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# Controlled mechanical vibration applied to driver's right heel to sustain alertness: Effects on cardiovascular behavior

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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.



## 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

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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