MAINTENANCE OF HIGH AROUSAL LEVEL BY VOLUNTARY DRIVING MANEUVER USING SENSORY FEEDBACK

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ABSTRACT

In order to prevent car driver sleepiness that may cause a serious accident, various stimuli have been proposed and tested to date. Although some of these stimuli have been proven effective, their effectiveness is limited and cannot be expected to last long enough. In this study we propose a new method to keep car drivers awake for a long period of time, and demonstrate its effectiveness by using driving simulation (DS). The proposed method lets the car driver perform a voluntary driving maneuver, which is lane-keep control with auditory or haptic feedback. In the DS, our subject was asked to drive on a straight road with a monotonous visual scene by following a car running in front at a constant speed. During the DS, recorded road noise was played back or the steering wheel was vibrated such that its intensity was altered in proportion to the amount of deviation from the center of the driving lane. This maneuver helps subjects keep to their driving lane without disturbing the focused attention required for safe driving. It was expected that the decrease of the road noise or the steering wheel vibration would work as a reward, while the increase would work as a disincentive. Pupil diameter, vestibulo-ocular reflex (VOR) and subjective sleepiness were monitored as measures of the subjects' sleepiness. We demonstrate that the steering wheel vibration is effective. Namely, when the proposed voluntary maneuver stimulus was initiated just after subject's sleepiness was predicted by using the physiological measure (VOR), the duration of the awake period was prolonged. This DS experiment employed only straight road driving, and lane-keep control should be more difficult on real roads. Thus actual driving situations require greater maneuvering that should result in greater effectiveness in maintaining a high arousal level. We conclude that to prolong the period of car driver's high-level alertness, the proposed voluntary driving maneuver is significantly more effective than conventional passive sensory feedback stimuli alone.

INTRODUCTION

When drivers operate a vehicle in a low arousal state with reduced physiological activity, oversights and operation errors occur with regard to predicted behavior and reaction speeds [e.g., 1][2]. When drivers in such a low arousal state face the danger of an impending collision, there is a likelihood that they will be unable to reduce speed of the car sufficiently and that may result in a serious accident. In order to prevent those accidents caused by drowsy driving due to low arousal, various means have been proposed for maintaining or heightening the degree of arousal by stimulating the five senses. For example, loud alarm, scent, and vibration. In cases when a lowered arousal is sustained over long periods of time, however, drivers may accustom to such sensory stimulus and soon it cannot be expected to have the same effect as it did immediately after the stimulus began to be applied. One way to resolve this problem is to prepare multiple sensory stimuli that are potentially effective, and apply them alternately so as to avoid sensory habituation. However, depending on the environment they are to be used, there may be limits on the number of devices that can be prepared, and a sufficient arousal effect may not

be readily obtainable. Here we propose a method for sustaining the arousal effect for long periods of time by using a single sensory feedback stimulus. The method applies a sensory stimulus whose intensity is correlated with the vehicle's deviation from the center of the driving lane. To keep the sensory feedback stimulus small, the driver has to maintain the car position close to the center of the driving lane as much as possible. We expect that this voluntary maneuver not only activates sensory processing system but sensory-motor transformation and motor control systems in our brain as well, which then results in helping maintain high arousal level. Reducing annoying sensory feedback stimulus by the voluntary maneuver might work as reward, and be expected to activate reward system as well. In the present study, we employed auditory and haptic stimuli for such a sensory feedback stimulus, and evaluated the effectiveness of the method in driving simulation.

METHOD

A. Experimental Setup

A driving simulator (DS) system was made up of a projector (EPSON ELP-73) for projecting a driving simulation scene on the screen, a driver's seat (Logicool PRC-11000) equipped with a steering wheel, brake and accelerator pedal, two speakers for auditory stimulus, and a steering wheel vibrator for haptic stimulus. A schematic diagram of the experimental setup is shown in Figure 1. A subject sat comfortably in the driver's seat. The seat was set so that the head of the subject faced the center of the screen. The distance between the subject's eyes and the screen was 2470 mm, and the screen size was 100 inches (horizontal visual angle: ±39.1 degrees, vertical visual angle: ±26.3 degrees). A device for adding seat motion that induces the vestibulo-ocular reflex (VOR) was also installed in the lower part of the driver's seat [3]. This device was modified from a commercially available health appliance (Daito Electric Machine Industry FD-003) so that it can generate similar head perturbations to those occurring during highway driving. The steering wheel was adjusted to maintain the subject in a comfortable position. The experiment was conducted in a dark room and the DS image was designed monotonous to easily lower subjects' alertness. The DS image projected on the screen remained unchanged except for the traffic lane and road shoulder that gave visual cue concerning the direction and speed of the vehicle. The brightness and contrast of the projector were adjusted so that the pupil diameter of the subject stayed within the medium range (about 6 mm).

B. Measured Data

During the DS experiment, we measured vertical and horizontal eye positions, pupil diameter, 3 axes angular head velocities, and 3 axes linear head accelerations together with subjective arousal levels (Table 1). The eye movements and pupil diameter were extracted in real time by image processing of eye image taken by an eye tracker (NEWOPTO ET-60-L) at a frame rate of 29.97 fps (NTSC). This real time image processing was

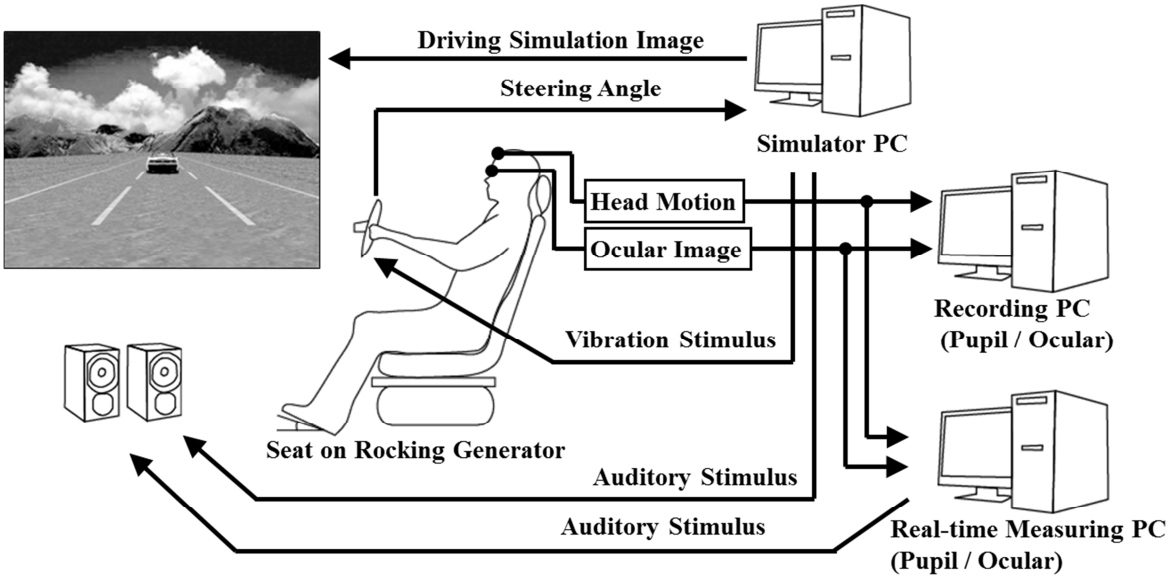

Figure 1. Schematic diagram of the experimental setup.

performed on a PC by using LabVIEW (National Instruments). The head movements were detected by an accelerometer (BestTechnology BTE071) and a gyroscope (BestTechnology BTE070) that were attached to the eye-tracking device, and their output were also fed into the PC running LabVIEW to evaluate VOR performance. These biological signals were synchronized with the eye tracking images using Spike2 software (Cambridge Electronic Design), digitized at the sampling rate of 1 KHz by an AD/DA device, Power1401 (Cambridge Electronic Design), and stored in another PC for off-line high precision data analyses (data not shown in this manuscript).

C. Subject

A total of 18 healthy subjects (mean ± SD: 22.8±7.1 years old) participated in the experiment. All of the subjects had given their informed consent prior to their participation to the experiment. Experimental procedures were considered with caution based on previous similar studies [3][4], following well-established methods. Careful attention was paid to prevent simulator sickness or any other pain to subjects during the experiment. The subjects made introspective reports on their sleepiness before the experiment to confirm that they were not sleepy. Farsighted and nearsighted subjects wore contact lenses to correct their vision.

D. Experimental Procedure

After having the eye-tracking device attached, each subject sat in the driver's seat in a natural comfortable posture, and practiced the driving simulator operation for one minute. Additional ten minutes were taken for each subject to adapt to the room light condition. During this period, subjects did not manipulate the DS system, and participated in ordinary conversation to maintain their arousal level. Following these preparations, the following task was given to the subjects.

The subjects were instructed to drive at a constant speed in the center lane of a monotonous straight 3-lane road, and keep their gaze on the rearview mirror of the vehicle. The position of the rearview mirror did not change as a result of steering operation. Seat motion to induce the VOR was applied from 20 seconds after the start of the experiment up to its end. In order to monitor the subjects' subjective degree of sleepiness, they were asked to make introspective reports (Table 1) verbally at a two-minute interval. That is, an arousal state with no sleepiness is level 0; a state unsure if perceiving sleepiness or not is level 1; a state that subjects have begun to perceive as sleepy is level 2; when the sleepiness is greater than level 2, it is level 3; and thereafter, the subjects were instructed to raise the level each time when their sleepiness increased, to 4, then 5, and so on, without placing an upper limit on the sleepiness level. In this measure, sleepiness level 2 is the state in which subjects first become aware of their sleepiness during the experiment. They reported only a number corresponding to their sleepiness state after moderate beep sound played every 2 minutes to prompt the verbal introspective report. The beep sound had a minimal effect on the subjects' sleepiness level.

Table 1. Subjective sleepiness level.

Level	Subjective sleepiness
Level 0	Not sleepy
Level 1	Not completely aroused but not sleepy
Level 2	Sleepy
Level 3	More sleepy than level 2
Level 4	More sleepy than level 3
Level 5	More sleepy than level 4, and so on

During the DS experiment, the subjects were presented with auditory stimulus so that they could perform lane-keep control as a voluntary driving maneuver. Namely, recorded road noise was played back as the auditory stimulus so that its volume was altered in proportion to the amount of deviation of the car from the center of the driving lane. This maneuver helps the subjects keep their driving lane without disturbing the focused attention required for safe driving. It was expected that the decrease of the road noise would work as a reward, while the increase would work as a disincentive. As an alternative, vibration of the steering wheel (similar to that of a cellular phone) was employed. Namely, the intensity of the vibration was increased in proportion to the amount of deviation of the car from the center of the driving lane. In these experiments, disturbance noise of 1/f was added to the vehicle angle in order to prompt corrective steering at the ordinary driving level.

In order to evaluate the effectivness of each sensory feedback stimulus, two timings were employed to initiate the presentation of stimuli; one when the subjects felt sleepiness, and the other when a premonitor of sleepiness was detected. The former timing was detected when our subjects reported sleepiness level 2. The latter was determined when either VOR gain or variability exceeds preset thresholds value (see below for more details). In the case of the experiment using the former timing (sensory feedback stimulus triggered by subjective sleepiness), the stimulus presentaiton continued until

the end of the experiment. In the case of the experiment using the latter timing (sensory feedback stimulus triggered by physiological premonitor of sleepiness), the stimulus was stopped when the premonitor of sleepiness disappeared. Experiments for each subject were conducted within the same time period on different days in a one-week period.

E. Data Analysis

Performance of the VOR and the pupil diameter were used to evaluate the physiological degree of arousal. Fluctuation of pupil diameter is under the control of the autonomic nervous system, and its effectiveness for detecting a subject's sleepiness and a premonitor of sleepiness has been demonstrated [4]. Namely, when subjects perceive their own sleepiness, large low-frequency fluctuation (LLFF) of the pupil diameter occurs, and prior to their awareness of their sleepiness, a monotonic gradual miosis (GM) occurs. It has been confirmed, therefore, that LLFF can serve as an indicator of sleepiness that rises to the level of consciousness, while GM is an indicator of a premonitor of sleepiness. Likewise, it has been demonstrated that the vestibulo-ocular reflex (VOR) induced by head movement indicates behavior that is closely related to sleepiness [5]. When head movements take place, compensatory eye movements are generated as VOR. It is an involuntary eye movement that prevents image slip on the retina. The VOR gain is defined as the ratio of the ideal angular eye velocity, which is the eye movement needed to compensate for head movement in a three-dimensional space, and the actual angular eye velocity. It has been confirmed that this VOR gain begins to diminish before subjects become aware of their sleepiness. The standard deviation of the residual obtained from a regression model of the ideal angular velocity of the eye and the actual angular eye velocity has also been confirmed to start increasing before subjects become aware of their sleepiness. In other words, VOR gain and residual standard deviation (VOR variability, hereafter) can be used to detect premonitors of sleepiness prior to subjects' awareness [3].

RESULTS

A. Awaking from sleepiness

Five subjects participated in this experiment. Figure 2 shows an example result of the monotonous driving simulation with audio feedback stimulus triggered by subjective sleepiness. From the top panel to the bottom, pupil diameter (a), VOR gain (b), VOR variability (c), and the subjective sleepiness level (d) are shown. The audio feedback stimulu was started at 8 min as indicated by a vertical line (Stimulus ON) when the subject's sleepiness level reached 2. Before that, the pupil fluctuation showed gradual miosys (GM) followed by a patial large low frequency

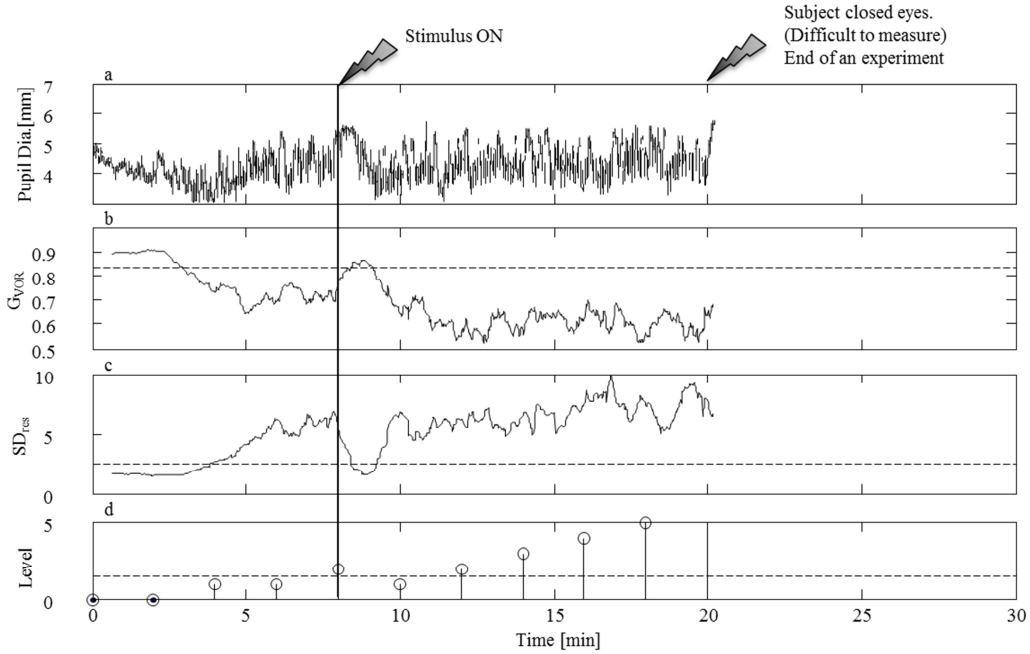

Figure 2. Changes in pupil diameter, VOR parameter and sleepiness level during the driving simulation in the active driving maneuver experiment with the road noise stimulus. a: Pupil diameter. b: VOR gain. c: VOR variability (standard deviation of residual). d: Sleepiness level.

fluctuation (LLFF). Both VOR gain and variability had crossed the preset threshold levels (dotted lines) for the sleepiness prediction as has been reported previously [6]. Two minutes after the beginning of the road noise feedback stimulus, the subjective sleepiness went down from level 2 to level 1, indicating that the subject's sleepiness has improved (see Table 1). Also the LLFF in pupil diameter was stopped, and briefly the pupil stayed dilated as well as the VOR gain and variability went back toward the original values, corssing back the thresholds. This means that the subject's sleepiness has been resolved in terms of physiological indicators. However, this situation didn't last long, and at 12 min (2 min after the initiation of the road noise feedback stimulus), subjective sleepiness came back together with physiological signes of sleepiness.

Figure 3 shows an example result from the expriment in which steering wheel vibration stimulus was employed when subjective sleepiness was reported. The format is the same as Figure 2. In this example, too, the subject reported his self-sleepiness at 8 min (d). In pupil fluctuation (a), GM and an initial part of LLFF were seen. VOR gain and variability have crossed the thresholds before the subjective sleepiness was reported. As soon as the sleepiness level 2 was reported at 8 min, the steering wheel vibration stimulus was initiated (vertical line, Stimulus ON). Although the subjective sleepiness level was not improved (d), it stayed the same and the physiological measures were actually imporoved. Namely, the pupil dilated, VOR gain increased and VOR variability decreased briefly for about one minute or so. After that, the pupil showed GM followed by LLFF, and VOR parameters were gradually degrated accordingly.

Table 2 summarizes the effetive duration of each of the two sensory feedback stimuli, which was defined as the time between the initiation of sensory feedback stimulus and the introspective report in which the subjects reported sleepiness level higher than 2 again. In the case of the road noise feedback, the maximum duration was 6 minutes and the minumum was 4 minutes while in the case of the steering vibration feedback, the maximum was 8 minutes and the minimum was 2 minutes.

Table 2. Time [sec] from initiation of stimulus to renewed increase in subjective sleepiness.

	SY	TK	YT	AM	AO
Road noise	240	360	360	360	360
Steering wheel vibration	360	240	120	480	240

Among those 5 subjects, the number of subjects whose sleepiness level was improved in 4 minutes

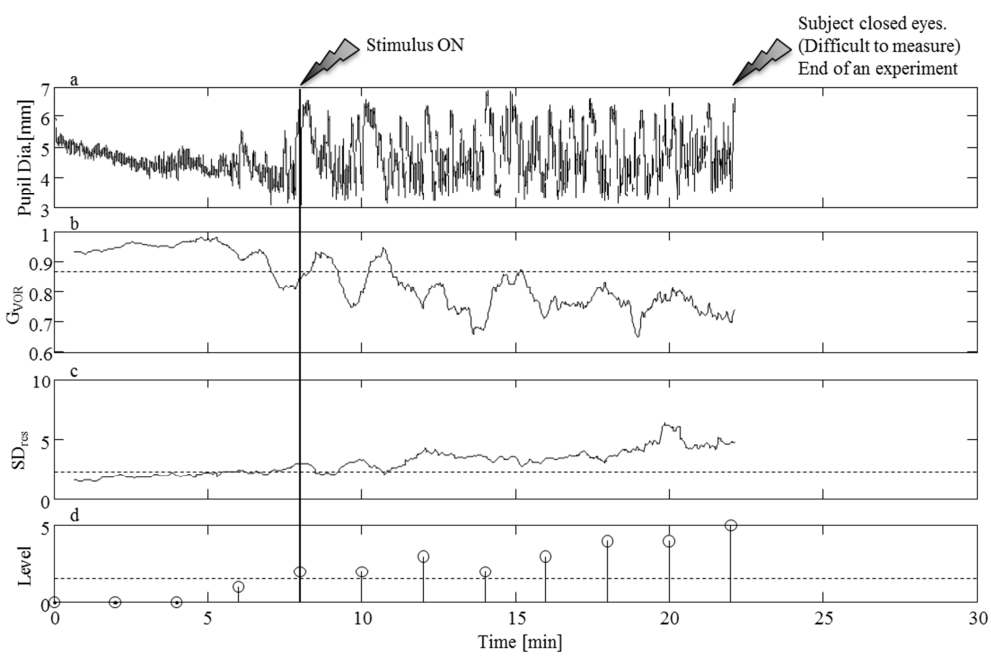

Figure 3. Changes in pupil diameter, VOR parameter and sleepiness level during the driving simulation in the active driving maneuver experiment with the steering wheel vibration stimulus. a: Pupil diameter. b: VOR gain. c: VOR variability (standard deviation of residual). d: Sleepiness level.

after the initiation of the sensory feedback stimulus was 2 for road noise, and 1 for steering vibration. In contrast, the number of subjects whose physiological indicators were either improved or maintained at the levels equal to those of arousal within four minutes after the stimulus initiation was three out of five (60%) for the road noise stimulus, and four out of five (80%) for the steering wheel vibration stimulus. Namely, in terms of physiological indices, the steering wheel vibration seems more effective than the road noise. Thus, we report the results from the steering wheel stimulus in the next experiment in which the stimulus was initiated when one of the physiological premonitors was detected.

B. Inhibiting sleepiness

Eight subjects who are different from those who participated in the experiment A participated in this experiment. Each subject underwent 3 conditions, namely control, subjective sleepiness, and predicted sleepiness. In the control condition, no steering vibration stimulus was given at any timing. In the subjective sleepiness condition, the stimulus was given from when self-aware sleepiness started till the end of the experiment. In the predicted sleepiness condition, the stimulus was started when premonitors of sleepiness are detected, and terminated when it disappeared. Figure 4 shows an example result from the experiment in which steering wheel vibration stimulus was given when premonitor of sleepiness was detected. The format is the same as Figures 3. In this example, the stimulus was initiated at 6 min when VOR variability exceeded its threshold for sleepiness prediction (First prediction of sleepiness. The beginning of the shadowed period). Soon after the initiation of the sensory feedback stimulus, VOR variability dropped back down to the threshold value or lower, thus the sensory feedback stimulus was terminated (the end of the shadowed period). After a while, at about 13 min, VOR gain exceeded the threshold value and the stimulus was initiated in the same way. The VOR gain increased back to the original threshold or higher due to application of the stimulus for 2.7 minutes (shadowed period around 14 min). The pupil diameter showed virtually no LLFF, indicating that physiological sleepiness has been limited by application of the stimulus based on premonitors of sleepiness. On the other hand, subjective sleepiness continued to rise gradually regardless of the application of sensory feedback stimulus. Clear correlation was not found in this case between the physiological measures of sleepiness and subjective sleepiness.

Table 3 summarizes the effecitive duration of the steering vibration feedback stimulus defined as the time between the initiation of the stimulus and the introspective report in which the subjects decleared sleepiness level higher than 2. The condition for the longest effective duration in terms of subjective sleepiness differed from subject to subject, and mean

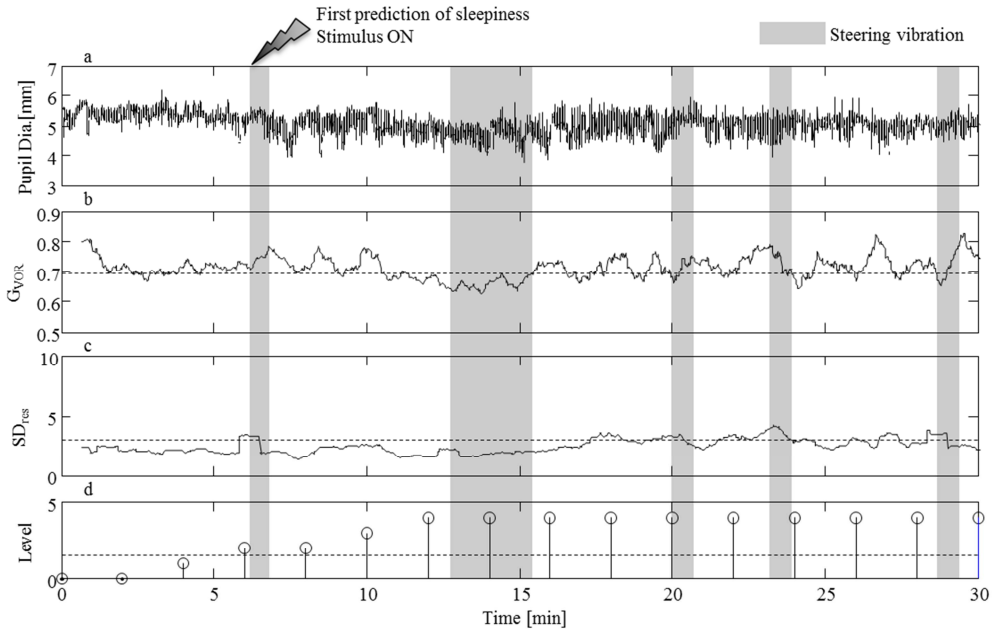

Figure 4. Changes in pupil diameter, VOR parameter and sleepiness level during driving simulation in the active driving maneuver experiment with the steering wheel vibration stimulus. a: Pupil diameter. b: VOR gain. c: VOR variability (standard deviation of residual). d: Sleepiness level.

Table 3. Time [min] from start of experiment to occurrence of self-aware sleepiness.

Subject	AI	KA	KK	YK	KO	SM	TM	SN	Ave.
Control	8	18	12	6	12	8	8	6	9.25
Subjective Sleepiness	6	10	16	6	8	8	6	10	9.25
Predicted Sleepiness	12	8	10	4	8	10	6	6	8.75

Table 4. Time [min] from start of experiment to occurrence of physiological sleepiness (LLFF).

Subject	AI	KA	KK	YK	KO	SM	TM	SN
Control	7.1	None	9.7	None	11.5	None	6.5	11.3
Subjective Sleepiness	8.0	None	19.5	13.9	13.8	None	7.3	9.8
Predicted Sleepiness	8.0	None	6.5	None	None	None	None	None

values over the 8 subjects for the 3 experimental conditions did not show significant differences.

On the other hand, Table 4 summarizes the effective duration of the steering wheel feedback stimulus defined as the time between the initiation of the stimulus and the initialtion of the pupillary LLFF for all the eight subjects in the 3 conditions. LLFF was not seen in two of the eight (KA and SM) under any of the 3 conditions, and they were therefore excluded from the following comparison. Results from comparison of the three conditions showed that in 5 of the 6 subjects (83%) the predicted sleepiness condition yielded the greatest effect on elongating the effective duration. Further, in 4 of the 6 subjects, LLFF was not observed until the end of the experiment, suggesting that these subjects were physiologically aleart during the monotonus DS experiment which easily makes most of our subjects sleepy in 10 minutes [3][6].

These results suggest that the active driving maneuver based on the steering wheel vibration feedback is effective in maintaining high-arousal level for a longer period of time, at least 6.5 minutes in the current experiment if the sensory feedback stimulus is started when physiological premonitor of sleepiness is detected.

DISCUSSION AND CONCLUSION

In the present study, we evaluated the effectiveness of voluntary driving maneuvers to maintain high arousal level for a long period of time by using driving simulation. We employed two kinds of sensory feedback stimuli whose intensity is modulated with the amount of deviation of the vehicle from the center of the driving lane. One is road noise and the other is steering wheel vibration. The voluntary maneuver that our subjects performed was to reduce the intensity of the sensory feedback by manipulating steering wheel to keep the vehicle at the center of the driving lane as close as possible. Thus this driving maneuver helps the driver keep in the driving lane at the same time with reducing somewhat annoying auditory or haptic stimulus, which may be regarded as a reward for the driver. In the first set of experiment, we compared the two sensory feedback stimuli by referring to our physiological sleepiness indices and showed that the road noise was effective in 3 out of 5 subjects while the steering wheel vibration was effective 4 out the same 5 subjects. Thus in the second set of experiment, we employed the steering wheel vibration, and evaluated the effective timings of initiation of the feedback stimulus in 8 new subjects, namely when subjective sleepiness was perceived or when a premonitor of sleepiness was detected. The prediction of sleepiness was done by referring to physiological measures (VOR gain and residual variability) that have been proposed previously [3]. As the result, it was demonstrated that initiating the steering wheel vibration feedback when the physiological predictor of sleepiness was detected was the most effective timing. Thus we conclude that the voluntary driving maneuver prompted to reduce the steering wheel vibration feedback stimulus is an effective novel method to prolong high arousal level during vehicle driving.

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