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An Investigation of the Effects of Changes in the Indoor Ambient Temperature on Arousal Level, Thermal Comfort, and Physiological Indices †

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Abstract: Thermal factors not only affect the thermal comfort sensation of occupants, but also affect their arousal level, productivity, and health. Therefore, it is necessary to control thermal factors appropriately. In this study, we aim to design a thermal environment that improves both the arousal level and thermal comfort of the occupants. To this end, we investigated the relationships between the physiological indices, subjective evaluation values, and task performance under several conditions of changes in the indoor ambient temperature. In particular, we asked subjects to perform a mathematical task and subjective evaluation related to their thermal comfort sensation and drowsiness levels. Simultaneously, we measured their physiological parameters, such as skin temperature, respiration rate, electroencephalography, and electrocardiography, continuously. We investigated the relationship between the comfort sensation and drowsiness level of occupants, and the physiological indices. From the results, it was confirmed that changes in the indoor ambient temperature can improve both the thermal comfort and the arousal levels of occupants. Moreover, we proposed the evaluation indices of the thermal comfort and the drowsiness level of occupants using physiological indices.

Keywords: thermal comfort; arousal level; physiological indices; electroencephalography; electrocardiography

1. Introduction

The control of indoor environmental quality (IEQ, which consists of visual elements, olfactory elements, and thermal factors, etc.) is important for improvements of the comfort and productivity of occupants. Among the factors of IEQ, thermal factors, such as ambient temperature, radiant temperature, humidity, and air velocity, are especially related with not only the thermal sensation and thermal comfort of occupants, but also productivity and health. With the high technology of heating, ventilation, and air conditioning systems (HVAC systems), the relationship between thermal factors and thermal sensation and thermal comfort has received attention from several researchers worldwide. In previous research, indices of thermal comfort, such as the predicted mean vote (PMV), predicted percent dissatisfied (PPD), and standard new effective temperature (SET*), have been proposed based on the relationship between thermal factors and the subjective evaluation of thermal comfort sensation [1,2]. Many studies have analyzed the indoor thermal quality based on the evaluation of thermal factors using these indices [3–7].

In addition, improvements of the productivity of occupants who are working, studying, and driving in indoor spaces, such as offices, classrooms, and vehicles, are needed. It is necessary to maintain a high arousal state of the occupants to improve their productivity. In previous studies, it was shown that productivity improved when the arousal level of occupants was high, and this was related to the indoor ambient temperature that occupants felt as cool or cold [8,9]. From the results of previous studies, the conditions of the ambient temperature to improve task performance were different from the conditions of the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers)'s thermal comfort zone [10]. Therefore, the conditions of the constant ambient temperature were not appropriate to improve both the task performance and thermal comfort levels. In previous studies, it was shown that the thermal comfort of occupants was immediately changed in accordance with changes in the indoor ambient temperature [11]. The arousal level was increased by outer stimulation and was maintained at a high state for several minutes [12,13]. Based on these results of previous studies, we hypothesized that thermal stimulation due to cooling can improve the arousal level of occupants. Furthermore, thermal comfort can be improved while maintaining high arousal levels due to the removal of thermal stimulation. When considering the possibility that changes in thermal factors can improve both arousal and thermal comfort levels, the physiological effects associated with such changes in thermal factors, and how they affect the arousal level and thermal comfort of occupants are not clear. Therefore, the design requirements for changes in ambient temperature to improve both the arousal level and thermal comfort are also not clear. Therefore, a continuous and quantitative evaluation of the thermal comfort and arousal level of occupants using indices, which can be measured both continuously and quantitatively, such as physiological signals, is needed to clarify the design requirements of changes in the indoor ambient temperature to improve both the arousal level and thermal comfort.

In this study, we aimed to investigate the characteristics of changes in the arousal level and feelings of thermal comfort of occupants, and the relationship between them when thermal factors are changed. There are many factors that affect the thermal comfort and arousal level of occupants, such as the ambient temperature, indoor air velocity, mean air radiant temperature, and metabolic activity [5–7]. Especially, we focused on the changes in the indoor ambient temperature as a fundamental investigation in this study. In addition, to propose evaluation indices that can evaluate the thermal comfort and arousal level of occupants continuously and quantitatively, we investigated the relationship between the arousal level, feelings of thermal comfort, and physiological indices, which can be measured continuously and quantitatively.

2. Strategy

2.1. Investigation of the Effects of Changes in the Indoor Ambient Temperature on Arousal Levels, Thermal Comfort, and Task Performance

To verify the hypothesis that thermal stimulation, due to cooling, can improve the arousal level of occupants, and that thermal comfort can be improved while maintaining high arousal levels due to the removal of thermal stimulation, several thermal conditions were set. Subjects were asked to conduct a mathematical task and periodically evaluate their sensation values (using a subjective sensation vote) in relation to their arousal level and thermal comfort. We attempt to clarify the effect of changes in the indoor ambient temperature on the arousal level, thermal comfort, and task performance of occupants by conducting an analysis of the results of the subjective sensation vote and task performance.

2.2. Investigation of the Relation between the Subjective Evaluation Value and Physiological Parameters, and a Recommendation for Evaluation Indices

Indices that can evaluate the arousal and thermal comfort levels of occupants continuously and quantitatively are necessary to clarify the design requirements of a temperature control that can improve the arousal and thermal comfort levels of occupants. However, as it was not possible to perform a subjective sensation voting continuously, we considered clarifying the design requirements for thermal environments using changes over time. This relied on the possibility to evaluate the arousal level and feelings of thermal comfort using physiological parameters that could be measured quantitatively and continuously. Previous studies have shown that the physiological indices measured utilizing electroencephalograms (EEG), electrocardiograms (ECG), and respiration rates were effective for the evaluation of arousal levels [14,15], and the skin temperature, EEGs, and ECGs of occupants were effective for the evaluation of the thermal comfort [16,17]. Therefore, in this study, we assumed a flow of physiological responses when the occupant was stimulated by thermal factors, as shown in Figure 1, based on the above-mentioned previous studies to clarify the characteristics of the physiological parameters under the condition of changes in both the arousal level and thermal comfort. A thermal stimulation is transmitted from the sensory organ, such as warm spots and cold spots of skin, to the central nervous system, which affects thermal and comfort sensation. This change in comfort sensation then affects the autonomic nervous system, and the response is then conducted through the locomotive organ. Based on this process, we selected the skin temperature as an indicator of heat transfer between the environment and the human body, EEGs as an indicator of the reaction of the central nervous system, and ECGs as indicators of the reaction of the autonomic nervous system. Next, we attempted to search for indices that could separately evaluate the arousal level and thermal comfort by performing a multiple regression analysis utilizing the physiological parameters and subjective evaluation values of the arousal level and feelings of thermal comfort. In Figure 1, the flow of physiological responses with the thermal stimulus is shown.

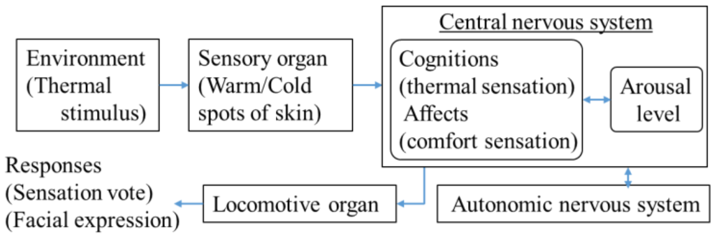


Figure 1. Flow of physiological responses with the thermal stimulus.

3. Methodology

3.1. Subjects

Ten subjects with vital statistics of a height of 173.5 ± 4.4 cm, weight of 61 ± 4.8 kg, age of 22.1 ± 1.2 years old, and who were right-handed participated in the experiment. The experimental contents and procedures, which were approved by the ethics committee of the University of Tokyo, were explained to the subjects before conducting the experiment. The subjects were then asked to avoid intense physical activity, alcohol, and caffeine for 24 h prior to the experimental session.

3.2. Experimental Task

The subjects were asked to conduct mental arithmetic tasks known as "MATH", which is based on the algorithm proposed by Tuner et al. [18]. A 1–3-digit addition or subtraction question is displayed for 2 s on the monitor, and then "equals to" is displayed for 1.5 s. Lastly, the answer is displayed for 1 s, and the next question is displayed after 0.5 s. Subjects had to determine if the answer was correct or incorrect when the answer was displayed and click the left mouse button if the answer was correct or the right mouse button if the answer was incorrect. The levels of questions in the original version of MATH consisted of 1–5 levels. In this study, the beginning level was 3 (which is 2-digit addition or subtraction), and the level of the next question was raised if the responses of the subjects were correct, and was reduced if answers were incorrect. We deduced that changing the levels affected the physiological indices. Thus, we did not change the level of the question, and fixed it to level 3. The MATH task included 50 questions for 250 seconds per set.

3.3. Experimental Conditions and Experimental Procedure

To evaluate the effects of the duration and degree of thermal stimulation, three environmental conditions (A–C) were set as follows.

- Condition A: The indoor ambient temperature was maintained at 27 °C.
- Condition B: The indoor ambient temperature was decreased from 27 °C to 20 °C, and then increased from 20 °C to 27 °C.
- Condition C: The indoor ambient temperature was decreased from 27 °C to 20 °C, and then maintained at 20 °C.

We set condition A as a thermally comfort condition [10], and condition C as a high arousal condition [8,9]. Condition B was set to verify the hypothesis that thermal stimulation due to cooling can improve the arousal levels of occupants, after which thermal comfort can be improved while maintaining high arousal levels due to the removal of thermal stimulation. There are many parameters which affect the thermal comfort and arousal levels of occupants, such as the indoor velocity, mean air radiant temperature, metabolic activity, and amount of clothing. In this study, we focused on only the indoor ambient temperature as a fundamental investigation, thus those parameters except the indoor ambient temperature were controlled in the experiment. The subjects wore short sleeves and short pants and were asked to remain in the pre-room. The room temperature was set at 27 ± 0.5 °C for approximately 1 h so that subjects could adjust to the thermal environment; they were asked to practice the "MATH" at least twice during this time. Sensors were then attached to the bodies of the subjects to measure their physiological indices. One set of tasks consisted of completing the subjective sensation vote and the "MATH" task. The subjects were asked to perform seven sets of tasks at time intervals of 10 min and to rest between each task for approximately 3 min. Physiological indices were measured from the start time (0 min) till the end time (70 min). The experimental procedure and environmental conditions are shown in Figure 2.

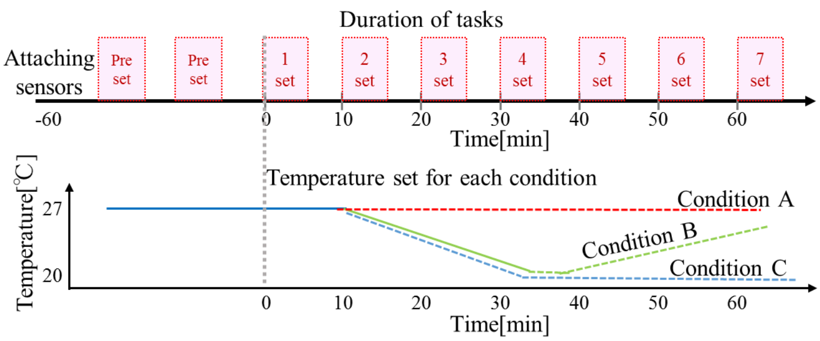


Figure 2. Experimental conditions and environmental procedure.

3.4. Measurement

3.4.1. Subjective Evaluation of the Drowsiness Level and the Thermal Comfort Sensation

Before completing the "MATH" task, the subjects were asked to complete a questionnaire related to their thermal sensation, thermal comfort sensation, and arousal level. The scale of thermal sensation was based on ASHRAE/ISO (International Organization for Standardization) [10], and was denoted using integral numbers from −3 to 3 (where −3, −2, −1, 0, 1, 2, and 3 are the meanings of cold, cool, slightly cool, neutral, slightly warm, warm, and hot, respectively.). The scale of comfort sensation was based on ISO10551 [19], and was denoted using integral numbers from −3 to 0 (where −3,

−2, −1, and 0 are the meanings of very uncomfortable, uncomfortable, slightly uncomfortable, and comfortable, respectively.). The scale of the arousal level was based on the drowsiness level of Zilberg's indicators [20], and was denoted using integral numbers from 0 to 4 (where 0, 1, 2, 3, and 4 are the meanings of alert, slightly drowsy, moderately drowsy, significantly drowsy, and extremely drowsy, respectively.).

3.4.2. Physiological Indices

(a) EEG

EEGs were recorded using an EEG-measuring instrument (EEG-1200, Nihonkohden Co., Japan) at a sampling rate of 500 Hz. EEG electrodes were attached on 16 channels (based on the internationally accepted 10–20 system, Fp1, Fp2, F7, F3, F4, F8, T7, C3, C4, T8, P7, P3, P4, P8, O1, O2). Next, raw data were processed using the Fourier transform method, and the spectral power of each frequency band, such as the content of theta wave (4–8 Hz), low-alpha wave (8–10 Hz), high-alpha wave (10–13 Hz), low-beta wave (13–20 Hz), high-beta wave (20–30 Hz), and SMR (12–15 Hz) bands, was calculated in addition to the values of the beta per alpha and alpha per high-beta for each channel.

(b) ECG

ECGs were recorded using an ECG-measuring instrument (WEB-7000 and ECG picker, Nihonkohden Co., Japan) at a sampling rate of 1000 Hz. Three electrodes were attached to the chests of subjects using the precordial leads method. The R-R interval (RRI) was calculated from the ECG waveform using MATLAB (Mathwork Co.) programs. The values of the mean of the RRI and the coefficient of variance of RRI [CVRR (100*SD/Mean of RRI)] were calculated from the RRI data. In addition, the spectral power of each frequency band, such as the very low frequency (VLF, 0.001–0.04 Hz), low frequency (LF, 0.04–0.15 Hz), and high frequency (HF, 0.15–0.45 Hz) bands, was calculated from the time series of the RRI using the fast Fourier transform method.

(c) Respiration

A thermal picker (WEB-7000, Nihonkohden Co., Japan) was used to measure the temperature of the breath of subjects. The peak values in the time series graph of the temperature were detected, and the mean and standard deviation of the respiratory cycle time were calculated.

(d) Skin Temperature

Thermocouples were attached at 7 places on the bodies of subjects based on the Hardy–Du Bois method [16] to measure the skin temperature (LT8, GRAM Co., Japan). Finally, the mean skin temperature was calculated using following Equation (1):

$$MST = 0.07\,T_1 + 0.14\,T_2 + 0.05\,T_3 + 0.35\,T_4 + 0.19\,T_5 + 0.13\,T_6 + 0.07\,T_7 \quad (1)$$

where MST is the mean skin temperature based on the Hardy-DuBois method [16], and T_1, T_2, T_3, T_4, T_5, T_6, and T_7 are the temperatures of the forehead, forearms, hands, abdomen, thighs, legs, and feet, respectively.

3.4.3. Facial Expression and Task Performance

The activities of subjects were recorded using the video camera, and the drowsiness levels were recorded by an observer at intervals of 10 s based on Zilberg's criteria [20]. After the experiment was completed, the mean of the data recorded when subjects were performing the MATH task was calculated. The task performance of MATH included the number of correct answers and the mean of the reaction time taken to solve 50 questions. Figure 3 shows a participant completing the experiment. Figure 3 shows photos of the field of experimental scene.

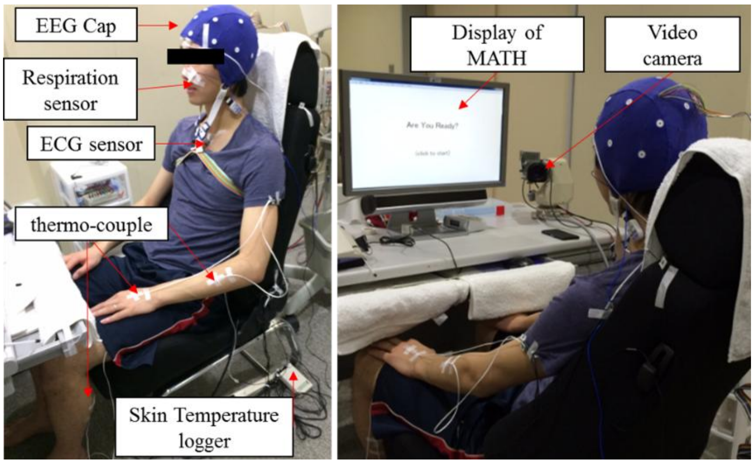


Figure 3. Field photos of the experimental scene.

4. Results and Discussion

4.1. Characteristics of the Arousal Level and Thermal Comfort Corresponding to Changes in the Indoor Ambient Temperature

4.1.1. Subjective Evaluation Value

The results of the subjective evaluation value corresponding to the drowsiness levels and the thermal comfort sensation vote of subjects under conditions A, B, and C are shown in Figures 4 and 5. We used multiple comparison based on the Bonferroni method to investigate significant differences of the subjective evaluation value due to changes in the indoor ambient temperature. There was a small change in the comfort sensation vote, but the drowsiness level increased under condition A, where the indoor temperature was maintained at 27 °C. Under condition B, the comfort sensation vote decreased to an uncomfortable state when the indoor ambient temperature dropped, and increased to a comfortable state when the indoor ambient temperature increased. Under condition C, the comfort sensation vote decreased to an uncomfortable state when the indoor temperature decreased and was then maintained in this uncomfortable state. Under conditions B and C, the drowsiness levels decreased and were maintained at an alert state, corresponding to the drop in the indoor temperature. After the completion of set 4, the comfort sensation vote increased, corresponding to the increase in the indoor temperature under condition B, but was maintained at an uncomfortable state under condition C. The drowsiness level was maintained at a low state under both conditions. According to this result, the arousal level was maintained at a high state even when the temperature increased, and subjects felt comfortable even when the temperature dropped, leading to an increased arousal level. This suggests that there is not always a dependence relationship between the arousal levels and feelings of thermal comfort. Figures 4 and 5 show that when condition B is applied in sets 6 and 7, it becomes possible to improve both the arousal level and thermal comfort of occupants by changing the indoor ambient temperature. These results show that the hypothesis that thermal stimulation due to cooling can improve the arousal level of occupants, after which thermal comfort can also be improved while maintaining a high arousal levels due to the removal of thermal stimulation was verified for condition B. Figure 4 shows the result of the thermal comfort sensation vote. Figure 5 shows the result of the drowsiness level sensation vote.

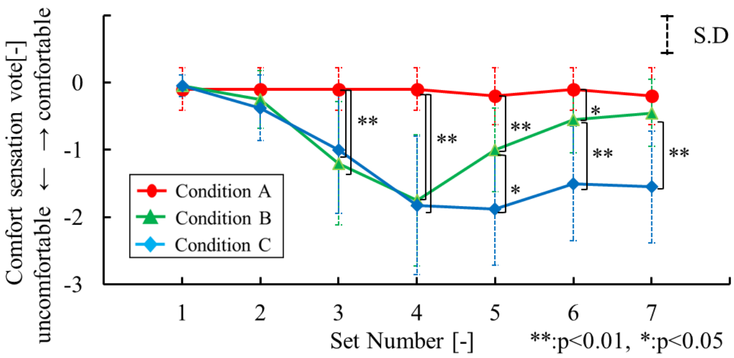


Figure 4. Results of the value of the thermal comfort sensation vote.

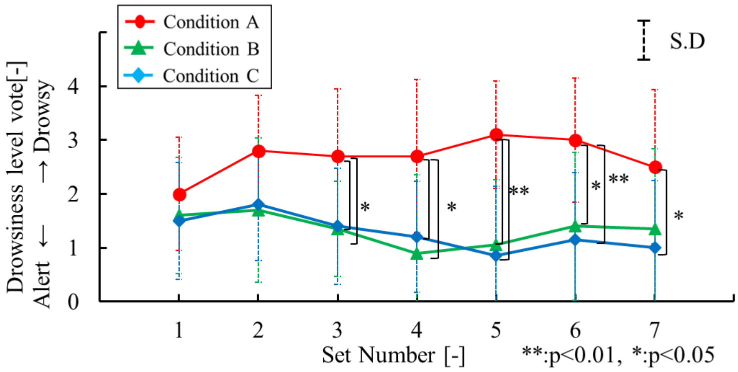


Figure 5. Results of the value of the drowsiness level sensation vote.

4.1.2. Rating Value of Zilberg's Drowsiness Level by Observer

The rating values of Zilberg's drowsiness level for each condition are shown in Figure 6, and it is evident from the figure that the results are similar to those of the subjective sensation vote. Multiple comparison based on the Bonferroni method was conducted to investigate significant differences of the drowsiness level due to the changes in the indoor ambient temperature. After the completion of set 3, the drowsiness levels under conditions B and C decreased significantly compared to that under condition A. From the result of condition B, it was confirmed that the drowsiness level was maintained at a low state after the completion of set 3.

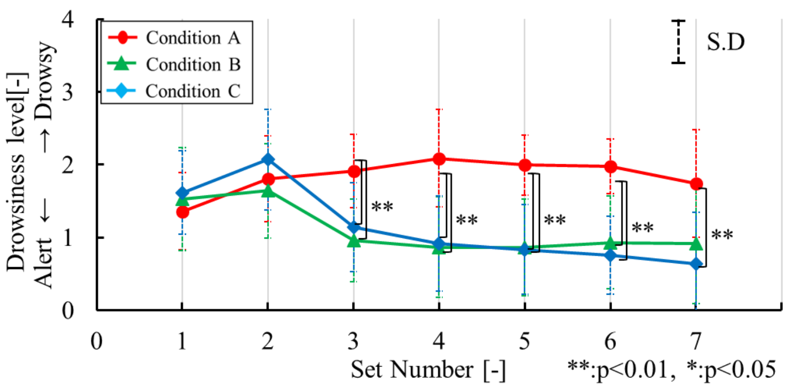


Figure 6. Drowsiness level reached when calculating MATH (analysis of facial expressions based on Zilberg's method [20]).

4.1.3. Task Performance of MATH

The results of the MATH score under each condition are shown in Figure 7, and the results of the response time taken to calculate MATH questions under each condition are shown in Figure 8. Multiple comparison based on the Bonferroni method was conducted to investigate significant differences in the task performance due to changes in the indoor ambient temperature. It can be seen from Figures 7 and 8 that the MATH score was high after set 4, and the response time taken to calculate MATH questions increases in the order of conditions C, B, and then A. Differences were observed between the conditions in the results of the subjective sensation vote and the rating value of Zilberg's drowsiness level. However, significant differences were observed only between the conditions in the result of the response time taken to calculate MATH for set 4, and the result of the MATH score for set 5. It was assumed that the MATH work was easy enough for the subjects to perform, even at a low state of arousal. Figure 6 shows the drowsiness level reached when calculating MATH (analysis of facial expressions based on Zilberg's method [20]). Figures 7 and 8 show the result of the MATH score and the response time from the display of the MATH question to the participant's click.

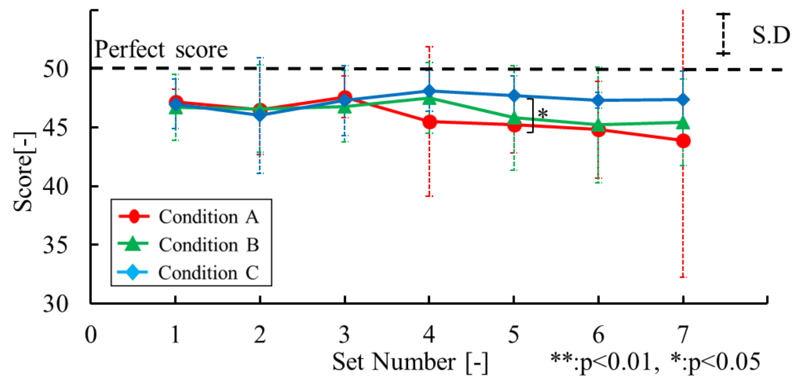


Figure 7. Result of MATH score.

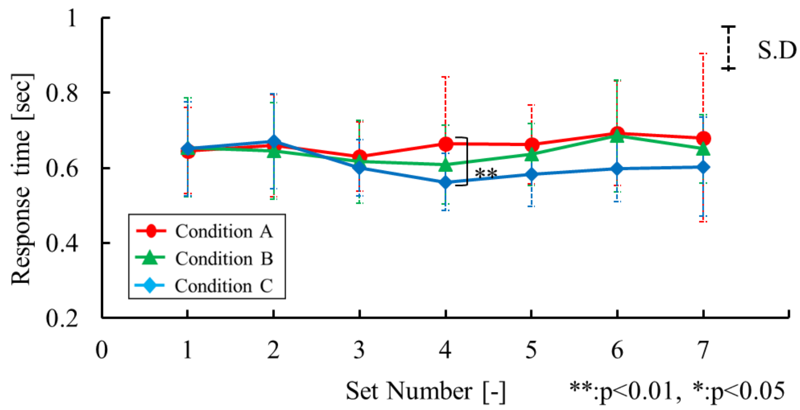


Figure 8. Result of response time.

4.1.4. Consideration of Thermal Stimulation for High Arousal Levels

In the previous studies of Yoshida et al. [12] and Mohri et al. [13], to maintain a high arousal level, the effects of several stimulation methods, such as the use of a fragrance, alarm, and shoulder oscillation, were confirmed. As a result, the sleeping rebound occurred 10 min after the stimulation in those studies. As in our results, high arousal states were maintained for over 10 min after the removal of thermal stimulation. Though further investigation of these comparisons of the time to rebound is necessary, our results showed that thermal stimulation is effective in improving the arousal levels of occupants. Especially, our method is useful in spaces where air conditioning systems are installed, because the installation of additional devices in the space to make stimulations, such as fragrances, alarms, and shoulder oscillation, is unnecessary.

4.2. Relationship between the Subjective Evaluation Value and Physiological Indices

Three hundred and twenty-nine physiological indices were calculated by using the data of the EEGs, ECGs, respiration rate, and mean skin temperature in the experiment (320 indices from EEGs, 7 indices from ECGs, 2 indices from respiration rate, and 1 index from skin temperature). By considering the result of the subjective evaluation value as the standard for the perception of state, we used correlative analysis to investigate the relationship between the subjective evaluation value and the physiological indices. According to the flow of the physiological response shown in Figure 1, changes in both the arousal level and thermal comfort affect the physiological response. To find indices (out of the 329 physiological parameters) that corresponded to the arousal level, we used data from sections when the arousal level changed, but the value of the thermal comfort sensation was maintained constantly. On the other hand, to find indices that corresponded to thermal comfort, we used data from sections when the value of the thermal comfort sensation changed and the arousal level was maintained constantly.

4.2.1. Relationship between the Drowsiness Level and Physiological Indices

As a result of the correlation analysis, the correlation coefficients between values of the drowsiness level vote and physiological indices were calculated using data from 57 sets in which the value of the drowsiness level vote varied, but the value of the comfort sensation vote remained at 0 (comfortable). There was a significant correlation between the drowsiness level and 102 physiological indices (data $N = 57$, $r > 0.339$, $p < 0.01$). The indices in relation to the ECGs were not included in these parameters; however, the indices in relation to the EEGs were included. Thus, this result showed that the relationship between the reaction of the central nervous system and changes in arousal levels is more significant than that between the reaction of the autonomic nervous system and changes in arousal levels.

4.2.2. Relationship between Thermal Comfort and Physiological Indices

As a result of the correlation analysis, the correlation coefficients between the values of the comfort sensation vote and physiological indices were calculated using the data from 98 sets in which the value of the comfort sensation vote varied, but the value of the drowsiness level vote was between 0 (alert) and 1 (slightly drowsy). There was a significant correlation between the value of the comfort sensation vote and seven physiological indices in relation to skin temperature, EEGs, and ECGs (data $N = 98$, $r > 0.259$, $p < 0.01$). The change in the mean skin temperature is related to thermal stimulation from the outer environment, which is transmitted to the central nervous system and perceived as thermal comfort, thus affecting the parameters of the EEGs. It was observed that changes in the thermal comfort affected the autonomic nervous system, which in turn affected the indices in relation to the ECGs. It appears that this process affected the result of the correlation analysis in this experiment.

4.2.3. Calculation of the Evaluation Index Using Multiple Regression Analysis

To propose an index that evaluates the changes in each arousal level and thermal comfort states, multiple regression analysis was performed using the physiological indices that have a significant correlation with the value of subjective evaluation. It was found that 102 parameters had a significant correlation with the drowsiness level vote, and seven parameters with the comfort sensation vote. These were thus considered as explanatory variables. Because an explanatory variable should have a high correlation with the subjective sensation vote, to obtain a high multiple regression coefficient, we selected an explanatory variable for use in the multiple regression analysis using the following process.

- Indices that had a significant correlation with the value of subjective evaluation were sorted according to their correlation coefficient from high to low ($x1$, $x2$, ... $x102$).
- $x1$ was selected as the explanatory variable, since it had the highest correlation coefficient with the value of subjective evaluation.

- $x2$ was selected as the explanatory variable if there was no significant correlation between $x2$ and $x1$.
- xn was selected as the explanatory variable if there was no significant correlation between xn and all the parameters selected previously as explanatory variables.

(a) Evaluation Index indicating the Arousal Level

The result of the multiple regression analysis 1 (Yd) is shown in Table 1, and the regression equation obtained from the result is expressed in Equation (2). The variables of the regression equation include the indices of the EEGs. As a result, the coefficient of determination, R^2, in relation to Yd was 0.750.

$$Yd = -3.31 + 0.134\ Xd_1 + 2.520\ Xd_2 + 0.088\ Xd_3 - 0.268\ Xd_4 + 0.271\ Xd_5 \quad (2)$$

where Xd_1, Xd_2, Xd_3, Xd_4, and Xd_5 are the high alpha content of T7, beta per alpha content of F7, beta content of F3, low beta content of F7, and alpha content of Fp1, respectively.

Table 1. Result of multiple regression 1 (Yd).

Model Summary				
R	0.8657		Std. Error	0.7358
R^2	0.7495		data N	57
Adjusted R^2	0.7249			
Index	**Coefficient**	**Std.Error**	**t**	***p*-value**
Intercept	−3.3123	0.4959	−4.6631	2.28×10^{-5}
T7_High-alpha	0.1338	0.0201	6.6478	1.96×10^{-8}
F7_Beta/Alpha	2.5196	0.3073	8.1996	7.09×10^{-11}
F3_Beta	0.0878	0.0245	3.5817	0.0008
F7_Low beta	−0.2684	0.0481	−5.5791	9.29×10^{-7}
Fp1_Alpha	0.2708	0.0315	8.5969	1.72×10^{-11}

We defined Yd as the index of the arousal level. To confirm the possibility that Yd can evaluate the arousal level even when the thermal comfort changed, we calculated Yd from the data obtained from five subjects for whom the arousal level and thermal comfort changed considerably, and then performed a correlation analysis between Yd and the evaluation value of the drowsiness level. As a result of the correlation analysis, the correlation coefficient (R) was calculated to be 0.726, and there was a significant correlation between Yd and the evaluation value of the drowsiness level. Therefore, this result suggests that Yd can be used to evaluate the drowsiness level, even when there are changes in the thermal comfort.

(b) Evaluation Index Indicating Thermal Comfort

The result of the multiple regression analysis 2 (Yc) is shown in Table 2, and the regression equation obtained from the result is expressed in Equation (3). The variable for the regression equation included the indices of the skin temperature and EEGs. As a result, the coefficient of determination, R^2, in relation to Yc was 0.528.

$$Yc = -23.372 + 0.697\ Xc_1 + 0.172\ Xc_2 + 0.142\ Xc_3 \quad (3)$$

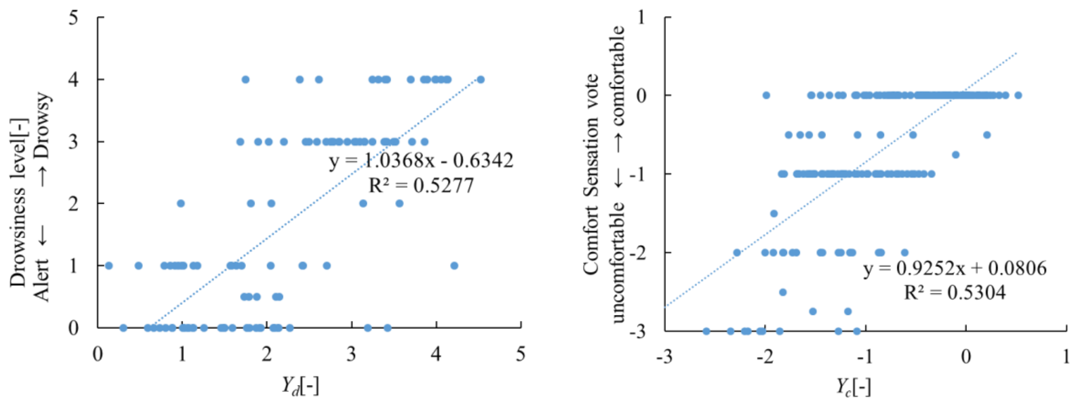
where Xc_1, Xc_2, and Xc_3 are the *MST* (Mean Skin Temperature), alpha per high-beta content of C4, and alpha per high beta content of P4, respectively.

Table 2. Result of multiple regression 2 (*Yc*).

Model Summary				
R	0.7267		Std. Error	0.6859
R^2	0.5276		data N	98
Adjusted R^2	0.5125			
Index	**Coefficient**	**Std.Error**	**t**	***p*-value**
Intercept	−23.3721	2.5461	−9.1795	1.02×10^{-14}
MST	0.6967	0.0765	9.1119	1.42×10^{-14}
C4_Alpha/HB	0.1718	0.0586	2.9295	0.0043
P4_Alpha/HB	−0.1418	0.0296	−4.7885	6.25×10^{-6}

We defined *Yc* as the index of thermal comfort. To confirm the possibility that *Yc* can evaluate thermal comfort even when there were changes in the drowsiness level, we calculated *Yc* from the data of nine subjects, excluding the data of participant *D* whose thermal comfort vote and drowsiness level vote changed slightly. We thus confirmed the relationship between *Yc* and the value of thermal comfort. As a result, the correlation coefficient (R) was calculated to be 0.728, and there was a significant correlation between *Yc* and the value of thermal comfort ($p < 0.01$). Therefore, this result suggests that *Yc* can be used to evaluate thermal comfort even when there are changes in the drowsiness level.

Table 1 shows the result of the multiple regression 1 (*Yd*), and Table 2 shows the result of the multiple regression 2 (*Yc*). Figure 9 shows the relationship between the drowsiness level vote and *Yd*(a), and the relationship between the comfort sensation and *Yc* (b)

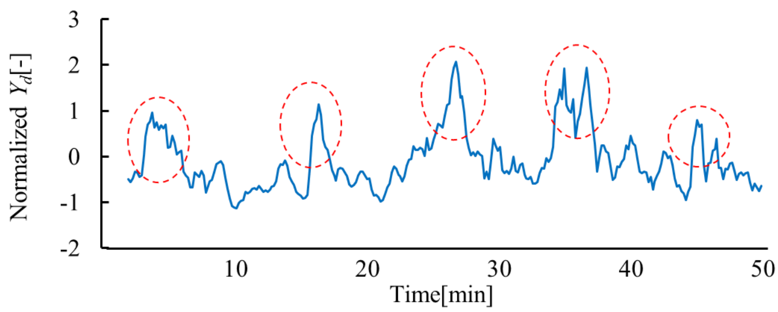


(**a**) (**b**)

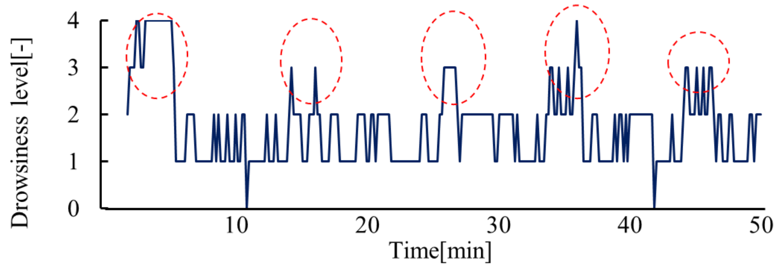
Figure 9. The relationship between the drowsiness level and *Yd* (**a**), the comfort sensation and *Yc* (**b**).

(c) Review of Continuous Evaluation using *Yd* and *Yc*

As mentioned in Section 2.2., indices that can continuously evaluate the drowsiness level and thermal comfort of occupants are needed to clarify the design requirements related to thermal factors that can improve these states of the occupants. Therefore, we conducted a time-series analysis with *Yd* and *Yc* to confirm the possibility that *Yd* and *Yc* can continuously evaluate arousal levels and thermal comfort. We calculated the time series of *Yd* using data from subject C, who seemed to be drowsy frequently throughout the experiment, and compared these data with those of the drowsiness level, which was recorded at intervals of 10 s by analyzing the facial expressions of the subject based on Zilberg's method [20]. The time series analyses of the normalized *Yd* and the drowsiness level of subject C are shown in Figure 10a,b. The figures clearly show the trend of changes in both indicators. It can be seen that *Yd* and values of the drowsiness level show a similar trend. For example, the red circles in Figure 10a,b indicate that values of the drowsiness level and the normalized *Yd* are higher than 3 (significantly drowsy) and 0, respectively, at the same time. Furthermore, it can be seen from Figure 11 that there is a similar trend between *Yc* and the value of the comfort sensation vote. In Figure 11a,b, the value of the comfort sensation drops to −3 (very uncomfortable) at 30 min, and at the same time, the value of *Yc* drops and becomes a negative number. Thereafter, the value of the comfort sensation vote remains at an uncomfortable state (−3: Very uncomfortable, −2: Uncomfortable), and similarly, the value of *Yc* remains at a negative value. These results suggest that *Yd* and *Yc* can be used to evaluate the drowsiness level and thermal comfort of occupants continuously. Figures 10 and 11 show, respectively, changes in the normalized *Yd* (a) and drowsiness level (b), (subject C) and changes in *Yc* (a) and the comfort sensation vote (b) (subject B).

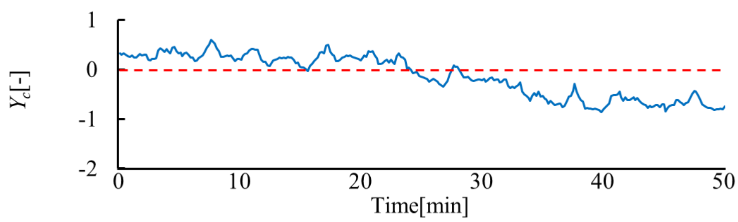


(**a**)

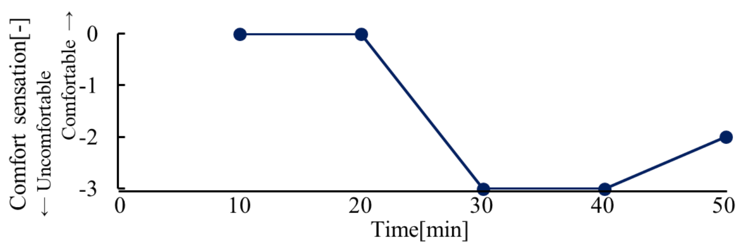


(**b**)

Figure 10. Changes in the normalized *Yd* (**a**) and drowsiness level (**b**), (subject C): (a) Time series of normalized *Yd*, (**b**) Time series of the value of the drowsiness level.



(**a**)



(**b**)

Figure 11. Changes in *Yc* (**a**) and the value of the comfort sensation vote (**b**): Time series of the value of the comfort sensation vote, (subject B).

(d) Review of the Utility and Validity of the Evaluation Index

To review the utility and validity of the evaluation index, as an example, we set the threshold value in relation to *Yd* and the drowsiness level. When the threshold value of *Yd* is sets as 2.3, as shown in Figure 12, *Yd* can be used as the classifier, which can classify the drowsiness level between level 0, 1, 2, or more with an 86.7% accuracy. This result suggests that there is a significant difference in the physiological reaction between the drowsiness level of 1 (slightly drowsy) and 2 (moderately drowsy), and is a similar trend to the results of a previous study about the relation between the arousal levels and physiological indices of a driver [21], though the task of the subjects is different from that of the previous study (arithmetic task vs driving). This result also suggests that *Yd* is a valid indicator of the drowsiness level of occupants to classify between the drowsiness level of 1 (slightly drowsy) and 2 (moderately drowsy). Figure 12 shows the setting of the threshold value in relation to *Yd*.

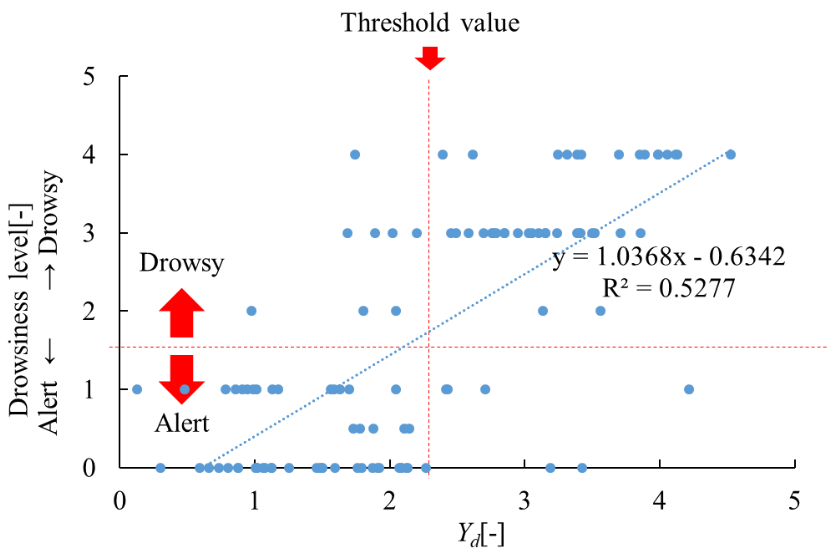


Figure 12. Setting of the threshold value in relation to *Yd*.

5. Conclusions

In this study, we aimed to design a thermal environment that can improve the indicators of both the arousal level and feelings of thermal comfort. We hypothesized that thermal stimulation due to cooling can improve the arousal level of occupants, after which thermal comfort can be improved while maintaining high arousal levels due to the removal of thermal stimulation. To verify the hypothesis, we measured physiological indices, values of subjective evaluation, and performances of arithmetic tasks throughout several thermal conditions in which the indoor ambient temperature was changed. In addition, we investigated the relationships between them to identify the indices that can be used to evaluate the arousal levels and thermal comfort of occupants. As a result, the following findings were noted:

- When the indoor ambient temperature decreased and then increased, both the arousal level and thermal comfort of occupants remained at high levels. This result suggests that the hypothesis of this study was verified and changes in the indoor ambient temperature can be used to improve both thermal comfort and the arousal level of occupants.
- We proposed the evaluation indices of thermal comfort and the drowsiness level of occupants. It was observed that the drowsiness level and thermal comfort of occupants can be evaluated quantitatively and continuously using *Yd* and *Yc*, which were obtained from the equation consisting of physiological indices in relation to EEGs, ECGs, and skin temperature.

In future work, we will investigate the relationship between the change patterns of the indoor ambient temperature, thermal comfort, and arousal levels of occupants. After that, we aim to design a novel thermal environment, considering all comfort parameters based on these findings, with the aim of improving both the arousal levels and feelings of thermal comfort of occupants, and then carry out an evaluation of the validity of the designed thermal environment.

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Formula Symbols

Index	Meaning	Unit
MST	Mean skin temperature	°C
T_1	Temperature of the forehead	°C
T_2	Temperature of the forearms	°C
T_3	Temperature of the hands	°C
T_4	Temperature of the abdomen	°C
T_5	Temperature of the thighs	°C
T_6	Temperature of the legs	°C
T_7	Temperature of the feet	°C
Yc	Index of thermal comfort	
Yd	Index of drowsiness level	
Xd_1	High alpha content of T7	
Xd_2	Beta content per alpha content of F7	
Xd_3	Beta content of F3	
Xd_4	Low beta content of F7	
Xd_5	Alpha content of Fp1	
Xc_1	Mean skin temperature	°C
Xc_2	Alpha content per high beta content of C4	
Xc_3	Alpha content per high beta content of P4	

References

1. ISO7730:2005. Ergonomics of the thermal environment-Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
2. De Dear, R.; Brager, G.S. Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans.* **1998**, *104*, 145–167.
3. Yang, Y.; Li, B.; Liu, H.; Tan, M.; Yao, R. A study of adaptive thermal comfort in a well-controlled climate chamber. *Appl. Therm. Eng.* **2015**, *76*, 283–291. [CrossRef]
4. Cannistraro, M.; Cannistraro, G.; Restivo, R. Some Observations on the Influence on Exchanges Radiative. *Int. J. Heat Techonol.* **2015**, *33*, 115–122. [CrossRef]
5. Cannistraro, M.; Lorenzini, E. The Applications of the New Techonologies E-Sensing in Hospitals. *Int. J. Heat Techonol.* **2016**, *34*, 551–557. [CrossRef]
6. Cannistraro, M.; Cannistraro, G.; Restivo, R. Smart Controll of Air Climatization System in Function on the Values of the Mean Local Radiant Temperature. *Smart Sci.* **2015**, *3*, 157–163. [CrossRef]
7. Liu, J.; Yao, R.; McCloy, R. A method to weight three categories of adaptive thermal comfort. *Energy Build.* **2012**, *47*, 312–320. [CrossRef]
8. McIntyre, D.A. *Indoor Climate*; Applied science publishers: London, UK, 1980.

9. Gohara, T.; Iwashita, G. Disscussion of relationship between indoor environmental comfort and performance in simple task. *J. Environ. Eng.* **2003**, *572*, 75–80. [CrossRef]
10. ASHRAE-55. *Thermal Environmental Conditions for Human Occupancy*; American Society of Heating, Refrigerating and Air-conditioning Engineers: Atlanta, GA, USA, 2004.
11. Kondo, E.; Kurazumi, Y.; Horikoshi, T. Human physiological and psychological reactions to thermal transients with air temperature step changes: A Case of Climacteric Aged Females in Summer. *J. Hum. Living Environ. Jpn.* **2014**, *21*, 75–84.
12. Yoshida, M.; Kato, C.; Kakamu, Y.; Kawasumi, M.; Yamasaki, H.; Yamamoto, S.; Nakano, T.; Yamada, M. Study on Stimulation Effects for Driver Based on Fragrance Presentation. In Proceedings of the MVA2011 IAPR Conference on Machine Vision Applications, Nara, Japan, 13–15 June 2011; pp. 332–335.
13. Mohri, Y.; Kawaguchi, M.; Kojima, S.; Yamada, M.; Nakano, T.; Mohri, K. Arousal retention effect of magnetic stimulation to car drivers preventing drowsy driving without sleep rebound. *Trans. Inst. Electr. Eng. Jpn.* **2016**, *136*, 383–389. [CrossRef]
14. Mardi, Z.; Naghmeh, S.; Ashtiani, M.; Mikaili, M. EEG-based drowsiness detection for safe driving using chaotic features and statistical tests. *J. Med. Signals Sens.* **2011**, *1*, 130–137. [PubMed]
15. Furman, G.D.; Baharav, A.; Cahan, C.; Akselrod, S. Early detection of falling asleep at the wheel: A heart rate variability approach. *Comput. Cardiol.* **2008**, *35*, 1109–1112.
16. Hardy, J.D.; Dubois, E.F. The technic of measuring radiation and convection. *Nutrition* **1938**, *5*, 461–475. [CrossRef]
17. Yao, Y.; Lian, Z.; Liu, W.; Jiang, C.; Liu, Y.; Lu, H. Heart rate variation and electroencephalograph-the potential physiological factors for thermal comfort study. *Indoor Air* **2009**, *19*, 93–101. [CrossRef] [PubMed]
18. Turner, J.R.; Hewitt, J.K.; Morgan, R.K.; Sims, J.; Carroll, D.; Kelly, K.A. Graded mental arithmetic as an active psychological challenge. *Int. J. Psychophysiol.* **1986**, *3*, 307–309. [CrossRef]
19. SO10551. First edition 1995-05-15, Ergonomics of the thermal environment–Assessment of the influence of the thermal environment using subjective judgement scales.
20. Zilberg, E.; Burton, D.; Xu, Z.M.; Karrar, M. Methodology and initial analysis for development of non-invasive and hybrid driver drowsiness detection systems. In Proceedings of the 2nd IEEE International Conference Wireless Broadband and Ultra Wideband Communications, AusWireless, Sydney, Australia, 27–30 August 2007; p. 16.
21. Gwak, J.S.; Shino, M.; Hirao, A. Eary detection of driver drowsiness using machine learning based on physiological signals, behavioral measures and driving performance. In Proceedings of the 21th IEEE International Conference on Intelligent Transportation Systems, Maui, Hawaii, USA, 4–7 November 2018; pp. 1794–1800.