Interaction between Thermal Comfort and Arousal Level of Drivers in Relation to the Changes in Indoor Temperature

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Received on November 15, 2017

ABSTRACT: Driving comfort and driving safety are essential factors for drivers. As the environment of vehicle affects the comfort sensation and the arousal level of the drivers, it is necessary to contemplate the way to design of environmental factors inside vehicle. In this study, we focus on the thermal factors inside vehicle, and we aim to design a thermal environment which can improve both the thermal comfort and the arousal level of drivers. In our previous research, we showed that the changes in indoor temperature have possibility to improve both the comfort sensation and the arousal level of driver by analyzing the subjective parameters. To clarify the design requirements, it is needed to evaluate the thermal comfort and the arousal level of drivers continuously, quantitatively and separately. So, we focused on the physiological parameters which can be measured continuously, we investigated the relationship between the thermal comfort sensation, the arousal level of drivers based on facial expression and the physiological parameters, such as Electroencephalogram (EEG) and Electrocardiogram (ECG) when the indoor temperature changed. As a result, we showed that it is possible to evaluate the thermal comfort sensation and the arousal level of drivers quantitatively, continuously and separately by using those physiological parameters.

KEY WORDS: Safety, Driver condition, Arousal level, Thermal comfort, Driver monitoring [C1]

1. Introduction

Driving comfort and driving safety are essential factors for drivers who used to drive for many hours in daily life. To improve driving comfort and driving safety, it is necessary to contemplate the way to design of environmental factors inside vehicle such as light, temperature, humidity and air quality, because the environmental factors affect psychophysiological conditions of drivers, such as comfort sensation, arousal level. Especially, as thermal factors such as temperature, humidity and air velocity directly stimulate the surface of the human body, they are closely related to not only the sensation of thermal comfort but also the arousal level (1) (2). The arousal level of drivers is one of the important factors for the improvement of driving safety. Since drowsy driving and inattentive driving are one of the major causes of the fatal accidents, it is thus required that the drivers maintain a high arousal level. In our research, we aim to design a thermal environment inside the vehicle that improves both the arousal level and thermal comfort of the drivers.

Previous researches showed that the improvement of arousal level occurred in relation to the indoor temperature that felt cool or cold (1) (2). However, feeling cool or cold means that humans feel thermally uncomfortable (3). In other words, there is a trade-off between the arousal level and the thermal comfort of constant indoor temperature. Therefore, it was considered that controlling the thermal factors constantly was not an appropriate method for use in improving both the arousal level and the thermal comfort. In addition, previous researches showed that the thermal comfort was immediately altered in accordance with changes in indoor temperature (4), on the one hand, the arousal level was increased by stimulation and was maintained at a high state for several minutes (5). From these results of previous researches, we formulated a hypothesis that there is not always a dependence relation between the arousal level and the thermal comfort when the indoor temperature changes, we thus focused on the possibility that the changes in indoor temperature can improve both the arousal level and the thermal comfort of drivers. To confirm the possibility, it is needed to clarify the relations among the changes in indoor temperature, the thermal comfort and the arousal level of drivers on driving, and also needed to evaluate the thermal comfort and the arousal level of drivers continuously and quantitatively in order to clarify the design requirements for changes in indoor temperature in relation to improving both the arousal level and the thermal comfort. In our previous research (6), we investigate the relations among the thermal comfort, the arousal level and the driving performance of drivers corresponds to changes in indoor temperature, so that we showed that the periodic changes in indoor temperature can improve both the thermal comfort and the arousal level of drivers, and can improve the driving performance.

In this paper, to propose the indices that can evaluate the thermal comfort and the arousal level of drivers on driving continuously and quantitatively, we attempt to clarify effects of interaction between the arousal level and the thermal comfort of driver on physiological parameter of driver when indoor temperature is changed.

2. Strategy

To clarify the effects of interaction between them on physiological parameter of driver when indoor temperature is changed, we assumed the flow of physiological responses of driver
in thermal environment that are shown in Figure 1, and which are based on the previous studies (8).

As shown in Figure 1, Thermal stimulation is transmitted from the skin to the central nervous system, affecting the thermal sensation and comfort sensation, and a change in comfort sensation affects the autonomic nervous system, and the response is performed through the locomotive organ.

In addition, the driving environment is transmitted from the optic nerves of eyes to the central nervous system, and then it is transmitted to the locomotive organs to perform the driving tasks after passing through the information processing (perception, recognition, and judgment) in the central nervous system. And it is thought that the performing of the driving tasks also affects the autonomic nervous system as mental workload.

In consideration of this process, in this study, we attempt to control the indoor temperature to change the arousal level and the thermal comfort of the driver during driving tasks in several states such as thermal comfort and discomfort, high arousal level and low arousal level. Simultaneously, we measured EEG as an indicator of central nervous system activity, and ECG as an indicator of autonomic nervous system activity. As reference values of the thermal comfort, subjective evaluation values relating to thermal comfort (9) are used. As reference values of the arousal level, drowsiness rating values based on facial expression analysis (10) are used.

Fig.1  Flow of the physiological responses adapted from(8)

3. Experimental Methods

3.1. Thermal environmental conditions

To change the arousal level and the thermal comfort of the driver during driving tasks in several states such as thermal comfort and discomfort, high arousal level and low arousal level, it is necessary that both the thermal environment where thermal comfort and arousal level independently change and mutual change. In this experiment, under the constraints on the air conditioning performance of the laboratory, the thermal environmental condition were set to the following conditions with reference to the thermal environmental condition in which the thermal comfort was constant and the arousal level was fell (condition A) and the thermal environmental condition in which the thermal comfort and the arousal level mutually changed (condition B) in previous study (11):

- Condition A: The indoor temperature of 26°C was maintained.
- Condition B: The indoor temperature was altered from 26°C to 20°C, and then altered from 20°C to 26°C.

3.2. Setting of driving simulator

A driving simulator (hereinafter referred to as DS) was used as an experimental method for driving task. DS is a device that presents a virtual driving environment on the screen and users can drive in the virtual space. It is easy to set, control, and reproduce various environments such as dangerous situations, and participants are safe even if they fall asleep due to a decrease in the arousal level. Experiments were conducted by installing a simple DS device (Logitech) consisting of a display that presents the driving environment, a steering wheel, and a pedal in the laboratory as shown in Figure 2 (used in the previous research (7)).

As a scenario where keeping of a high arousal state is required, the driving course was created assuming driving for a long time on a highway by using 3 dimensional real-time virtual reality software (UC-win/Road, manufactured by Forum 8), and realized on the display. To evaluate whether it is possible to keep a proper distance with the preceding vehicle by appropriate speed selection and pedal operation, we set a scene that runs along the second lane of a three-lane highway with a road width of 3.5 m, and there is a preceding car that runs at about 100 km/h in front of the own vehicle, and sets a driving environment that follows the preceding vehicle and keeps the distance between the preceding vehicle and 100 m or more. We installed a pole every 50 m on the left side of the road and ordered to adjust the distance between vehicles with reference to that pole. To evaluate whether lane keeping can be maintained by appropriate handle operation, a straight road and a curved road (R = 500 m) are alternately set so that left curve and right curve appear once a minute when the vehicle speed is about 100 km/h. A part of the DS course is shown in Figure 3 (used in the previous research (9)). The course shown in Figure 3 (10) is repeated in whole course and participants were ordered to drive the whole course for 70 minutes.

Fig.2  Devices of driving simulator

3.3. Measurement and data processing

3.3.1. Reference value of thermal comfort and arousal level

a) Subjective sensations of thermal comfort
To clarify the transition of the thermal comfort of the driver, the participants were asked to complete a value relating to their thermal comfort sensation. The scale of thermal comfort is presented on the display every 5 minutes, and the participants were asked to speak with a number of the scale of thermal comfort at that time. The scale of thermal comfort sensation was based on ISO10551 (9), and denoted using integer numbers from -3 to 0 (-3: Very uncomfortable, -2: Uncomfortable, -1: Slightly uncomfortable, 0: comfortable);

b) Facial expression
The participants were recorded by the video camera, and the arousal level was recorded by the viewer in 10-s intervals in accordance with Zilberg’s criteria (10) after the experiment. The scale of the participants’ arousal level was based on the drowsiness level of Zilberg (10) and denoted using integer numbers from -4 to 0 (-4: Extremely drowsy, -3: Significantly drowsy, -2: Moderately drowsy, -1: Slightly drowsy, 0: Alert).
3.3.2. Physiological data

a) EEG

The indices of central nervous activity reflect the information processing of the central nervous system and the change of emotion due to the external stimulus. The information processing, the type of emotion, the activity state of the brain, etc. can be calculated for each measurement site or frequency band of brain wave and evaluated in detail (12) (13). EEGs were recorded using an EEG measuring instrument (EEG-1200, Nihonkohden Co., Japan) at the sampling rate of 500 Hz. EEG electrodes were attached on 16 Channels (based on the international 10–20 system, Fp1, Fp2, F7, F3, F4, F8, T7, C3, C4, T8, P7, P3, P4, P8, O1, O2) as shown in Figure 4. EEG data was filtered with a 30 Hz low-pass filter, and then artifact elimination for EEG data, such as EOG and EMG was performed manually. The data were divided into 10.24 sec periods (512 data points), and each periods were then processed using the Fourier transform method, and the spectral power of each frequency band was calculated, such as theta (4–8Hz), alpha (8–13Hz), beta (13-30Hz) band for each channel.

b) ECG

The indices of autonomic nervous activity reflect sympathetic nervous activity and parasympathetic nervous activity due to external stimuli and can be calculated from time series data of R wave intervals of heart beat (14). ECGs were recorded using an ECG measuring instrument (WEB-7000, Nihonkohden Co., Japan) at the sampling frequency of 1000 Hz. Electrodes were attached to the participants’ bodies using precordial leads as shown in Figure.5. The R wave which is the highest peak were extracted by using peak detection algorithm, and each R-R Interval (RRI) was calculated. The RRI processed using the fast Fourier transform method, and the spectral power of each frequency band was calculated, such as the VLF (very low frequency, 0.001–0.04Hz), LF (low frequency, 0.04–0.45Hz), HF (high frequency, 0.15–0.45Hz) was calculated.

3.3.3. Thermal environmental factors

To confirm the thermal condition around the participants in the laboratory in accordance with the set temperature, we measured the thermal factors around the participants. Specifically, the ambient temperature around the participant was measured by using the thermo-couples and the temperature logger (LT 8, manufactured by Gram) at intervals of 2 seconds. The position of thermo-couples was located at 2 points near the head and 2 points near the ankle when the participant was sitting on the seat. The relative humidity was measured at 1 minute intervals using a temperature and humidity data logger (MK scientific, 9606 U), and the air velocity near the head of the experiment participant was measured using a hot wire anemometer (DT8880, manufactured by MK scientific) at intervals of 10 seconds.

3.4. Experimental procedure

Experiments were conducted from July to September 2016 for 10 healthy males with vital statistics of 168.9 ± 3.4 cm, 62.9 ± 4.4 kg, 24.6 ± 1.6 years old. Experimental procedures, which were approved by the ethics committee of the University of Tokyo, were explained to the participants before the experiment. To reduce the influence on the arousal level, the participants were asked to avoid intense physical activity, alcohol, and caffeine for 24 h prior to the experimental session. The start time of the experiment was unified from 13:30 after lunch, and only one trial per day was conducted for one person. To reduce the influence on the thermal comfort sensation due to the seasonal influence and the difference in the external temperature, the clothes amount is unified as half-shorts and short sleeves, and participants were asked to rest for 60 minutes in the room set as 26 °C, which is known to be thermally neutral, and during that time, sensors for measuring EEG and ECG were attached. In addition, subjective evaluation of thermal comfort was conducted, and the experiment was started after confirming that the subjective evaluation value of thermal comfort was 0 (0: comfortable). To confirm that there is no difference in the arousal level on the day of execution of each condition, questionnaire on exercise time, sleeping time on the previous day and subjective level on the day of execution of each condition, questionnaire was carried out to get used to the operation of a DS device. At that time, participants were ordered to drive in the middle of the second lane and keep the distance between the preceding vehicle of 100 m or more by referring to the distance between the poles installed on the left side of the road. The driving time was 70 minutes, and the participants answered verbally the subjective evaluation value of the thermal comfort presented on the screen every 5 minutes while driving. Under the constraints of the air conditioning capacity in the experiment room, it was set to condition A or condition B for 70 minutes using cooling and heating. Each thermal environment of condition A and condition B were conducted once per 1 day, at the same time on different days. The experimental protocol and the time series of the indoor temperature are shown in Figure 6, and the view of the experiment is shown in Figure 7.
4. Results and Discussion

4.1 Classification of states related to the arousal level and the thermal comfort

To investigate the relationship among the arousal level, the thermal comfort and the physiological indices, the physiological parameters which were mentioned at the chapter 3.3.2 were measured during driving on DS for 70 minutes, and then a rectangular moving window is used and the window size is 10 seconds in the physiological parameters analysis, finally a data string of 420 columns (for 4200 seconds) was calculated in one trial. Then, we set the coordinate plane as shown in Figure 8, which is representing the thermal comfort on the x-axis of the coordinate plane and the arousal level on the y-axis of the coordinate plane. The data string was classified into each quadrant of the coordinate plane based on the value of the arousal level and the value of the thermal comfort contained in the data string calculated by averaging every 10 seconds. The first quadrant of the coordinate plane shows a state of high arousal level and thermally comfortable state, the second quadrant shows a state of high arousal level and a thermally uncomfortable state, the third quadrant of the coordinate plane shows a state of low arousal level and thermally uncomfortable state, the fourth quadrant shows a state of low arousal level and a thermally comfortable state. Based on Zilberg’s criteria (10), the boundary value between high arousal level and low arousal level was set to -2 (Moderately drowsy). The boundary value between thermally comfortable state and thermally uncomfortable state was set to -1 (slightly uncomfortable), which is a standard that the participants noticed thermal stimulus and began to feel uncomfortable.

The data strings obtained in this experiment were a total of 8268 rows. As a result of classifying the data string based on the boundary value, data strings of 4158 rows distributed on the first quadrant of the coordinate plane, data strings of 2084 rows distributed on the second quadrant, data strings of 709 rows distributed on the third quadrant of the coordinate plane, data strings of 1317 rows distributed on the fourth quadrant. The number of data strings distributed in the third quadrant (thermally unpleasant, low arousal state) is fewer than the number of data strings distributed in the second quadrant (thermally uncomfortable state and high arousal level). From this result, it was assumed that the thermal stimulus caused by the decrease in the indoor temperature raised the arousal level of the driver.

4.2 Characteristics of the parameters of the ECG in each states related to the arousal level and the thermal comfort

To investigate the characteristics of the indices of autonomic nervous system in each of the quadrants in Figure 8, we performed multiple comparisons by using the parameters of the ECG of data strings distributed in each of the quadrants based on the Bonferroni method. The result of LF/HF value which represents the activity of sympathetic nervous system is shown in Figure 9, and the result of HF content which represents the activity of parasympathetic nervous system is shown in Figure 10.

As shown in Figure 9, the LF/HF value in the third quadrant is the highest (p <0.001) and the LF/HF value in the first quadrant was the lowest (p <0.001). There was no significant difference between the second quadrant and the fourth quadrant. On the other hand, as shown in Figure 10, the HF content in the third quadrant was the lowest (p <0.001) and the HF content in the first quadrant was the highest (p <0.001). There was no significant difference between the second quadrant and the fourth quadrant. This result shows that sympathetic nervous activity is dominant and parasympathetic nervous activity is suppressed when driving in the state of low arousal level and thermally uncomfortable state. It is confirmed that these indices are affected by both the arousal level and the thermal comfort.
It is known that parasympathetic nerve activity is dominant and sympathetic nerve activity is suppressed during decreasing of arousal level (19). However, these results are contrary to the general results. It is considered that the results were affected the paradoxical response of physiological index in the awake effort state (16). On the other hand, as for the influence of the thermal comfort, the similar results as the previous research were obtained (17). It is thus clear that sympathetic nerve activity was dominated by thermal stress regardless of task execution.

4.3 Characteristics of the parameters of the EEG in each states related to the arousal level and the thermal comfort

To investigate the characteristics of the indices of central nervous system in each of the quadrants in Figure 8, we performed multiple comparisons by using the parameters of the EEG of data strings distributed in each of the quadrants based on the Bonferroni method. As an example of the results, the result of the theta, alpha, beta wave content of the frontal lobe (Fp1) is shown in Figure 11. The theta wave content of the frontal lobe in the state of high arousal level (the first quadrant and the second quadrant) was significantly higher than the state of low arousal level (the third quadrant and the fourth quadrant) (p<0.001). On the other hand, the alpha and the beta wave content of the frontal lobe in the state of high arousal level was significantly lower than the state of low arousal level (p<0.001).

Generally, it is known that the θ wave content increases in the low arousal state. However, this result is contrary to the general result. As known in a paradoxical reaction of the physiological indices in the awake effort state (conflict between sleeping desire and task execution) (16), it is thought that brain reaction due to conflicts that the driver must carry out the driving task in a drowsy state was more active than a state when the driver can perform the driving task in an awake state.

In addition, the theta and the beta wave content rate of the frontal lobe has a significant difference only between states with different arousal levels. Since there was no significant difference between the quadrants with different states of the thermal comfort (between the first quadrant and the second quadrant or between the third quadrant and the fourth quadrant), there is a possibility that can evaluate only the arousal level of the driver by using the θ wave content rate of the frontal lobe in an environment where thermal comfort is changed.

As the other example of the results, the result of the theta, alpha, beta wave content of the occipital lobe (O2) is shown in Figure 12. The theta wave content of the occipital lobe in the state of high arousal level (the first quadrant and the second quadrant) was significantly higher than the state of low arousal level (the third quadrant and the fourth quadrant) (p<0.001), and there was also a significant difference between the first quadrant (thermally comfortable) and the second quadrant (thermally uncomfortable).

On the other hand, the alpha wave content of the occipital lobe in the state of high arousal level was significantly lower than the state of low arousal level (p<0.001), and there was also a significant difference between the third quadrant (thermally uncomfortable) and the fourth quadrant (thermally comfortable). The beta wave content of the occipital lobe in the state of high arousal level was significantly higher than the state of low arousal level (p<0.001), and there was also a significant difference between the third quadrant (thermally uncomfortable) and the fourth quadrant (thermally comfortable).

These results suggested that there are both the indices which are affected by the arousal level only (for example, the theta wave content of the frontal lobe) and indices which are affected by both arousal level and the thermal comfort (for example, the beta wave content of the occipital lobe) in the indices of central nervous system.

4.4 Summary of the results

From the result of the relations among the subjective sensation value of thermal comfort, the criteria of the drowsiness level based on analysis of facial expression and the physiological parameters, it was shown that the parameters of the ECG were affected by both the arousal level and the thermal comfort. These results suggested that autonomic nervous system was affected by the interaction between the thermal comfort and the arousal level. On the other hand, the parameters of the EEG measured in the frontal lobe were not affected by the thermal comfort but the arousal level. These results also suggested that it is possible to evaluate the thermal comfort sensation and the arousal level of drivers quantitatively and continuously by using the physiological parameters.
were affected by both the arousal level and the thermal comfort. These results suggested that autonomic nervous system was affected by the interaction between the thermal comfort and the arousal level.

The parameters of the EEG consist of the parameters which were only affected by the arousal level, and the parameters which were affected by both the arousal level and the thermal comfort.

5. Conclusion

Through the results of our study, we confirm that the relations among the thermal comfort, the arousal level and the physiological parameters of drivers corresponds to changes in indoor temperature. To clarify effects of interaction between the arousal level and the thermal comfort on physiological parameter of driver, we investigated the subjective evaluation of thermal comfort, facial expression and the parameters of ECG and EEG. As a result, the following things were noted.

- It was shown that the parameters of the ECG were affected by both the arousal level and the thermal comfort. These results suggested that autonomic nervous system was affected by the interaction between the thermal comfort and the arousal level.
- The parameters of the EEG consist of the parameters which were only affected by the arousal level, and the parameters which were affected by both the arousal level and the thermal comfort.

This paper is written based on a proceeding presented at JSAE FAST-zero'17 Meeting

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