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Relaxation Induced by Comfortable Thermal Stimulation of the Feet Presented with Various Sensory Stimuli

– Evaluation via Autonomic Nervous Activity –

Seiya FUJIWARA, Haruki OITA, Mayumi UEMAE,
Hiroaki YOSHIDA and Masayoshi KAMIJO

Graduate School of Shinshu University, 3-15-1 Tokida, Ueda, Nagano 386-8567, Japan

Abstract: We examined the degree to which relaxation was induced by the presentation of a comfortable thermal foot stimulation paired with other sensory stimuli. We presented a movie of an underwater scene, classical music, light blue illumination, vibrations to the trunk, and grapefruit odor as relaxing stimuli in combination with thermal stimulation, and measured physiological responses of the autonomic nervous system (electrocardiogram, respiration, fingertip pulse wave, peripheral blood flow, and sweating). All stimulus combinations induced parasympathetic activation compared with an initial control. In particular, the presentation of an odor with thermal stimulation elicited a remarkable degree of parasympathetic activation. We verified differences in the latency and duration of physiological responses depending on the stimuli combination. However, subjective relaxation was not confirmed, and parasympathetic activation for combined stimuli did not remarkably differ from that for thermal stimulation alone. These results indicate that thermal stimulation has a powerful effect on relaxation induction.

Keywords: *Thermal comfort, Physiological measurement, Multisensory integration*

1. INTRODUCTION

In this study, we examined the degree to which simultaneous presentation of various types of stimuli (such as visual and auditory) with thermal stimulation of the soles of the feet could induce the relaxation effect. In our previous study [1], we examined the different physiological responses of the central nervous system to simultaneous presentation of comfortable thermal stimuli applied to the soles of the feet with other sensory stimuli. We found that “thermal + other sensory stimuli” suppressed brain activity and induced relaxation. In this study, we used the physiological response of the autonomic nervous system as a measure of the relaxation-inducing effect. The relaxation effect is usually evaluated according to parasympathetic activity in the autonomic nervous system. In this paper, we calculated the physiological indices of parasympathetic nervous system activity and verified whether this system was activated by the presentation of multisensory stimuli. These methods revealed the degree to which different combinations of stimuli with thermal stimulation could induce relaxation.

In terms of the effects of thermal stimulation combined with other forms of sensory stimulation, a few studies have examined the effects of a foot bath with simultaneous odor presentation. Seki et al. [2] presented lavender oil during a foot bath. They found that the application of

lavender oil significantly reduced the LF/HF and prolonged the increase in blood flow at the fingertips. Similarly, Shirakawa et al. [3] reported a significant decrease in average heart rate after simultaneous presentation of a foot bath and lavender oil, accompanied by strong subjective feelings of relaxation. In terms of other stimulus combinations, Fukumitsu et al. [4] revealed that the simultaneous presentation of a hot pack and music to patients with knee osteoarthritis significantly changed the brain wave α -band (8.0 to 13 Hz). These studies indicate that the simultaneous presentation of thermal and other sensory stimuli can induce relaxation. However, no studies have investigated the effects of different stimulus combinations.

In this study, we tested the effects of simultaneous thermal stimulation of the feet with stimuli targeting other sensory modalities, including music, video, illumination, odor, and vibration (applied to the trunk). Our goal was to examine the relaxation-inducing effects of simultaneous thermal stimulation and that of other sensory organs, using physiological responses as a measure of autonomic nervous system activity.

2. METHODS

2.1 Stimuli Selection

Table 1 shows a list of the stimuli presented in this study. In our previous studies, these stimuli had the strongest relaxation-inducing effects [1]. We conducted a

Table 1: Stimulus presentation conditions

Stimulus	Presentation stimulus	Presentation method	Other stimulus candidates
Thermal	Thermal stimulation to the soles (40°C)	Silicon rubber heater (HAKKO FINE THERMO Co., Ltd.)	36°C, 44°C
Movie	Underwater movie	Projector: EB-535W (EPSON Co., Ltd.)	Sunset, Animal, Flower, Forest
Music	Beethoven - Pathetique Piano Sonata No.8 Op.13-2	Headphone: WH-1000X M2 (SONY Co., Ltd.)	Chopin – Nocturnes Nocturne No.2 Es-Dur Op.9-2, Mozart - Konzert für Klavier und Orchester Nr.23 A-Dur K.488 Mov.2 Adagio, Satie - Gymnopédies No.1, Bach - Orchestral Suite No. 3 in D major, BWV 1068
Illumination	Light blue Illumination (50lx)	LED Cube (THOUSLITE Co., Ltd.)	Deep blue, Green, Yellow green, Orange
Vibration	Vibration to trunk (55Hz)	Cushion speaker (Shima System Co., Ltd.)	40 Hz, 70 Hz, 85 Hz, 100 Hz
Odor	Grapefruit /Injection of odor	Aroma shooter (aroma join Co., Ltd.)	Citron, Orange

pilot study in which we used Scheffe's paired comparison method (Ura's variation, odor stimuli were evaluated using Nakaya's variation) to determine the most relaxing stimuli. Participants were asked to rate their "feelings of comfort", "feelings of relaxation", and "preferences" on a 7-point scale (−3 to 3), with "neither", "slightly", "very", and "extremely" as adjectives. We recruited a total of 20 participants (10 men and 10 women). The stimulus candidates are shown in Table 1.

1. Thermal stimulation

- Reasons for focusing on thermal stimulation of the feet

There are many possible ways to provide warmth to humans. For instance, hot baths, air conditioner, and heating wire heaters, whose thermal stimuli are presented to the entire body or body parts. Here, we focused on thermal stimulation of the extremities, specifically, the feet. Thermal stimulation of the extremities has been found to evoke feelings of relaxation and comfort. Shin et al. [5] revealed that the psychological and physiological responses of the human body to thermal stimuli vary according to the body part at which the stimulus is presented. Kuji et al. [6] reported that the simultaneous application of heat to the hands and feet was effective for inducing a feeling of warmth. Additionally, heat more effectively induced positive feelings when applied to the feet compared with the hands. Several studies have evaluated the degree of comfort elicited by the application of heat to human body according to autonomic nervous system activity [2, 7-10]. These studies evaluated changes in heart rate variability and peripheral blood flow that reflect autonomic nervous activity. Among them, Yamamoto et al. [7] reported that subjecting participants to a foot bath at 42°C significantly decreased the sympathetic nervous activity index LF/HF (an index obtained by frequency analysis of heart rate variability). Similarly, Saeki [2] reported that a 40°C foot

bath increased blood flow at the fingertips and significantly decreased the LF/HF. These results suggest that a foot bath can suppress sympathetic nerve activity and enhance parasympathetic nerve activity. Zhu et al. [8] examined changes in autonomic nervous system activity when the whole body was exposed to hot and cold environments. They revealed an increase in LF/HF at low (22°C) and high temperature environments (30°C), and a small LF/HF value at neutral temperatures (26°C). Together, these findings indicate that the warming of the whole body causes discomfort and enhances sympathetic nerve activity, while thermal stimulation of the extremities activates parasympathetic nerve activity and evokes positive feelings of comfort, even at a slightly higher temperature (more than 40°C).

- Thermal stimulation method

We presented thermal stimulation at to the soles of the feet. The participants were asked to place their bare feet on a silicon rubber mat-shaped heater (Hakko Fine Thermo Co., Ltd.), which comprised a resistance wire positioned between two silicon sheets. A brass diffuser and a 100% cotton cloth were installed on the heater to control the temperature of the contact surface. The pilot test indicated that a temperature of 40°C elicited the strongest relaxation effect, so this was used in the main study.

2. Video stimulation

Many previous studies have used video stimulation to evoke various emotions, enabling examination of the physiological responses of the autonomic nervous system that correspond to psychological states (e.g. [11-13]). In the pilot study, a movie depicting underwater scenes evoked the strongest feelings of relaxation. Accordingly, this movie was projected on a screen in the main study (1.5 meters from the participants) using a projector (EB-535W, EB-535W, Epson Co., Ltd.). The video

contained 30 underwater photos, each of which was displayed for 10 seconds (300 seconds in total).

3. Music stimulation

Many studies have reported that classical music evokes relaxation, and music is known to suppress sympathetic and enhance parasympathetic nervous system activity (e.g. [14, 15]). The pilot study indicated that Beethoven's "Pathétique Piano Sonata No. 8, Op. 13–2) elicited the strongest relaxation effect. Accordingly, we presented the first 5 minutes of the music file, which was 5 minutes and 40 seconds long, to the participants in the main study using stereo headphones (WH-1000X M2, Sony Co., Ltd.).

4. Illumination stimulation

Illumination was presented using a color-changing LED cube (THOUSLITE Co., Ltd) installed on the ceiling at an angle of 2.0 meters squared, such that illumination was presented from above. The horizontal illuminance was set to 50 lx at a height of 1.5 meters.

Despite the findings of Matsui et al. [16], who revealed that green illumination (200 lx) significantly enhanced the HF (parasympathetic activity index), the pilot study indicated that light blue illumination had the most relaxing effect. Thus, we used light blue stimulation in the main study.

5. Vibration stimulation

Participants were asked to hold a cushion speaker (Shima System Co., Ltd.) that produced a vibration. This speaker vibrated at a low frequency to match the rhythm of the music. The speaker unit was attached to a soft rubber plate inside the cushion, which absorbed the vibration in the mid-range and transmitted the bass range to the front, making it easier to vibrate the speaker. A sine wave was outputted using MATLAB (Mathworks Co., Ltd.). The vibration frequency in the main study was 55 Hz, as the pilot study indicated that this produced the most relaxing effect. Additionally, to prevent habituation, the amplitude was set to randomly change 0.25, 0.50, 0.75, and 1.00 times every 2.5 seconds. The cushion was connected to a laptop via a PDP-SAI digital amplifier (Sima System Co., Ltd.).

To our knowledge, no previous studies have examined the physiological response to vibrations presented to the trunk. However, Otsuki et al. [17] measured the physiological response to a 26-Hz whole body vibration (WBV) delivered to standing participants. They reported an acute decrease in arteriosclerosis after WBV, although there was no difference in blood pressure or heart rate.

6. Odor stimulation

Previous studies have reported that pleasant odors can suppress sympathetic nerves and activate parasympathetic

nerves [18, 19]. In the pilot study, the aroma of grapefruit oil was rated as the most relaxing odor stimulus. Accordingly, this stimulus was used in the main study. For stimulus delivery, we used an aroma shooter (Aroma Join Co., Ltd.), which ejects an odor from a cartridge inserted into the device. The device was positioned to the front of the participant's right side. To prevent habituation to the odor, injections were performed at 10-second intervals.

In the main study, we presented a total of six types of stimuli with two conditions: thermal stimulation alone and thermal stimulation plus that targeting other sensory organs.

2.2 Physiological Measurement

We measured autonomic activity according to electrocardiograms (ECGs), respiration, sweating, fingertip pulse wave, and peripheral blood flow. All biological signals were recorded at a sampling frequency of 1000 Hz.

1. ECG

ECG electrodes were attached to the participants at the upper sternum and apical region via the chest bipolar induction method using a MP150WS ECG100C amplifier system (BIOPAC Systems, Inc.). R waves were detected from the ECG data, and the R-R intervals (RRI) were calculated. The instantaneous heart rate (IHR), coefficient of variation of RRI (CVRR), LF/HF, and HF were calculated using the time-series changes in RRI. The IHR is the R-R interval converted to heart rate per minute and is calculated by dividing 60 by the RRI. The CVRR reflects heartbeat fluctuations and was used as an index of parasympathetic nerve activity. The CVRR was calculated by dividing the mean of the RRI during 1 minute by the standard deviation of the RRI. Spline complementation was performed on the RRI time series data, and frequency analyses were performed on the obtained waveform. The range of the low frequency component LF (0.04 to 0.15 Hz) and the high frequency component HF (0.15 to 0.4 Hz) were integrated with respect to the obtained spectrum, and LF and HF were calculated. LF/HF was calculated by dividing LF by HF. LF/HF is regarded as an index of sympathetic nerve activity, and thus a reflection of stress. HF reflects parasympathetic nerve activity. LF/HF and HF were calculated in 3-minute windows, and the calculation window was moved every 1 minute (i.e., 0–3 minutes, 1–4 minutes).

2. Respiration

We measured respiration by attaching a temperature probe (TSD202A, BIOPAC Systems, Inc.) to each participant near the nostrils, and the signal was amplified using a SKT100C unit (BIOPAC Systems, Inc.). Respiration

was estimated according to the temperature change around the nostrils. We conducted frequency analysis for the respiratory waveform and calculated the respiration peak frequency from the spectral waveform. This index reflects respiration rate. As the autonomic nervous system controls respiration, a small peak frequency indicates that parasympathetic nerve activity is dominant.

3. Fingertip pulse wave

We measured the fingertip pulse wave by attaching a pulse wave transducer (TSD200, BIOPAC Systems, Inc.) to the second finger of each participant's left hand. The signal was amplified using a PPG100C unit (BIOPAC Systems, Inc.). We calculated the pulse transit time (PTT) from the time difference between the rise point of the pulse wave waveform and the R wave of the ECG. The pulse wave velocity increases as the blood vessels contract with the activation of the sympathetic nerves. As blood pressure rises, the arterial wall stretches more strongly and the pulse wave velocity increases. Therefore, there is a negative correlation between PTT and blood pressure because PTT decreases with vasoconstriction. A small PTT value indicates sympathetic nerve activation.

4. Peripheral blood flow

We used a MoorVMS-LDF laser Doppler blood flow meter and a VT1T optical probe (Zero C Seven Co., Ltd.) to measure peripheral blood flow. The probe was attached to the third finger of the participant's left hand. Blood perfusion units (BPU) were calculated from this sensor. We calculated the section average for each minute from the obtained waveform to use as an index of blood flow. Contracted blood vessels and decreased blood flow reflect sympathetic nerve dominance.

5. Sweating

We used an SKN-2000 (SKINOS Co., Ltd.) unit to measure the amount of sweating. Sweating of the human body can be roughly classified as mental sweating caused by stress and thermal sweating to suppress an increase in internal temperature. We attached a probe to the fourth finger of the left hand to measure mental sweating. From the obtained signal, we calculated the section average for each minute and used this as an index of sweating amount.

In this study, 8 physiological indicators related to autonomic nerve activity were calculated from biological signals. We used these indicators as a measure of relaxation-inducing effect. Among these indices, the indicators whose values increase in the relaxed state (parasympathetic nerve is dominant) are CVRR, HF, PTT, and BPU, and the indicators which decrease in relax state are IHR, LF/HF, Respiration peak frequency, and Sweating rate.

2.3 Experimental Protocol

Participants were 10 healthy students at Shinshu University (5 men and 5 women aged 20–24 years), having experience in participating experiments that performed physiological response measurements and sensory tests. Additionally, the participants had no autonomic nervous system dysfunction and did not take medications that affect the autonomic nervous system. The experimental protocol is shown in Figure 1, and the experimental environment is shown in Figure 2. One trial comprised a cognitive load task (180 seconds) and a stimulus presentation (300 seconds). One stimulus condition was presented per trial, for a total of six trials, performed on the same day. The entire experiment was conducted twice (two days in total). The datasets collected on a day with no data loss were analyzed. The experiment was carried out in a room with constant temperature and humidity (25°C, 55% relative humidity). While not presenting light blue illumination, the LED cube produced white illumination (horizontal illuminance: 50 lx). Thermal stimulation was constantly presented, including during the load task. The participants were seated in a car seat. The angle of the backrest of the car seat was 120°, and the angle of the seat surface was 5°. This seat angle has been reported to be comfortable for humans [20].

Figure 1: Experimental Protocol

Figure 2: Experimental Environment

Figure 3: ATMT

The participants performed the Advanced Trail Making Test (ATMT) to control their initial state. The ATMT is a cognitive load task in which the participant selects numbers displayed on a screen in sequence using a computer mouse (Figure 3). The numbers range from 20 to 75, with 25 numbers displayed in each round. When the participant chooses a number; the displayed number arrangement changes randomly. When the number reaches 75, the task restarts at 20.

2.4 Sensory Test

A sensory test was performed after each trial. The participants were asked about their comfort/discomfort and arousal/sedation level using the semantic differential (SD) method after each trial. The evaluation scale comprised seven points (−3 to +3), and “Neither”, “Slightly”, “Very” and “Extremely” were used as the adjectives. The participants were asked to rate their “feeling of relaxation” and “fatigue state” using a four-point scale (0 to 3) with

“None”, “Slightly”, “Very” and “Extremely” as adjectives. They were asked about their state after the load task and after stimulus presentation for all trials.

2.5 Statistical Analysis

We used a two-way analysis of variance (ANOVA) to verify the statistical significance of the two main effects, stimulus and time course, and the interaction between them. Given the robustness of ANOVA, we assumed that the scores for each sensory test and biological indices follow a normal distribution. Because two-way ANOVAs do not accommodate non-parametric tests, we used parametric tests in this paper. Additionally, we used Tukey’s test for multiple comparisons.

2.6 Ethical Considerations

This study was conducted with the approval of Shinshu University’s ethical committee for research on humans (approved number: 2019-249). All participants were informed regarding the experimental methods and confidentiality, and provided consent prior to engaging in the study.

3. RESULTS

3.1 Sensory Test

Figure 4 (a)–(d) shows the mean sensory scores obtained from the 10 participants. A two-way ANOVA was performed for the mean value of each evaluation term

Figure 4: Mean scores for evaluation terms

(n = 10) (** $p < 0.01$, * $p < 0.05$)

(factor 1: six levels, stimulation condition; factor 2: two levels, before-after). We found a significant main effect of factor 2 (before-after) for all evaluation terms, “comfort – discomfort”; $F(1, 108) = 31.56, p < 0.01, \eta_p^2 = .13$, “arousal – sedation”; $F(1, 108) = 128.24, p < 0.01, \eta_p^2 = .33$, “feeling of relaxation”; $F(1, 108) = 100.72, p < 0.01, \eta_p^2 = .29$, and “fatigue state”; $F(1, 108) = 35.33, p < 0.01, \eta_p^2 = .08$. Regarding “comfort-discomfort”, a significant factor 1 $\times$ factor 2 interaction was confirmed, $F(5, 108) = 2.40, p < 0.05, \eta_p^2 = .04$. Additionally, multiple comparisons using Tukey’s test revealed significant differences between the presentation stimuli and before-after scores. When comparing the scores collected before and after stimulus presentation, those for “comfort – discomfort” and “feeling of relaxation” increased significantly, and the scores for “arousal – sedation” and “fatigue state” decreased significantly after presentation ($p < 0.01$). Moreover, when comparing scores for the different stimuli, those for “music + thermal” stimulation was significantly higher than those for the other stimuli.

3.2 ECG

Figure 5 (a)–(d) shows the mean scores for the four indices calculated from ECG. IHR and CVRR were calculated every minute, and the IHR ratio was calculated by dividing the value for each time point by the value from 1 minute of the load task. The LF/HF and HF were calculated for each minute by moving the analysis

window in 3-minute steps. A two-way ANOVA was performed for each index for the different stimuli (6 levels) and elapsed time factors (7 levels for IHR, 8 levels for CVRR, 6 levels for LF/HF and HF). The main effect of the time factor was significant for CVRR and HF; CVRR; $F(7, 432) = 5.66, p < 0.01, \eta_p^2 = .16$, HF; $F(5, 324) = 3.34, p < 0.05, \eta_p^2 = .04$. The main effect of stimulus factor for IHR ratio approached significance, $F(6, 378) = 2.33, p = 0.053, \eta_p^2 = .04$.

Additionally, we performed multiple comparisons using Tukey’s test for the differences between the elapsed time for each stimulus and those between the stimuli for each time point. The following sections describe the observed trends and the results of the multiple comparisons.

1. IHR ratio

Changes in the IHR ratio during stimulus presentation differed depending on the stimulus type. The lowest IHR value for each stimulus occurred at 5 minutes after stimulus onset for “music + thermal”, 6 minutes for “vibration + thermal”, 7 minutes for “odor + thermal”, and 8 minutes for “thermal stimulation alone” and “movie + thermal”. Multiple comparisons using Tukey’s method revealed a significant difference between the lowest IHR values and those collected during the load task. The IHR for “music + thermal” at 5 minutes was significantly lower than that at 3 minutes ($p < 0.05$), that for “vibration + thermal” at 6 minutes was significantly lower than that at 2 and 3 minutes ($p < 0.05$), that for “movie + thermal” at 8 minutes

(a) Mean scores for IHR ratio

(b) Mean scores for CVRR

(c) Mean scores for LF/HF

(d) Mean scores for HF

Figure 5: Mean scores for heart rate variability indices

(n = 10)

was significantly lower than that at 2 and 3 minutes, and that for “odor + thermal” at 6 and 7 minutes was significantly lower than that at 2 and 3 minutes. Regarding differences between stimuli, the IHR for “odor + thermal” was significantly lower at 7 minutes than that for the other stimuli ($p < 0.05$). These results indicate that the degree to which IHR persisted varied depending on the type of stimuli. Regarding “illumination + thermal”, the IHR at 4 minutes was significantly higher than that for the other stimuli ($p < 0.05$). In this regard, participants answered that they felt strange when the illumination color changed from white to blue. The increase in IHR might have been caused by this discomfort.

2. CVRR

The CVRR data were similar regardless of the type of stimulus. We observed a significant difference between 1–3 minutes after the load task began and immediately after stimulus presentation (4 minutes after the start of the trial) for all stimuli ($p < 0.05$). Further, the CVRR increased at the stimuli onset for all of the stimuli. This tendency indicated that parasympathetic nervous system activity increased because of the release from the load task and the presentation of the novel stimuli. Focusing on the time-series of the trials, the CVRR at 6 minutes was significantly higher in the trials in which the thermal stimulation was presented alone versus with other stimuli ($p < 0.05$). However, the CVRR at 8 minutes in the “illumination + thermal” and “vibration + thermal” trials was higher than that in the other stimulus trials ($p < 0.05$). The CVRR values in the “music + thermal” and “movie + thermal” trials at 7 minutes were significantly higher than those during the load task (1–3 min). These results showed that, similar to the IHR, the reaction rate of the CVRR depended on the stimulus type.

3. LF/HF

The two-way ANOVA revealed no significant main effects of LF/HF or significant interactions. A multiple comparison between each stimulus at 5 minutes revealed that the LF/HF values in the “illumination + thermal” trials were significantly higher than those for the other stimuli ($p < 0.05$). This indicated that the stimuli increased sympathetic nerve activity, as well as the IHR.

4. HF

HF increased uniformly for all stimuli, which indicates that all stimuli enhanced parasympathetic activity. The HF value in the “movie + thermal” trials was higher than that for the other stimuli at 5 and 8 minutes. At 8 minutes, we found no significant differences between any stimuli and the thermal stimulation alone, except for the “illumination + thermal” trials.

Figure 6: Mean scores for respiration peak frequency

3.3 Respiration

Figure 6 shows the average peak respiratory frequency per minute. A two-way ANOVA and multiple comparisons using Tukey’s test were performed under the same conditions as the IHR analyses. The main effect of time was significant, $F(7, 432) = 14.04$, $p < 0.01$, $\eta_p^2 = .14$, and the main factor of stimulation was significant, $F(5, 432) = 2.98$, $p < 0.05$, $\eta_p^2 = .02$. The interaction was also significant, $F(35, 432) = 1.54$, $p < 0.05$, $\eta_p^2 = .04$. Additionally, the respiratory peak was significantly lower than that in the load task for all stimuli ($p < 0.05$), which indicates that the stimulus presentation slowed respiration and enhanced parasympathetic nerve activity. Focusing on the time-series of each trial, the “movie + thermal” condition at 4 minutes and “music + thermal” conditions at 5 minutes had the lowest respiratory peak values, and there was a significant difference between respiration in these trials and that with thermal stimulation alone ($p < 0.05$). The peak frequency increased after 4 minutes, which indicates that activation of the parasympathetic nerve activity occurred for a limited time. Regarding the “vibration + thermal” and “odor + thermal” trials, the respiratory peak frequency gradually decreased during the stimulus presentation, and the values for these two trials were significantly different from those for the other stimuli at 7 minutes ($p < 0.05$). The above findings indicated that the latency and duration of the effect on respiration depended on the type of stimulus.

3.4 PTT

Figure 7 shows the average PTT per minute. A two-way ANOVA revealed no significant main effects or interaction. Multiple comparisons using Tukey’s test revealed that the PPT in the “movie + thermal” trials was significantly higher than that for the other stimuli at 4 minutes ($p < 0.05$). Further, the PTT in the “vibration + thermal” and “odor + thermal” trials was significantly larger than that for the other stimuli at 7 minutes ($p < 0.05$). These results indicated that the three above-mentioned stimuli activated parasympathetic nerve activity, and that the stimulus type modified the PTT latency.

Figure 7: Mean PTT scores

3.5 Sweating and Peripheral Blood Flow

Figures 8 and 9 show the average amount of changes in sweating and peripheral blood flow. The amount of change was calculated by subtracting 1 minute from the value for each section after calculating the section average for each minute. A two-way ANOVA for factor 1 (elapsed time, 7 levels (excluding the value at 1 minute)) and factor 2 (6 levels, stimulus) for these changes revealed no significant main effect or interaction. Multiple comparisons by Tukey's method indicated a significant difference in sweating between the load task (2–3 minutes) and the stimulus trials (7–8 minutes) for all conditions except “odor + thermal” and “vibration + thermal” ($p < 0.05$). The highest values for “vibration + thermal” were observed at 4 minutes, and these were significantly higher than the values at 5–8 minutes ($p < 0.05$). The data indicated that presentation of stimuli decreased the sweating rate. Focusing on differences between the stimuli, the sweating rate of the “thermal alone” trials at 8 min was significantly smaller than that for the music, vibration, and odor + thermal trials ($p < 0.05$). These data indicate that the simultaneous presentation of two stimuli increased sweating rate that correspond to cognitive process. Regarding blood flow, that in the “movie + thermal” trial

Figure 8: Mean scores for sweating rate

Figure 9: Mean BPU scores

at 5–7 minutes and “odor + thermal” trial at 5–8 minutes was significantly smaller than that in the “thermal alone” trial ($p < 0.05$).

4. DISCUSSION

Table 2 summarizes the results and discussion of this study. For all conditions, stimulus presentation led to an increase in CVRR, a decrease in respiratory peak frequency, and an increase in HF. This indicates that the stimuli elicited an increase in parasympathetic nerve activity. Regarding the IHR, PTT, and pulse wave index, we confirmed the tendency of change and the differences in latency for each stimulus. In the following section, the physiological and psychological response data are

Table 2: Summary of Results and Discussion

Stimulus	Sensory Test Results Compared with Thermal Alone	Characteristic Physiological Responses	Relaxation Effect
Movie + Thermal	N.S.	PTT and HF increased (4 min) Respiratory peak frequency showed the lowest value (4 min) IHR showed the lowest value (8 min)	Quickly Induced relaxation Enhance parasympathetic nerve activity
Music + Thermal	The most positively evaluated comfort - discomfort : **	IHR and respiratory peak frequency decreased (5min), and increased over time HF gradually increased	Quickly Induced relaxation Brief activation of the parasympathetic nerve
Illumination + Thermal	N.S.	IHR and LF/HF increased immediately after stimulus presentation HF and CVRR gradually increased	Induced relaxation Gradually enhance parasympathetic activity
Vibration + Thermal	N.S.	IHR and respiratory peak frequency decreased (6–7 min) PTT showed the highest value (7 min)	Induced relaxation Enhance parasympathetic activity
Odor + Thermal	N.S.	IHR and respiratory peak frequency decreased (7–8 min) CVRR and PTT value higher than the other stimuli	Highly induced relaxation Slowly enhanced parasympathetic activity

(**: $p < 0.01$)

integrated and examined to verify whether the combined presentation of two stimuli induced relaxation.

1. Movie + thermal stimulation

In the sensory test, the “movie + thermal” stimulation did not exhibit a significant difference from other stimuli. In terms of physiological responses, the PTT and HF were significantly higher immediately after the stimulus presentation (4 minutes) compared with the other stimuli, and the respiratory peak frequency was smaller. The CVRR was also increased compared with the other stimuli at 4 minutes. The above results indicated that the stimulus presentation activated the parasympathetic nervous system and that the physiological indices changed earlier than in the other stimulus conditions. In contrast, the lowest IHR occurred at 8 minutes, and the timing at which the effect of the stimulation appeared was remarkably different. Additionally, the amount of sweating was larger than that for the other stimuli, and the peripheral blood flow was smaller. This tendency indicated that the sympathetic nerve activation was dominant in the peripheral body parts. In summary, the “movie + thermal” stimulation appeared to enhance parasympathetic nerve activity and induce relaxation.

2. Music + thermal stimulation

The “music + thermal” stimulation was the most positively evaluated stimulus in the sensory test. The IHR and respiratory peak frequency decreased immediately (5 minutes) after stimulus presentation, revealing that the stimulus elicited a faster physiological response than the other stimuli. The CVRR and HF also increased, suggesting that parasympathetic nerve activity was enhanced by “music + thermal” stimulation. Labbe et al. [14] found that listening to classical music after stress loading reduced the respiration and heart rate. The physiological responses to “music + thermal” stimulation was consistent with that to classic music alone. However, the IHR and respiratory peak frequency increased over time. Thus, the parasympathetic hyperactivity elicited by this stimulus had a short duration. From the above results, we concluded that “music + thermal” stimulation quickly induced relaxation, although activation of the parasympathetic nervous system was relatively brief.

3. Illumination + thermal stimulation

The “illumination + thermal” stimulation elicited no significantly different effects compared with the other stimuli in the sensory test. However, many participants complained that they felt strange and dazzled when the illumination switched from white to blue. We attribute the increase in IHR and LF/HF observed immediately after the stimulus presentation to this subjective impression. In contrast, that the HF and CVRR gradually increased indicates that parasympathetic nerve activity was enhanced

after the participants become accustomed to the light blue illumination. From the above results, we speculate that “illumination + thermal” stimulation can induce relaxation, although the illumination method should be carefully considered.

4. Vibration + thermal stimulation

The “vibration + thermal” stimulation received a slightly lower subjective evaluation. The IHR (6 minutes) and respiratory peak frequency (7 minutes) were smaller than those for the other stimuli, and the PTT was largest at 7 minutes. These tendencies indicated that the stimulus enhanced parasympathetic nerve activity. Thus, the vibrational stimulus induced relaxation when co-presented with thermal stimulation.

5. Odor + thermal stimulation

In the sensory test, we found no significant differences between the effects of the “odor + thermal” stimulation and the other stimuli. However, in terms of physiological responses, this stimulation elicited the largest increase in parasympathetic nerve activity. The IHR and respiratory peak frequencies were lower than those for the other stimuli at 7–8 minutes, and the CVRR and PTT values were also higher than those for the other stimuli. This is consistent with previous studies on “foot bath + odor presentation” [2,8] and studies reporting a decrease in heart rate and an increase in HF when a pleasant odor was presented alone [19]. We speculate that “odor + thermal” stimulation elicits a slow response. Regarding changes in the biological indices of peripheral regions, the amount of sweating was higher than that for the other stimuli, and a decrease in blood flow was also confirmed. This tendency was the same as that for the “movie + thermal” trials, which indicates activation of sympathetic nerves in peripheral body regions. We concluded that “odor + thermal” stimulation actively enhanced parasympathetic activity and slowly induced relaxation.

From the above results, we concluded that all stimuli were able to activate parasympathetic nerve activity and induce relaxation. However, we could not confirm remarkable differences in the physiological responses elicited by the paired stimuli compared with the thermal stimulation alone except for in the “thermal + odor” trials. This result indicates that thermal stimulation has a large effect on the induction of relaxation. Regarding visual stimuli (movie / illumination), cold-colored stimuli were presented in this study. We speculate that the matching between these stimuli and the thermal stimulus was poor. As a future research, we plan to verify the relaxation inducement effect by presenting warm-colored movie / illumination stimuli together with thermal stimuli. Additionally, the

vibration + thermal stimulation activated the parasympathetic nerve, however the subjective evaluation of the vibration stimulus itself tended to be low. The presentation method and stimulus selection need to be reexamined.

5. CONCLUSION

We examined the degree to which thermal stimulation presented to the soles of the feet combined with other sensory stimuli could induce relaxation. There are no studies that have verified the relaxation-inducing by the combination of thermal stimulation and stimulation to other sensory organs. Here, we were able to characterize the relaxation-inducing effects of thermal stimuli plus stimuli targeted at other sensory organs, as well as the differences in the latency and duration of the physiological responses to each stimulus. Thermal stimulation had a powerful effect on the feeling of relaxation, although the degree to which multisensory integration enhanced this effect could not be confirmed.

Our data can be applied in attempts to improve the comfort of in-vehicle spaces. As self-driving electric cars are expected to be increasingly widespread in the future, in-vehicle comfort is likely to become more important. There are many possible stimuli that could enhance comfort and relaxation within a vehicle, such as those tested in the present study. Based on our findings, we expect that interior spaces with enhanced comfort will be possible in the future.

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Seiya FUJIWARA (Non-member)

Seiya Fujiwara is doctoral student in Graduate School of Medicine, Science and Technology, Shinshu University. His research interests include Kansei measurement and human comfort evaluation using physiological measurement.

Haruki OITA (Member)

Haruki Oita is master's student in Graduate School of Science and Technology, Shinshu University. His research interests include Kansei measurement and thermal comfort evaluation.

Mayumi UEMAE (Member)

Mayumi UEMAE is a researcher of the Faculty of Textile Science and Technology at Shinshu University, Japan. She received her Ph.D. in Engineering from Shinshu University. Her research interests include Affective Engineering, Kansei Measurement and Clothing Science.

Hiroaki YOSHIDA (Member)

Hiroaki Yoshida is a Professor of Kansei Engineering at Shinshu University, Japan. He received his Ph.D. degree in Engineering from Kyoto University in 2001. He was a Postdoctoral Fellow at Johns Hopkins University, U.S.A from 2003 to 2004, a Research Scientist at the Digital Research Center of AIST, Japan from 2005 to 2007, and Assistant Professor at Shinshu University from 2007 to 2010. His current interests include Kansei measurement and comfort evaluation of products using computer simulation.

Masayoshi KAMIJO (Member)

He received the Dr. Eng. degree from Shinshu University in 1995. He is currently a professor in interdisciplinary graduate school of science and technology of Shinshu University. He is engaged in research on measurement and assessment system on human health and comfort.

E-mail : kamijo@shinshu-u.ac.jp