philip, P., Taillard, J., Moore, N., Delord, S., Valtat, C., Sagaspe, P., Bioulac, B., 2006. The effects of coffee and napping on nighttime highway driving: a randomized trial. *Ann. Intern. Med.* 144(11), 785-791. doi: 10.7326/0003-4819-144-11-200606060-00004

Philip, P., Vervialle, F., Le Breton, P., Taillard, J., Horne, J.A., 2001. Fatigue, alcohol, and serious road crashes in France: factorial study of national data. *BMJ* 322(7290), 829-830. doi: 10.1136/bmj.322.7290.829

Ren, F., Huang, J., Terauchi, M., Jiang, R., Klette, R., 2010. Lane detection on the iPhone, in: Huang, F., Wang, R.C. (Eds.), *Arts and Technology*. Springer Berlin Heidelberg, pp. 198-205. doi: 10.1007/978-3-642-11577-6_25

Royal, D., 2003. National survey of distracted and drowsy driving attitudes and behavior: 2002 (vol. 1: Findings). U.S. Department of Transportation NHTSA, Washington, DC.

Sagberg, F., 1999. Road accidents caused by drivers falling asleep. *Accid. Anal. Prev.* 31(6), 639-649. doi: 10.1016/S0001-4575(99)00023-8

Sawada, Y., Nagano, Y., Tanaka, G., 2002. Mirror tracing and the provocation of vascular-dominant reaction pattern through heightened attention. *J. Psychophysiol.* 16(4), 201-210. doi: 10.1027//0269-8803.16.4.201

Sepulcre, M., Gozalvez, J., Hernandez, J., 2013. Cooperative vehicle-to-vehicle active safety testing under challenging conditions. *Transport. Res. C Emerg. Technol.* 26, 233-255. doi: 10.1016/j.trc.2012.10.003

Snyder, A.Z., 1992. Steady-state vibration evoked potentials: descriptions of technique and characterization of responses. *Electroencephalogr. Clin. Neurophysiol.* 84(3), 257-268. doi: 10.1016/0168-5597(92)90007-X

Takegami, M., Suzukamo, Y., Wakita, T., Noguchi, H., Chin, K., Kadotani, H., Inoue, Y., Oka, Y., Nakamura, T., Green, J., Johns, M.W., Fukuhara, S., 2009. Development of a Japanese version of the Epworth Sleepiness Scale (JESS) based on item response theory. *Sleep Med.* 10(5), 556-565. doi: 10.1016/j.sleep.2008.04.015

Thiffault, P., Bergeron, J., 2003. Monotony of road environment and driver fatigue: a simulator study. *Accid. Anal. Prev.* 35(3), 381-391. doi: 10.1016/S0001-4575(02)00014-3

Tideman, M., van der Voort, M.C., van Arem, B., 2010. A new scenario based approach for designing driver support systems applied to the design of a lane change support system. *Transport. Res. C Emerg. Technol.* 18(2), 247-258. doi: 10.1016/j.trc.2009.09.001

Tobimatsu, S., Zhang, Y.M., Kato, M., 1999. Steady-state vibration somatosensory evoked potentials: physiological characteristics and tuning function. *Clin. Neurophysiol.* 110(11), 1953-1958. doi: 10.1016/S1388-2457(99)00146-7

Tobimatsu, S., Zhang, Y.M., Suga, R., Kato, M., 2000. Differential temporal coding of the vibratory sense in the hand and foot in man. *Clin. Neurophysiol.* 111(3), 398-404. doi: 10.1016/S1388-2457(99)00278-3

Warm, J.S., Parasuraman, R., Matthews, G., 2008. Vigilance requires hard mental work and is stressful. *Hum. Factors* 50(3), 433-441. doi: 10.1518/001872008X312152

Yamakoshi, K., 2004. Sensors in Medicine and Health Care (Sensors Applications, Volume 3), in: Oberg, P.A., Togawa, T., Spelman, F. (Eds.), *Non-invasive cardiovascular haemodynamic measurements*. Wiley-VCH Verlag, Weinheim, pp. 107-160.

Yamakoshi, K., Shimazu, H., Togawa, T., 1980. Indirect measurement of instantaneous arterial blood pressure in the human finger by the vascular unloading technique. *IEEE Trans. Biomed. Eng.* 27(3), 150-155. doi: 10.1109/TBME.1980.326616

Yamakoshi, T., Matsumura, K., Hanaki, S., Rolfe, P., 2013. Cardiovascular hemodynamic effects of Red Bull® Energy Drink during prolonged, simulated, monotonous driving. *SpringerPlus* 2(1), 215. doi: 10.1186/2193-1801-2-215

Yamakoshi, T., Park, S.B., Jang, W.C., Kim, K., Yamakoshi, Y., Hirose, H., 2009a. Relationship between salivary Chromogranin-A and stress induced by simulated monotonous driving. *Med. Biol. Eng. Comput.* 47(4), 449-456. doi: 10.1007/S11517-009-0447-Y

Yamakoshi, T., Rolfe, P., Yamakoshi, Y., Hirose, H., 2009b. A novel physiological index for Driver's Activation State derived from simulated monotonous driving studies. *Transport. Res. C Emerg. Technol.* 17(1), 69-80. doi: 10.1016/j.trc.2008.09.002

Yamakoshi, T., Yamakoshi, K., Nogawa, M., Sawada, Y., Rolfe, P., Kusakabe, M., 2005. Assessing the effectiveness of increased FIO2 for enhancing driver's activation state using simulated monotonous driving. *Conference proceedings : 27th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* 7, 6706-6709. doi: 10.1109/IEMBS.2005.1616042

Figure captions

Fig. 1. Schematic representation of the vibration waveforms applied to the right heel at two modulation frequencies. The carrier frequency is 128 Hz. The stimulus intensity is arbitrarily plotted against the time axis.

Fig. 2. Summarized results of the effects of condition (*20Hz*, *1.5Hz*, and *0Hz*) and period (0–30, 30−60, and 60−90 min) on cardiovascular variables and SRR. *SD* = standard deviation; *SEM* = standard error of the mean; *MBP* = mean blood pressure; *CO* = cardiac output; *TPR* = total peripheral-vascular resistance; *SRR* = steering wheel reversal rate.

Fig. 3. Summarized results of the effects of condition (*20Hz*, *1.5Hz*, and *0Hz*) and period (0–30, 30–60, and 60–90 min) on KSS-J. *KSS-J* = Japanese version of the Karolinska sleepiness scale.

Tables

Table 1. Summary of the study design. The study was a double-blind, controlled, 2 × 6 crossover trial with a three-stage, within-subjects design.

Group	Number of Subjects	1st Stage	Reversal period	2nd Stage	Reversal period	3rd Stage
A	2	*0Hz*	2 or 3 days	*1.5Hz*	2 or 3 days	*20Hz*
B	2	*0Hz*		*20Hz*		*1.5Hz*
C	2	*1.5Hz*		*0Hz*		*20Hz*
D	2	*1.5Hz*		*20Hz*		*0Hz*
E	2	*20Hz*		*0Hz*		*1.5Hz*
F	2	*20Hz*		*1.5Hz*		*0Hz*

0Hz = no vibration administered, *1.5Hz* = 1.5 Hz vibration, *20Hz* = 20 Hz vibration.

Table 2. Summary of results of two-way repeated-measure analysis of variance.

Measures		Main Effect						Interaction		
		Condition			Period			Condition × Period		
		$F_{2, 22}$	p	η_P^2	$F_{2, 22}$	p	η_P^2	$F_{4, 44}$	p	η_P^2
Hemodynamics										
	MBP	2.43	0.11	0.18	32.53	0.00	0.75	4.61	0.00	0.30
	CO	0.01	0.99	0.00	0.30	0.74	0.03	0.16	0.96	0.01
	TPR	3.66	0.04	0.25	22.76	0.00	0.67	5.37	0.00	0.33
Performance										
	SRR	1.55	0.24	0.12	0.50	0.92	0.00	0.59	0.59	0.05
		$F_{10, 100}$	p	η_P^2	$F_{10, 110}$	p	η_P^2	$F_{20, 220}$	p	η_P^2
Subjective										
	KSS-J	3.67	0.04	0.25	49.52	0.00	0.82	1.57	0.06	0.13

MBP = mean blood pressure, *CO* = cardiac output, *TPR* = total peripheral-vascular resistance, *SRR* = steering wheel reversal rate, *KSS-J* = Japanese version of the Karolinska sleepiness scale.
Each condition n = 12.

Table 3. Summary of results of effect size for cardiovascular variables and SRR.

Measures		0−30 min	30−60 min	60−90 min
MBP	*0Hz vs. 1.5Hz*	0.44	0.64	0.31
	0Hz vs. 20Hz	0.09	0.01	0.30
	1.5Hz vs. 20Hz	0.47	0.51	0.59
CO	*0Hz vs. 1.5Hz*	0.01	0.14	0.00
	0Hz vs. 20Hz	0.02	0.11	0.06
	1.5Hz vs. 20Hz	0.02	0.00	0.09
TPR	*0Hz vs. 1.5Hz*	0.07	0.13	0.16
	0Hz vs. 20Hz	0.21	0.65	0.84
	1.5Hz vs. 20Hz	0.14	0.76	1.14
SRR	*0Hz vs. 1.5Hz*	0.04	0.30	0.09
	0Hz vs. 20Hz	0.17	0.10	0.17
	1.5Hz vs. 20Hz	0.15	0.42	0.24

Note. $d = 0.2$: small effect size, $d = 0.5$: medium effect size, $d = 0.8$: large effect size (Cohen 1992).

MBP = mean blood pressure, *CO* = cardiac output, *TPR* = total peripheral-vascular resistance, *SRR* = steering wheel reversal rate.

Table 4. Summary of results of effect size for KSS-J.

	Rest	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
0Hz vs. 1.5Hz	0.11	0.46	0.06	0.26	0.13	0.32	0.25	0.25	0.36	0.33	0.21
0Hz vs. 20Hz	0.00	0.00	0.24	0.05	0.55	0.40	0.39	0.48	0.79	0.81	0.90
1.5Hz vs. 20Hz	0.14	0.47	0.20	0.31	0.69	0.70	0.62	0.69	0.26	0.33	0.58

Note. $d = 0.2$: small effect size, $d = 0.5$: medium effect size, $d = 0.8$: large effect size (Cohen 1992).

KSS-J = Japanese version of the Karolinska sleepiness scale.

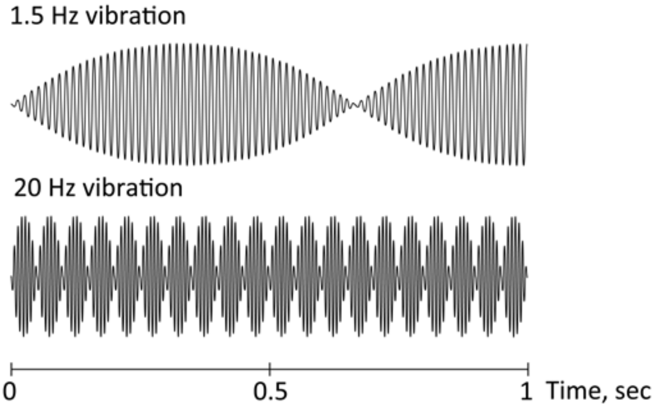

Fig. 1 © Takehiro Yamakoshi

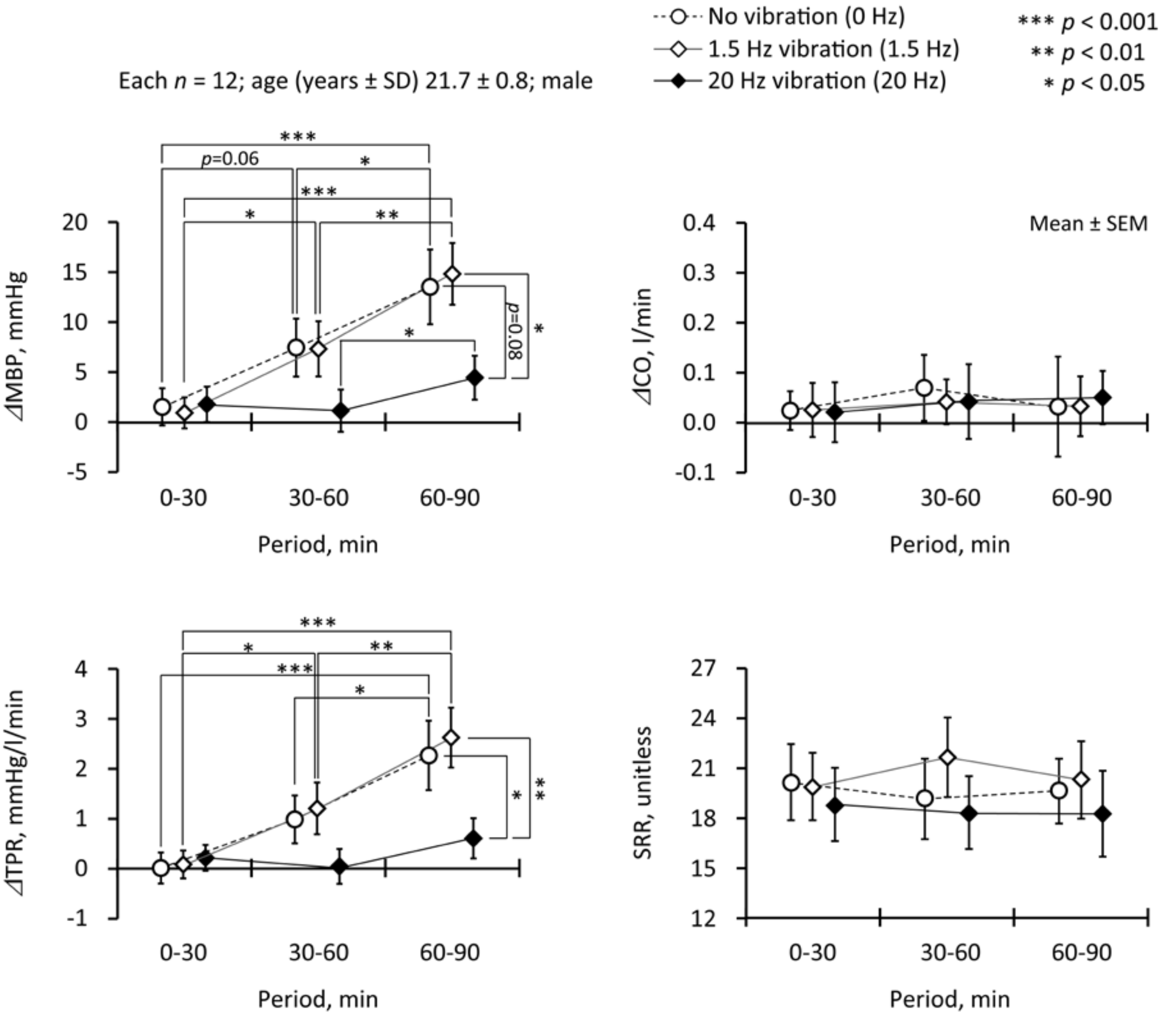

Fig. 2 © Takehiro Yamakoshi

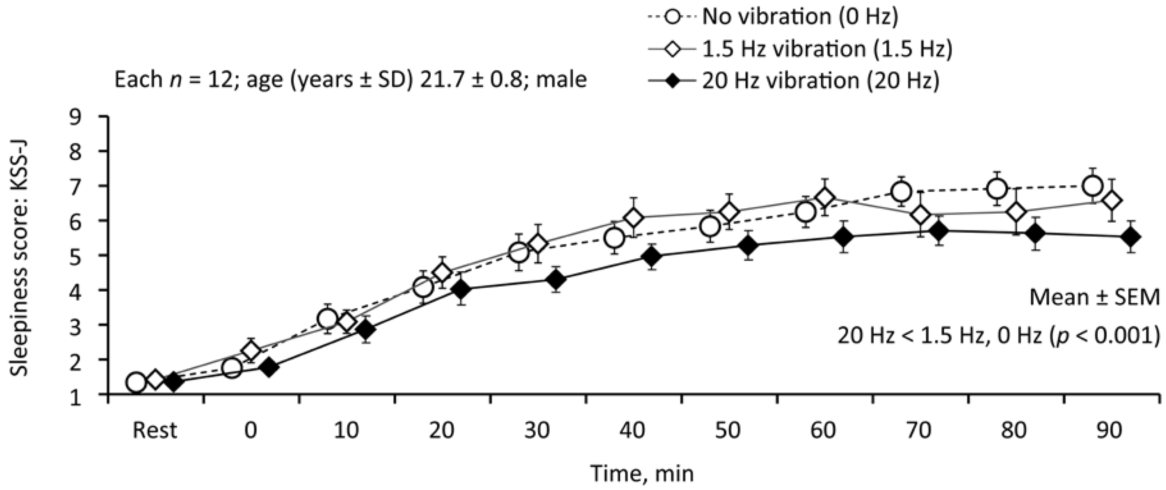

Fig. 3 © Takehiro Yamakoshi