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Study on relaxation induction by multisensory stimulation based on thermal stimulation by measuring physiological responses

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Seiya Fujiwara

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Chapter 1

Introduction

1.1 Background

1.1.1 Inducing relaxation in indoor environments

Promoting human comfort is an important issue in the development of next-generation smart homes and self-driving cars. In future smart homes, highly comfortable indoor environments will be implemented by coordinating multiple internet of things (IoT) devices and providing functions that match human behavior. Additionally, as self-driving electric cars become widespread in the future, in-vehicle comfort will be increasingly important. In spaces where people spend a substantial amount of time, such as indoors and in-vehicle environments, the development of methods for inducing a state of relaxation is important for providing comfort in daily life.

In Russell's circumplex model, emotions are expressed in a two-dimensional annulus (such as pleasant - unpleasant and arousal - sedation [1]), and relaxation is classified as sedative comfort. Relaxation can be considered a sedative and calm state, both physically and psychologically. In addition, "comfortability" can be broadly divided into (1) comfort that actively induces comfort (pleasantness) and (2) comfort that removes unpleasant elements. The state of relaxation targeted in the current study was a comfortable state, such as the state immediately before falling asleep in the absence of unpleasant factors. In this state, sympathetic nervous system activity is suppressed and parasympathetic nervous system activity is enhanced, additionally, brain activity is suppressed. The aim of the current study was to identify a method of stimulus presentation to positively induce physiological and psychological relaxation states. Clarifying a stimulus presentation method for inducing a relaxed state in humans may inform approaches for designing highly comfortable interior environments.

Various sensory stimuli induce relaxation in humans, including thermal, audible, olfactory, vibratory, and visual stimuli. Among these stimuli, thermal stimulation is a fundamental and important factor, particularly for relaxation in indoor environments. Additionally, in real-world situations, thermal stimuli are often experienced simultaneously with stimuli in other sensory modalities. Combinations of multiple stimuli can induce higher levels of comfort and enhance users' impressions of stimuli compared with a single stimulus modality alone. In the current study, I focused on the relaxation-inducing effect of multisensory integration. Several previous studies have examined psychological and physiological responses by presenting multiple comfortable stimuli at the same time [2-6]. For instance, it has been reported that the presentation of footbath + aroma oil odor enhances parasympathetic nerve activity [2,3], whereas the presentation of music + vibration significantly reduces heart rate [4] and enhances subjective relaxation [4,5]. Additionally, the presentation of auditory + illumination stimulation was reported to exert a stress-reduction effect [6]. In terms of clinical applications, Snoezelen therapy uses multiple stimulus types and equipment for comfortably stimulating the user's sense of sight, hearing, and smell to promote relaxation. Originally devised as a recreational activity for people with severe intellectual disabilities, Snoezelen therapy is also being applied in facilities for the elderly, hospitals [7], and architectural design [8].

As mentioned above, a relaxation-inducing effect of multisensory integration has been reported. However, the optimal combinations of stimuli for most effectively inducing relaxation have not been clarified. Therefore, it is important to identify effective relaxation induction methods to implement more comfortable interior spaces. Although there are many potentially beneficial combinations of stimuli, this study focused on multisensory integration involving thermal stimuli.

1.1.2 Relevant studies of thermal comfort and multisensory integration based on thermal stimulation

Thermal comfort is an important factor in interior space. There are many possible methods for providing warmth to humans, such as air conditioning, hot baths and heating wire heaters, in which thermal stimuli are presented to the entire body or parts of the body. This study focused on warming the soles of the feet, because this body part constantly conducts heat to the outside world in daily life in both the standing and sitting positions. In previous studies, thermal stimulation of the extremities was reported to evoke feelings of comfort and relaxation. Shin et al. [9] reported that the physiological and psychological responses of the human body differ depending on which part of the body thermal stimuli are presented to. Kuji et al. [10] reported that the simultaneous application of heat to the hands and feet was effective for inducing a feeling of warmth. Moreover, warming of the feet was found to be more effective for providing warmth than warming of the hands. Yamamoto et al. [11] reported that a footbath is effective for relaxation, causing an increase in parasympathetic nervous system activity and a decrease in sympathetic nervous system activity. Common methods for presenting warmth to the feet in daily life include footbaths, floor heating, and “kotatsu” (a widely used heating appliance in Japan).

Regarding the effects of thermal stimulation combined with other types of sensory stimulation, some studies have examined the effects of a footbath with simultaneous odor presentation [2,3,12]. Saeki et al. [2] presented lavender oil during a footbath and researchers reported that the application of lavender oil significantly reduced the low-frequency to high-frequency (LF/HF) ratio and prolonged the increase in blood flow at the fingertips [2]. Shirakawa et al. [4] reported a significant decrease in average heart rate after simultaneous presentation of a footbath and lavender oil, accompanied by strong subjective feelings of relaxation. Fukuzawa et al. [12] revealed that oxy-Hb in the frontal cortex decreased immediately after odor presentation when an aroma (lavender, lemongrass, tea tree) was presented during a footbath. In other combinations of stimuli, Fukumitsu et al. [13] revealed that the simultaneous presentation of a hot pack and classical music to patients with knee osteoarthritis significantly changed brain activity in the α-band (8–13 Hz). The findings discussed above indicate that the simultaneous presentation of thermal and other sensory stimuli can induce relaxation.

However, few studies have examined the effects of different stimulus combinations on relaxation-inducing effects. Therefore, it may be valuable to clarify the psychological and physiological responses when presenting other stimuli in combination with thermal stimulation.

1.2 Purpose

The purpose of the current study was to examine the relaxation-inducing effects of simultaneous thermal stimulation and that of other sensory organs. This study investigated the effects of simultaneous thermal stimulation of the feet with stimuli targeting other sensory modalities, including sound (music), light (movie and illumination), odor, and vibration (applied to the trunk). These stimuli were intended to induce a relaxed state. Additionally, these stimuli can be implemented in indoor and in-vehicle environments in the future. This study tested the hypothesis that the presentation of thermal stimuli and other stimuli would significantly induce relaxation. In this study, relaxation was defined as a comfortable state just before sleeping. The relaxation-inducing effect of multisensory integration was evaluated by measuring the physiological responses of the central nervous system and autonomic nervous system.

1.3 Outline

Figure 1.1 outlines the structure of this thesis. The most relaxing stimulus for each sensory stimulus type were selected in advance, and those stimuli were presented at the same time as the thermal stimulation. In addition, the relaxation-inducing effects of the presentation of multisensory stimuli were verified using physiological and psychological response measurement.

Chapter 2 reports a method for evaluating relaxation effects using physiological response measurement. In this chapter, the measurement method of the physiological responses of the central nervous system and autonomic nervous system and the physiological indices related to the state of relaxation were shown. Objective evaluation using physiological response measurement is an important method for quantitatively evaluating relaxation effects. In addition, time-series physiological responses during stimulus presentation were measured, and changes in physiological state induced by each combination of stimuli were evaluated.

In Chapter 3, stimuli that had strong relaxation-inducing effects were identified from various comfort-related stimulus candidates. Scheffe's paired comparison method was conducted to determine the most relaxing stimuli. This chapter discusses previous studies on physiological responses when stimuli were presented to each sensory organ, and selected candidates for relaxation-inducing stimulation on the basis of previous findings.

In Chapter 4, the relaxation-inducing effect of simultaneously presenting thermal stimulation and that of other sensory organs was examined using physiological response measurements and sensory tests. The stimuli selected in Chapter 3 were presented as relaxing stimuli. Differences in the latency and duration of physiological responses depending on the stimuli combination were also verified.

Chapter 5 describes a summary of the findings, and prospects for future research.

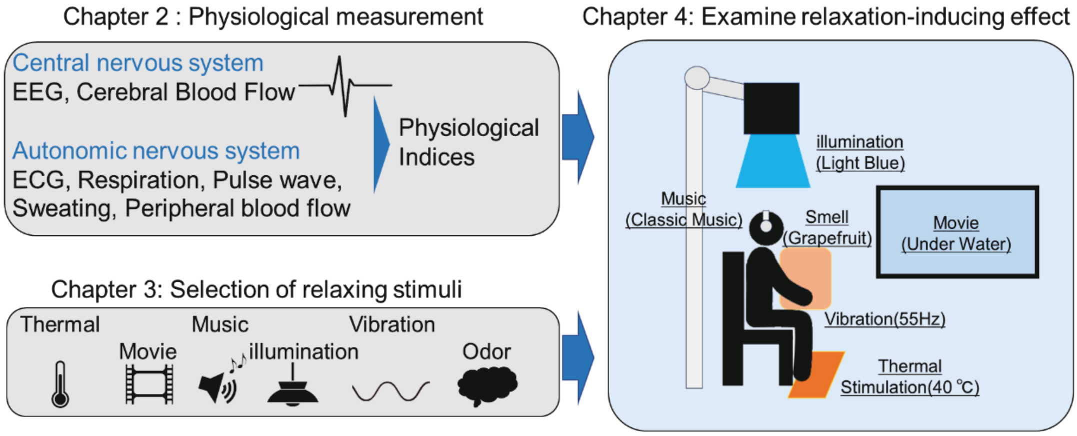

Figure 1.1 Outline of the structure of this thesis

Chapter 2

Method for evaluating relaxation effects using physiological response measurements

2.1 Introduction

This chapter describes a method for quantitatively evaluating relaxation by measuring physiological responses. Evaluation of physiological responses is used not only in clinical settings, but also in the field of engineering. In the current experiment, multiple physiological responses of the autonomic nervous system and the central nervous system were measured, and physiological indices associated with relaxation were calculated. I expected that the effects of stimuli and relaxation would be verified in more detail by measuring the state of the body during the presentation of stimuli using multiple biological signals.

Because this study was focused on evaluating relaxation, it was necessary to adopt a measurement method that did not cause stress for participants. Therefore, non-invasive and low-restraint biological sensors were selected. Additionally, to measure physiological responses during the presentation of a relaxing stimulus, sensors that can perform continuous measurement were used. The following biological signals were measured in this study:

- Autonomic nervous system activity: electrocardiogram (ECG), respiration, fingertip pulse wave, sweating, peripheral blood flow.
- Central nervous system activity: electroencephalogram (EEG), cerebral blood flow in the prefrontal cortex.

2.2 Autonomic nervous system

Autonomic nervous system activity autonomously controls the body without commands from the cerebrum, and performs the function of regulating blood circulation, respiration, and body temperature. The autonomic nervous system consists of the sympathetic nervous system and the parasympathetic nervous system, which antagonize and regulate each other. The sympathetic nervous system works to increase the activity level and athletic ability of the body, causing an increase in heart rate, blood pressure, respiratory rate and sweating. Conversely, the parasympathetic nervous system works to calm the mind and body, reducing the heart rate and respiratory rate. Relaxation effects are usually evaluated by measuring parasympathetic activity in the autonomic nervous system.

2.2.1 ECG

The ECG is derived from the potential change that occurs with the contraction of the heart, measured as the difference in potential between two electrodes attached to the chest or limbs. The ECG single waveform appears as the P wave indicating atrial excitement, the QRS waves indicating ventricular depolarization, and the T wave indicating ventricular repolarization. It is desirable to use the P-P interval to measure heart rate variability, but detection of P wave position is difficult. Therefore, the R-R interval (RRI) is generally used as substitute.

The heart rate is controlled by both the sympathetic and parasympathetic nervous systems. Sympathetic nervous system activity increases the heart rate and parasympathetic nervous system activity decreases the heart rate. The heartbeat is not constant like a metronome, and exhibits fluctuations of approximately 0.03–0.5 Hz. This fluctuation includes respiratory and blood pressure variation.

In this study, ECG electrodes were attached to the participants at the upper sternum and the apical region via the chest bipolar induction method using a MP150WS ECG100C amplifier system (BIOPAC Systems, Inc.). The ECG was recorded at a sampling frequency of 1,000 Hz. R waves were detected from the ECG data, and the RRIs were calculated. The instantaneous heart rate (IHR), coefficient of variation of RRI (CVRR), LF/HF, and HF were calculated using the time-series analysis 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 nervous system activity. The CVRR was calculated by dividing the mean of the RRI during 1 minute by the standard deviation of the RRI. The CVRR is an index originally discovered from the small variation in RRI in patients with diabetic autonomic neuropathy [14] and is often used as an autonomic nervous activity evaluation index.

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 (0.04–0.15 Hz) and the high-frequency component HF (0.15–0.4 Hz) were integrated with respect to the obtained spectrum, and LF and HF were calculated. The LF/HF ratio was calculated by dividing LF by HF. HF is associated with parasympathetic-controlled respiratory sinus arrhythmia (RSA), and LF is associated with sympathetic and parasympathetic-controlled reflex effects (Mayer waves) [15,16]. HF is strongly influenced by respiration, and its spectrum changes as the respiration frequency fluctuates. The LF/HF ratio is regarded as an index of sympathetic nervous system activity, and thus a reflection of stress. HF reflects parasympathetic nervous system activity

In summary, in the relaxed state (parasympathetic nervous system activity is dominant), IHR and LF/HF decrease, and the CVRR and HF increase.

2.2.2 Respiration

Respiration consists of inspiratory and expiratory movements, and a periodic rhythm is formed by the respiratory center in the medulla oblongata of the brain stem. Additionally, respiration exhibits both autonomous control and voluntariness and is controlled both consciously and unconsciously. The autonomic nervous system controls respiration: sympathetic nervous system activity induces fast and constant respiration, whereas parasympathetic nervous system activity slows respiration. There are three main methods for measuring respiration: (1) wearing a mask to collect exhaled gas and analyzing exhaled gas; (2) measuring the circumference of the thorax; and (3) measuring temperature changes near the nostrils. In the current study, the temperature near the nostrils was measured using a thermistor to measure respiration because attaching the temperature sensor does not cause stress for participants. Because accurate ventilation volume cannot be measured using this method, changes in respiratory rhythm were calculated by frequency analysis of the respiratory waveform (temperature change waveform).

Respiration was measured 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 waveforms were recorded at a sampling frequency of 1,000 Hz. Frequency analysis was conducted for the respiratory waveform and the respiration peak frequency (PF) and respiratory center of gravity frequency (GF) were calculated from the spectral waveform. The respiratory center of gravity frequency is the frequency of the center of gravity position within the half width of the spectral amplitude of the respiratory peak frequency. The difference between PF and GF increases in cases of irregular respiration [17]. The PF reflects the speed of respiration and decreases when the parasympathetic nervous system is dominant.

2.2.3 Fingertip pulse wave

The fingertip pulse wave is measured as a waveform of the volume change of peripheral blood vessels that occurs with the heartbeat. Parasympathetic nervous system activity increases the pulse wave amplitude, and sympathetic nervous system activity decreases the pulse wave amplitude

[18]. This phenomenon is associated with peripheral vasodilation and contraction in response to autonomic function. In the reflected photoelectric volume pulse wave method, infrared light (approximately 550 nm) is irradiated from an infrared LED, and the reflected light is measured using a photodiode. Oxidized hemoglobin exists in the blood of arteries and has the property of absorbing incident light. Because the amount of reflected light from tissues other than arteries does not change during beating, pulse waves can be measured by changes in the amount of light received.

The fingertip pulse wave was measured 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.). The sampling frequency was 1,000 Hz. The pulse transit time (PTT) was calculated from the time difference (Δt) between the rise point of the pulse wave waveform and the R wave of the ECG (Figure 2.1). 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 [19,20]. A large PTT value indicates parasympathetic nervous system activation.

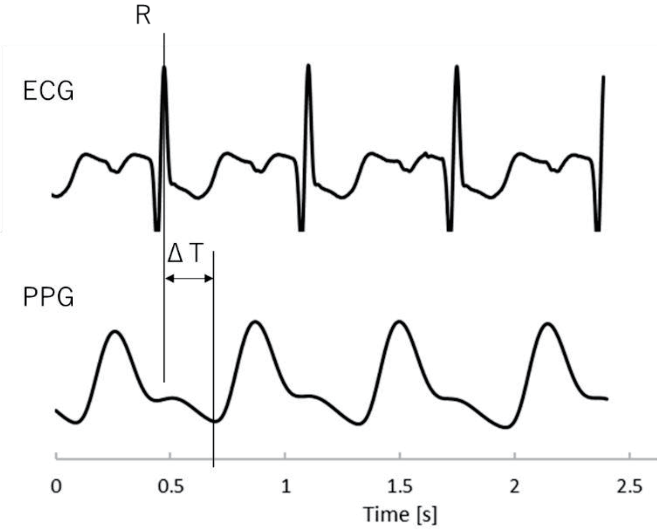

Figure 2.1 Pulse transit time

2.2.4 Peripheral blood flow

Peripheral blood vessels are controlled by the autonomic nervous system: sympathetic nervous system activity reduces peripheral blood flow, and parasympathetic nervous system activity increases peripheral blood flow. This function is also related to thermoregulation, and blood vessels expand and contract in response to changes in core body temperature and skin temperature, causing heat dissipation and heat retention of the human body. One of the methods for measuring blood flow non-hemodynamically is a laser Doppler blood flow meter. When the irradiated laser light is reflected by an object (mainly red blood cells) moving in the capillaries, the frequency of the laser light shifts. The percentage of shifted light is proportional to the amount of red blood cells, and the magnitude of the frequency shift is proportional to the blood flow velocity. Thus, blood flow can be estimated from the product of the amount of red blood cells and blood flow velocity [21]. Intracapillary blood flow at a depth of approximately 0.5 mm from the skin surface can be measured.

The MoorVMS-LDF laser Doppler blood flow meter was used with a VT1T optical probe (Moor Instruments Co., Ltd.) to measure peripheral blood flow. The sampling frequency was 1,000 Hz. The probe was attached to the third finger of the participant’s left hand. Blood perfusion units (BPU) were calculated from this sensor. The section average for each minute was calculated from the obtained waveform to use as an index of blood flow. Dilated blood vessels and increased blood flow reflect parasympathetic nervous system dominance.

2.2.5 Sweating

Sweating of the human body can be roughly classified as mental sweating and thermal sweating to suppress an increase in internal temperature. Mental sweating is caused by mental stress, emotional changes and sensory stimuli, and occurs in the palms and soles. Humans constantly sweat, even at an ambient temperature, and sympathetic nervous system activity increases the amount of sweating. A ventilation capsule type sweating meter was used to measure the amount of continuous sweating. A capsule-shaped probe is attached on the surface of the skin in a sealed state, and air is ventilated inside the probe. The air humidity before passing through the skin and the humidity of the air (including the evaporated moisture of sweat) after passing through the skin are detected by two humidity sensors, and the amount of sweating is derived from the difference [22].

The SKN-2000 (SKINOS Co., Ltd.) unit was used to measure the amount of sweating. The sensing probe was attached to the fourth finger of the left hand to measure mental sweating. The sweating waveform was recorded at sampling frequency of 1,000 Hz. From the obtained signal, the section average was calculated for each minute and used as an index of sweating amount. Small value of sweating amount indicates a relaxed state.

2.3 Central nervous system

The central nervous system is composed of the spinal cord and the brain. In this study, the activity of the cerebral cortex of the cerebrum was measured. The cerebrum is involved in human perception, movement, emotion, and decision-making, and has a central function in the cerebral cortex. The frontal lobe governs higher level emotions [23]. There is functional localization in the cerebral cortex, with different parts related to movement, emotion, and other processes. Non-invasive methods for measuring brain activity include EEG, magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and near infrared spectroscopy (NIRS). Among these methods, EEG and NIRS can measure brain activity relatively easily without the need for special laboratories or expensive large-scale equipment. In this study, I measured EEG, and estimated cerebral blood flow in the frontal cortex using NIRS.

2.3.1 EEG

The EEG signal is the sum of action potentials and synaptic potentials generated by a large number of neurons in the brain, and is measured from the scalp. The frequency of the EEG signal changes in relation to activity and stimulation. Generally, the frequency of the EEG signal is high when the subject is active and awake, and low when the subject is calm or drowsy. The frequency (f) of the EEG can be divided into four bands: δ-wave ($f < 4$ Hz), θ-wave ($4 \text{ Hz} \leq f < 8$ Hz), α-wave ($8 \text{ Hz} \leq f \leq 13$ Hz), and β-wave ($13 \text{ Hz} < f$).

Low-frequency bands of brain waves, such as the α waves and θ waves, has been reported to be associated with relaxation [24].

In this study, a Polymate AP-1000 (Miyuki Giken Co., Ltd.) device was used for EEG measurement. EEG electrodes were attached to Pz and A1 according to the international 10-20 electrode system [25]. EEG was derived from the difference in potential in relation to the earlobe using a reference electrode method. The sampling frequency was 500 Hz. Here, α-wave activity was calculated by dividing the α-wave power spectrum by the sum of the θ-wave, α-wave, and β-wave power spectra. The whole activity of the brain was evaluated from the α-wave content. A large value of α-wave content indicates a relaxed state.

2.3.2 Cerebral blood flow in prefrontal cortex

Near infrared light is absorbed by hemoglobin when passing through the living body. As a result, NIRS can measure changes in the concentration of oxygenated (or deoxygenated) hemoglobin as a function of time. Blood flow increases locally at a site where neurons have become active, and the oxygenated hemoglobin concentration in the blood increases. Thus, local cerebral blood flow can be used as an indicator of local neuronal activity. There are two reasons for measuring brain activity at the frontal lobe. First, the frontal lobe governs higher level emotions [23]. Second, the orbitofrontal cortex (OFC) of the frontal lobe is activated by inhaling odors [26]. Cerebral blood flow in the prefrontal cortex decreases when the subject is in a relaxed state and increases when the subject is in a stressed state [27].

Cerebral blood flow in the prefrontal cortex was estimated using NIRS, with Hb-132 (Astem Co., Ltd.). The amount of oxygenated hemoglobin (oxy-Hb) was calculated relative to a pre-rest reference point. A five-channel sensor was used, and the channels were arranged at 35-mm intervals on the left and right sides. Channel 3 was located at the center of the prefrontal cortex and was set to Fpz [25]. Channels 1 and 2 were attached over the left frontal lobe and Channels 4 and 5 were attached over the right frontal lobe. The sampling frequency was 2 Hz. Low oxy-Hb in the prefrontal cortex indicates a relaxed state.

2.4 Summary

In this chapter, the physiological response measurement method of the autonomic nervous system and the central nervous system and the calculated physiological indices were described. Table 2.1 shows the measured physiological responses items, sensor attempt position and physiological indices. From seven types of biological signals, 11 types of physiological indicators were calculated. The indices that exhibited increased values in the relaxed state were the CVRR, HF, PTT, BPU and α-wave content, and the indices that exhibited decreased values in the relaxed state were IHR, LF/HF, respiration PF, GF, sweating rate and oxy-Hb in the prefrontal cortex. Using the physiological indices described in this chapter, the relaxation-inducing effect of multisensory integration was examined in Chapter 4.

Table 2.1 Physiological measurement items and physiological indices

	Physiological reponses	Sensor attempt position	Calculated indices
Autonomic nervous system	ECG	Upper sternum and apical region	IHR, CVRR, LF/HF, HF
	Respiration	Near the nostrils	Peak Frequency (PF) Center of Gravity Frequency (GF)
	Fingertip pulse wave	Second finger of left hand	Pulse Transit Time (PTT)
	Peripheral blood flow	Third finger of left hand	Section average for each minute
	Mental sweating	Fourth finger of left hand	Section average for each minute
Central nervous system	EEG	Pz and A1	α-wave contain
	Cerebral blood flow	Forehead (Prefrontal cortex)	Oxy-Hb

Chapter 3

Investigation of stimuli in each sensory modality that induced a strong feeling of relaxation

3.1 Introduction

Various sensory stimuli induce a state of relaxation in humans. For example, classical music stimulating the sense of hearing and pleasant odors stimulating the sense of smell are widely known to induce relaxation in humans. This chapter focused on thermal stimulation, visual stimulation, music stimulation, illumination stimulation, vibration stimulation and odor stimulation as stimuli to induce relaxation. Previous studies have examined the psychological and physiological responses when stimuli are presented to each of these sensory organs [9-11,27-56,58-63]. However, the types of sensory stimuli in each modality that are most effective for inducing relaxation remain to be clarified.

In investigating the relaxation-inducing effects of multisensory integration, it is important to select stimuli that cause a strong feeling of relaxation for each sensory modality. By combining multiple types of relaxing stimuli, a stronger relaxation induction effect was expected. Therefore, this chapter describes an experiment that was conducted to identify the most relaxing stimuli from multiple candidates that were expected to evoke a feeling of relaxation using Scheffe’s paired comparison method. Candidates for stimulation were selected with reference to previous studies. The selected sensory stimuli in this section are described below:

・Thermal stimulation: Identification of a relaxing temperature of thermal stimulation presented to the soles of the feet.

- Movie stimulation: Identification of relaxing movie stimuli from candidate movies showing natural scenes.
- Music stimulation: Identification of relaxing classical music.
- Illumination stimulation: Identification of relaxing illumination color.
- Odor stimulation: Identification of relaxing odor from citrus aroma oil odor candidates.

3.2 Identification of relaxing stimuli using paired comparison method

In this study, Scheffe's method was used to evaluate the stimuli. Scheffe's method evaluates the criteria for comparing two samples by scoring them on a 5-point or 7-point scale. Except for odor stimulation, the selection of all stimuli was carried out using Ura's variation method. In Ura's variation method, participants compare all paired combinations, and both A→B and B→A are evaluated to account for the order effect. In the current experiment, the selection of odor stimuli was conducted using Nakaya's variation method. In Nakaya's variation method, participants compared all combinations once, without considering the order effect. Because participants evaluated the two odors by sniffing them at the same time in the current study, Nakaya's variation method was adopted.

A total of 20 healthy participants without color blindness and olfactory dysfunction (10 men and 10 women aged 20–24 years) were recruited from Shinshu University Students. Participants rated 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.

The average degree of preference was calculated from the obtained scores. In addition, analysis of variance (ANOVA) was performed on the scores of each sensory stimulus. When the main effect was observed using ANOVA, the difference in the average degree of preference of each stimulus and the yardstick Y (0.05) were calculated. A larger difference in the average degree of preference compared with the value of the yardstick indicated a statistically significant difference. The average degree of preference and Y (0.05) were calculated by Eq. 3.1–3.4 and Eq. 3.1–3.2 using Ura’s variation method, and by Eq. 3.3–3.4 using Nakaya’s variation method.

(a) Ura's variation

When comparing stimulus *i* first and then stimulus *j*,

$$\hat{a}_i = \frac{1}{2tN}\left(X_{i\cdot\cdot} - X_{\cdot j\cdot}\right) \qquad (3.1)$$

$$Y = q\sqrt{\frac{\sigma^2}{2Nt}} \qquad (3.2)$$

where, t = number of presentation stimuli

N = number of participants

$X_{i\cdot\cdot}$ = total score when stimulus i is presented first

$X_{\cdot j\cdot}$ = total score when stimulus j is presented first

q = student's q-value

σ^2 = unbiased variance of error

(b) Nakaya's variation

$$\hat{a}_i = \frac{1}{tN} X_{i\cdot\cdot} \qquad (3.3)$$

$$Y = q\sqrt{\frac{\sigma^2}{Nt}} \qquad (3.4)$$

where, t = number of presentation stimuli

N = number of participants

X_i = total of score each stimulus

q = student's q-value

σ^2 = unbiased variance of error

3.3 Thermal stimulation

3.3.1 Background

This study focused on the thermal stimulation to the soles of the feet. Previous studies have reported that thermal stimulation of the limbs (especially the feet) leads to a feeling of comfort [9,10]. Additionally, several studies have evaluated the degree of comfort elicited by the application of heat to the human body according to autonomic nervous system activity [2,11,28]. Saeki [2] reported that a 40 °C footbath increased blood flow in the fingertips and significantly decreased the LF/HF ratio. Similarly, Yamamoto et al. [11] reported that a footbath at 42 °C significantly decreased the sympathetic nervous system activity index LF/HF ratio. These results suggest that a footbath can suppress sympathetic nervous system activity and enhance parasympathetic nervous system activity. Regarding presentation of heat to the whole body, Zhu et al. [28] investigated changes in autonomic nervous system activity when the whole body was exposed to hot and cold environments. They reported 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). The studies described above indicate that the warming of the whole body enhances sympathetic nervous system activity, while thermal stimulation of the feet activates parasympathetic nervous system activity, even at a slightly higher temperature (more than 40 °C). In addition, these findings indicate that applying warmth to the foot at approximately 40 °C is effective for inducing relaxation.

Regarding the physiological responses caused by differences in temperature under high temperature conditions, Hou et al. [29] reported that cerebral blood flow in the prefrontal cortex during the presentation of local hot-cold stimuli to the hand using an aluminum plate exhibited increased or decreased oxy-Hb under specific temperature conditions. With hot stimulation, oxy-Hb increased at 45 °C and decreased at 39 °C. This indicates that thermal stimulation of 39 °C induced relaxation, while thermal stimulation of 45 °C caused discomfort. Therefore, it is necessary to identify a relaxing temperature when thermal stimuli are presented to the feet.

3.3.2 Presentation stimulus and presentation method

I presented thermal stimulation to the soles of the feet while participants were barefoot. A silicon rubber heater (Hakko Fine Thermo Co., Ltd.) was fixed under participants' feet (Figure 3.1 (a)). This sheet is a mat-shaped heater, in which a resistance wire is arranged between two silicon sheets, and the temperature can be set. A brass diffuser and a 100% cotton cloth were placed on the heater to unify the temperature of the contact surface (Figure 3.1 (b)). Because the temperature setting accuracy of this rubber heater is ± 3 °C, the thermal stimuli to be presented were set at 4 °C intervals, and the presentation temperatures were 36 °C, 40 °C, and 44 °C.

(a) Silicon rubber heater (b) Diffuser plate and cotton cloth

Figure 3.1 Thermal stimulus presentation equipment

3.3.3 Experimental procedure

Three temperatures (36 °C, 40 °C, 44 °C) were compared using a paired comparison evaluation approach (Ura's variation method). A total of 20 participants (10 men and 10 women) were recruited. The experiment was conducted in a room with constant temperature and humidity (20 °C, 55% relative humidity).

Participants wore experimental clothes (long-sleeved and shorts jerseys) after entering the room at a constant temperature and humidity, and rested in a sitting position for 10 minutes to adjust to the temperature. Figure 3.2 shows the installation position of the silicon rubber heater and the experimental environment. Two temperatures were selected from the three temperatures and set for each heater.

Participants were asked to put their bare feet on one rubber heater (Temperature A) for 1 minute and then on the other rubber heater (Temperature B) for 1 minute. Participants rated 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. There were three combinations for evaluating two of the three temperatures, and the order was changed in consideration of the order effect. The stimulation evaluations were performed six times in total. The presentation order was randomly selected for each participant.

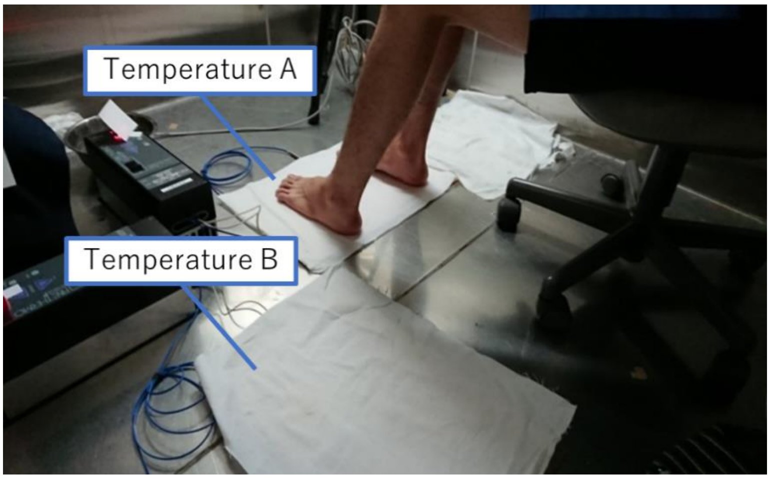

Figure 3.2 Experiment environment

3.3.4 Results and Discussion

The average degree of preference and the difference in the average degree of preference between temperature conditions were calculated (Table 3.1). ANOVA was performed for each evaluation term, and the main effect was significant for all terms: "feelings of comfort"; $F(2,59 = 8.38, p < 0.001$, "feelings of relaxation"; $F(2,59) = 7.71$, $p = 0.0011$, and "preference"; $F(2,59) = 6.63$, $p = 0.0025$. Focusing on differences in the average degree of preference between temperature conditions, the absolute value of difference between "40 °C–44 °C" and "40 °C–36 °C" was larger than Y (0.05) for all evaluation terms. Additionally, there was no significant difference in “36 °C–44 °C.” Because the average degree of preference in the 40 °C condition had the highest value, the 40 °C condition was the most relaxing stimulus. This result was consistent with the temperature presented for the footbath in previous studies [1,30]. Kaneko et al. [30] reported that a footbath (40 °C) promoted and maintained peripheral circulation without overloading the cardiovascular system. The researchers also confirmed that parasympathetic nervous system activity was increased and sympathetic nervous system activity was suppressed after the footbath. In addition, because 40 °C is a common bathing temperature, it was speculated that participants evaluated the temperature they were accustomed to as preferable.

Table 3.1 Average degree of preference and difference in degree for each stimulus

		Temperature condition [°C]	Average degree of preference	Difference in average degree of preference				Y (0.05)
				-No.2		- No.3		
Feelings of comfort	No.1	36	-0.058	-0.425	*	0.250		
	No.2	40	0.367			0.675	*	0.401
	No.3	44	-0.308					
Feelings of relaxation	No.1	36	-0.058	-0.375	*	0.200		
	No.2	40	0.317			0.575	*	0.357
	No.3	44	-0.258					
Preference	No.1	36	-0.233	-0.558	*	-0.142		
	No.2	40	0.325			0.417	*	0.383
	No.3	44	-0.092					

(*$p < 0.05$)

3.4 Movie stimulation

3.4.1 Background

Movie stimuli are commonly used to evoke various emotional states. Many previous studies have investigated the physiological responses of the autonomic nervous system [31-33,36-42-35], the central nervous system [27,38,39] and both the autonomic and central nervous system [40-42] that correspond to psychological states. This study focused on movies showing natural scenes to examine the induction of relaxation. Previous studies reported that viewing movies of the natural landscape induced decreased heart rate, increased CVRR (an index of parasympathetic nervous system activity) [31], and increased amplitude of the fingertip plethysmogram (i.e., activation of the parasympathetic nervous system) [32]. Tsujiura et al. [33] revealed that viewing a movie showing a forest scene increased the subjective feeling of comfort and predominantly induced parasympathetic nervous system activity of the heart rate variability index during movie presentation. Hoshi et al. [27] reported that unpleasant images increased oxy-Hb in bilateral ventrolateral prefrontal cortex, and pleasant images decreased oxy-Hb in the left dorsolateral prefrontal cortex.

Because there are many types of natural scenes, I tested a range of movies to identify the most relaxing movie stimulus type using the paired comparison method.

3.4.2 Presentation stimulus and presentation method

Five types of movies of natural scenes were presented: underwater, sunset, animals, flowers, and forest. Each video was composed of six images, and the images were displayed at 10-second intervals for a total of 60 seconds. These movies were projected on a screen (1.5 meters from the participants) using a projector (EB-535W, EB-535W, Epson Co., Ltd.).

3.4.3 Experimental procedure

A total of 20 participants without color blindness (10 men and 10 women) were recruited. Two types of movie stimuli were selected from five types of movie stimuli, presented for 1 minute each, and evaluated using Scheffe's paired comparison method (Ura's variation method). Participants were asked to rate their "feelings of comfort," "feelings of relaxation," and "preferences" on a 7-point scale (−3 to 3), using the same procedure as that in the other stimulus selection process. Five types of movies were evaluated using the paired comparison method in all combinations to account for the order effect, and a total of 20 evaluations was carried out. The presentation order was randomly selected for each participant.

3.4.4 Results and discussion

Table 3.2 shows the average degree of preference and the difference of the average degree of preference between each stimulus. ANOVA was conducted for each evaluation term, and a significant main effect was confirmed for all terms: “feelings of comfort”; *F*(4,294 = 59.56, $p < 0.001$, “feelings of relaxation”; *F*(4,294) = 59.10, $p < 0.001$, and “preference”; *F*(4,294) = 25.76, $p < 0.001$. In “feelings of comfort” and “feelings of relaxation,” the average degree of preference for the underwater and forest movie stimuli was higher than that for the other movie stimuli, and the absolute value of the difference between the average preference for these movie stimuli and the other movie stimuli was larger than Y (0.05). In addition, the evaluation of the sunset movie was intermediate, and a significant difference was confirmed between the low-rating stimuli group (animals / flowers) and the high-rating stimuli group (forest / water). In summary, movies showing landscapes were rated more highly than movies with other types of content, and cold-colored movies were rated more highly than warm-colored movies. From a color psychological point of view, blue and green are considered to be calming and relaxing colors, and it has been reported that parasympathetic nervous system activity is enhanced when blue and green light stimuli are presented [34,35]. The colors of the forest movie and underwater movie were mainly green and blue, possibly causing the feeling of relaxation to be rated highly when viewing these stimuli. There was no significant difference in the average degree of preference for “feelings of comfort” and “feelings of relaxation” between the underwater movie and the forest movie, but the underwater movie was rated most highly for preference, and the difference in the average degree of preference was close to Y (0.05). The results described above indicated that the underwater movie was the most relaxing movie stimulus.

Table 3.2 Average degree of preference and difference in degree of each stimulus

		Movie	Average degree of preference	Difference in average degree of preference				$Y_{0.05}$
				-No.2	- No.3	- No.4	- No.5	
Feelings of comfort	No.1	Underwater	0.370	0.305 *	0.805 *	0.860 *	-0.120	0.228
	No.2	Sunset	0.065		0.500 *	0.555 *	-0.425 *	
	No.3	Animal	-0.435			0.055	-0.925 *	
	No.4	Flower	-0.490				-0.980 *	
	No.5	Forest	0.490					
Feelings of relaxation	No.1	Underwater	0.510	0.475 *	0.890 *	1.210 *	-0.025	0.257
	No.2	Sunset	0.035		0.415 *	0.735 *	-0.500 *	
	No.3	Animal	-0.380			0.320 *	-0.915 *	
	No.4	Flower	-0.700				-1.235 *	
	No.5	Forest	0.535					
Preference	No.1	Underwater	0.420	0.385 *	0.620 *	0.855 *	0.240	0.256
	No.2	Sunset	0.035		0.235	0.470 *	-0.145	
	No.3	Animal	-0.200			0.235	-0.380 *	
	No.4	Flower	-0.435				-0.615 *	
	No.5	Forest	0.180					

3.5 Music stimulation

3.5.1 Background

The relaxation-inducing effect of classical music is widely known, and physiological responses when presenting classical music have been reported in many previous studies [e.g., 43-46]. Listening to classical music has been reported to increase power spectrum components of the α-wave of the EEG signal [43], decrease cerebral blood flow in the frontal lobe [44], and suppress sympathetic nervous system activity while enhancing parasympathetic nervous system activity [45-46]. These changes in physiological responses indicate a relaxing state.

Because different classical music was used in each of these studies, in the current study music that induced a strong feeling of relaxation was selected using the paired comparison method (Ura’s variation method).

3.5.2 Presentation stimulus and presentation method

Five pieces of classical music were selected from a compact disc titled “NEW BEST Relaxing Classics 100 (WARNER MUSIC JAPAN).” The selection criteria were: (1) the music was slow; and (2) the tone of the music did not change significantly within a 5-minute period (because the selected music was presented for 5 minutes in Chapter 4). The following songs were selected:

- Beethoven - “Pathetique Piano Sonata No. 8 Op. 13-2,” slow piano piece in C minor.

・Chopin - “Nocturnes Nocturne No. 2 Es-Dur Op. 9-2,” slow piano piece in E flat major.

・Mozart - “Concerto for piano and orchestra Nr. 23 A-Dur K.488 Mov. 2 Adagio,” slowly paced piano concerto in A major.

・Satie - “Gymnopédies No. 1,” slow piano piece in D major and D minor with 3/4 time.

・Bach - “Orchestral Suite No. 3 in D major, BWV 1068,” a piece known as “Air on G String”, the orchestra version, was presented in this study.

Music was presented via headphones (WH-1000X M2, Sony Co., Ltd.). Participants adjusted the volume to a comfortable level.

3.5.3 Experimental procedure

Participants without hearing impairment (10 men and 10 women) were recruited. Participants were asked to wear headphones while in the sitting position. Two pieces of music were presented for 1 minute each and evaluated using a paired comparison method (Ura’s variation method). Considering the order effect, the comparison was performed 20 times in total. Participants rated their “feelings of comfort,” “feelings of relaxation,” and “preferences” on a 7-point scale (−3 to 3), as in the other stimulus selection procedure.

3.5.4 Results and discussion

Table 3.3 shows the average degree of preference and the difference compared with the average degree of preference between each music stimulus. ANOVA revealed significant main effects for all terms: “feelings of comfort”; $F(4,294) = 14.76$, $p < 0.001$, “feelings of relaxation”; $F(4,294) = 30.86$, $p < 0.001$, and “preference”; $F(4,294) = 23.02$, $p < 0.001$. In all sensory terms, the average degree of preference was in the following order: “Pathetique Piano Sonata No. 8 Op. 13-2,” “Nocturnes Nocturne No. 2 Es-Dur Op. 9-2” and “Gymnopédies No. 1,” “Orchestral Suite No. 3 in D major, BWV 1068,” and “Concerto for piano and orchestra Nr. 23 A-Dur K.488 Mov. 2 Adagio.” “Pathetique Piano Sonata No. 8 Op. 13-2” had the highest average degree of preference, and there was a significant difference in average preference (i.e., the absolute value of difference in average degree of preference was close to Y [0.05]). “Nocturnes Nocturne No. 2 Es-Dur Op. 9-2” and “Gymnopédies No. 1” were intermediate evaluations, and a significant difference was confirmed between them and “Concerto for piano and orchestra Nr. 23 A-Dur K.488 Mov. 2 Adagio.” Together, slow music played on the piano was rated higher than music played by the orchestra. Kusunose et al. [48] reported that classical music in minor and slow tempo enhanced parasympathetic activity and exhibited a relaxation-inducing effect. The highly rated music in this study was in a minor key and had a slow tempo. The above results indicated that “Pathetique Piano Sonata No. 8 Op. 13-2” was the most relaxing music stimulus tested.

Table 3.3 Average degree of preference and difference in degree of each stimulus

		Music	Average degree of preference	Difference in average degree of preference								$Y_{0.05}$
				-No.2		- No.3		- No.4		- No.5		
Feelings of comfort	No.1	Pathetique Piano Sonata No.8 Op.13-2	0.345	0.255		0.680	*	0.305	*	0.485	*	0.260
	No.2	Nocturnes Nocturne No.2 Es-Dur Op.9-2,	0.090			0.425	*	0.050		0.230	*	
	No.3	Concerto for piano and orchestra Nr. 23	-0.335					-0.375	*	-0.195		
	No.4	Gymnopédies No.1,	0.040							0.180		
	No.5	Orchestral Suite No. 3 in D major,	-0.140									
Feeling of relaxation	No.1	Pathetique Piano Sonata No.8 Op.13-2	0.430	0.295	*	0.930	*	0.210		0.715	*	0.269
	No.2	Nocturnes Nocturne No.2 Es-Dur Op.9-2,	0.135			0.635	*	-0.085		0.420	*	
	No.3	Concerto for piano and orchestra Nr. 23	-0.500					-0.720	*	-0.215		
	No.4	Gymnopédies No.1,	0.220							0.505	*	
	No.5	Orchestral Suite No. 3 in D major,	-0.285									
Preference	No.1	Pathetique Piano Sonata No.8 Op.13-2	0.380	0.295	*	0.815	*	0.220		0.570	*	0.259
	No.2	Nocturnes Nocturne No.2 Es-Dur Op.9-2,	0.085			0.520	*	-0.075		0.275	*	
	No.3	Concerto for piano and orchestra Nr. 23	-0.435					-0.595	*	-0.245		
	No.4	Gymnopédies No.1,	0.160							0.350	*	
	No.5	Orchestral Suite No. 3 in D major,	-0.190									

3.6 Illumination stimulation

3.6.1 Background

Illumination is an important factor in creating spaces that induce a strong feeling of relaxation. Previous studies have reported that high-illuminance and high-color temperature lighting enhances sympathetic nervous system activity [48,49]. On the contrary, low light and low color temperature lighting smoothly reduces the activity of the central nervous system [50].

Because color stimulation affects psychological and physiological responses, the selection of illumination color is also an important factor in indoor space design. In a study of physiological responses when presenting color stimuli, Yamashita et al. [51] presented participants with red, blue, and green colored light and reported that bright tones induced enhancement of the $\alpha 2$ (10 ± 1.0 Hz) EEG band. Oomori et al. [34] revealed that the more a hue turned from red to green and blue, the more α-wave activity was evoked in the occipital lobe.

The effect of colored illumination has been increasingly reported in recent studies because color can be finely dimmed using LED lighting with blue emitting diodes. Chiang et al. [52] reported that yellow and blue were subjectively rated as highly comfortable, and red and green were evaluated highly for physiological fatigue reduction and work efficiency in a workspace. Matsui et al. [35] reported that green illumination significantly enhanced HF (parasympathetic activity index).

Thus, colorful illumination with low color temperature and low illumination was expected to be a relaxing stimulus. In this chapter, the relaxing properties of illumination color were verified using a paired comparison method (Ura’s variation method).

3.6.2 Presentation stimulus and presentation method

Five illumination colors (blue, light blue, green, yellow-green, orange) were presented as illumination stimuli. Because previous studies have reported that green and blue colors have a strong relaxing effect [34,35,51,52], dark blue, blue, green and yellow green were selected. In addition, orange was selected as a warm color because of the relaxing effect of the illumination color with a high color temperature [48,49]. Illumination stimuli were presented using an LED cube (THOUSLITE Co., Ltd), which enabled the presentation of illumination in a range of colors. The LED cube was installed on the celling with a 2.0 m square angle, such that illumination was presented from above (Figure 3.3). The experiment was conducted in a dark room. The horizontal illuminance was set to 50[lx] ± 3% at a height of 1.5 meters. While not presenting light blue illumination, the LED cube presented white illumination (color temperature: 5,500 k, horizontal illuminance: 50[lx] ± 3%). Figure 3.4 and Table 3.4 show the spectral distribution and photometric values measured using a spectral irradiance meter CL500A (KONICA MINOLTA Co., Ltd) in the horizontal direction with a height of 1.5 meters.

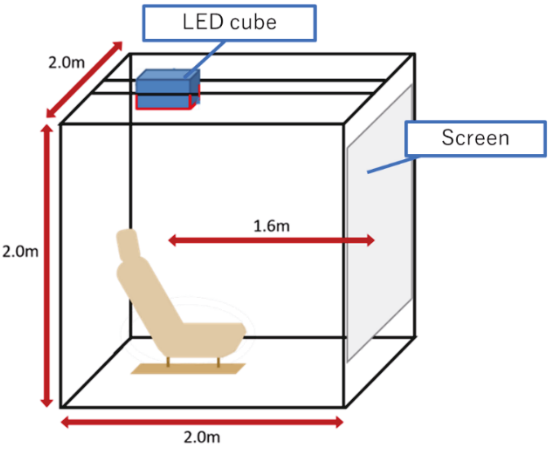

Figure 3.3 Equipment installation position

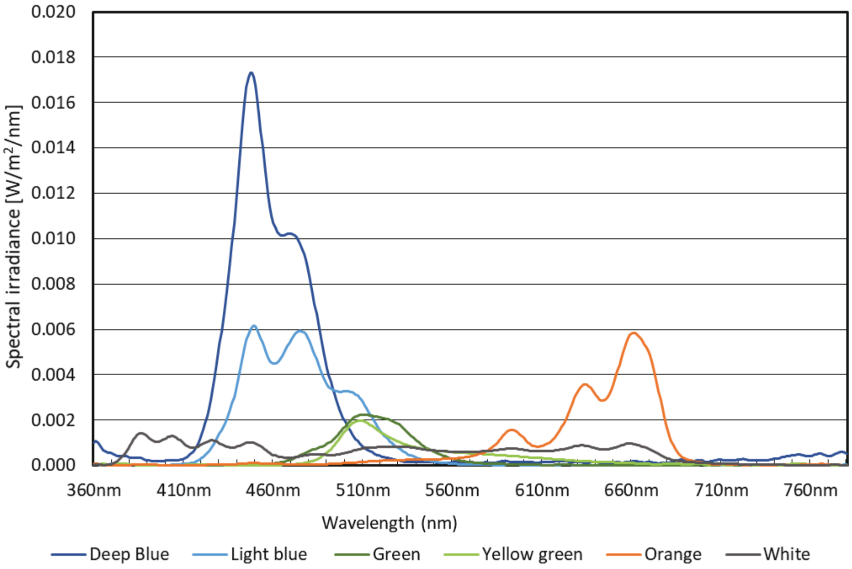

Figure 3.4 Spectral irradiance distribution

Table 3.4 Photometric value of LED illumination

	Illuminance[lx]	Peak wavelenght[nm]	Tristimulus values			Chromaticity	
			X	Y	Z	x	y
Deep Blue	49.5	447	130	50	686	0.151	0.057
Light blue	51.1	449	51	51	285	0.132	0.132
Green	49.8	510	12	50	18	0.150	0.624
Yellow green	50.7	509	26	51	10	0.295	0.585
Orange	51.3	661	85	51	5	0.602	0.365
White	50.3	386	51	50	53	0.333	0.326

3.6.3 Experimental procedure

A total of 20 participants without color blindness (10 men and 10 women) were recruited. The experimental protocol is shown in Figure 3.5. After entering the dark room, participants were asked to rest for 10 minutes in a sitting position under 50 [lx] white illumination to adjust to the brightness. The white illumination was presented in an initial control state, and illumination A was presented for 1 minute after 10 seconds of darkness. The room then returned to a dark state, and illumination B was presented for 1 minute. Paired comparison evaluation was performed under white illumination, which was the same as the initial state. Scheffe’s paired comparisons (Ura’s variation) were performed 20 times for all combinations of the illumination stimuli, considering the ordinal effect. Participants were asked to rate their “feelings of comfort,” “feelings of relaxation,” and “preferences” on a 7-point scale (−3 to 3).

Figure 3.5 Experimental protocol

3.6.4 Results and discussion

Table 3.5 shows the average degree of preference and the test results of the difference between them. ANOVA revealed the significant main effect in all terms, “feelings of comfort”; $F(4,294) = 31.59$, $p < 0.001$, “feelings of relaxation”; $F(4,294) = 29.16$, $p < 0.001$, and “preference”; $F(4,294) = 27.82$, $p < 0.001$. Light blue and yellow green illumination were highly rated for all evaluation items, and a significant difference was confirmed between these two colors and the other three colors (green, deep blue and orange). There was no significant difference in “feelings of comfort” or “feelings of relaxation” between light blue and yellow green, but a significant difference was confirmed in “preference,” in which light blue illumination was most highly evaluated. The evaluation of green illumination was intermediate, and there was a significant difference between dark blue and orange in term of “feelings of relaxation.” The high evaluation of blue and green colors was consistent with the results of previous studies [34,35,51,52]. Additionally, the less saturated light blue and yellow-green of the same blue and green were highly evaluated than deep blue and green. Many participants gave the deep blue illumination a low rating because they felt that it had a strong glare. As shown in Figure 3.4, the deep blue illumination had a larger spectral irradiance (410 nm to 460 nm) compared with the other illumination conditions. The evaluation of orange illumination varied greatly among individuals, and the average evaluation was lower than that for other illumination colors.

In summary, light blue illumination was the most highly rated for “preference” and “feelings of relaxation.” The light blue illumination was selected as the most relaxing stimulus.

Table 3.5 Average degree of preference and difference in degree of each stimulus

		Illumination color	Average degree of preference	Difference in average degree of preference				$Y_{0.05}$
				-No.2	- No.3	- No.4	- No.5	
Feelings of comfort	No.1	Deep blue	-0.375	-0.900 *	-0.245	-0.680 *	-0.050	0.281
	No.2	Light bulue	0.525		0.655 *	0.220	0.850 *	
	No.3	Green	-0.130			-0.435 *	0.195	
	No.4	Yellow Green	0.305				0.630 *	
	No.5	Orange	-0.325					
Feelings of relaxation	No.1	Deep blue	-0.340	-0.825 *	-0.295 *	-0.625 *	0.045	0.295
	No.2	Light bulue	0.485		0.530 *	0.200	0.870 *	
	No.3	Green	-0.045			-0.330 *	0.340	
	No.4	Yellow Green	0.285				0.670 *	
	No.5	Orange	-0.385					
Preference	No.1	Deep blue	-0.200	-0.780 *	-0.040	-0.335 *	0.155	0.274
	No.2	Light bulue	0.580		0.740 *	0.445 *	0.935 *	
	No.3	Green	-0.160			-0.295 *	0.195	
	No.4	Yellow Green	0.135				0.490 *	
	No.5	Orange	-0.355					

3.7 Vibration stimulation

3.7.1 Background

Low-frequency vibration stimulation is clinically used for improving many somatic and functional disorders, and relieving mental tension [53-55]. Ruutell et al. [53] reported that a decrease in pain, physical discomfort, and anxiety was induced by the presentation of vibration to the whole body at 40 Hz using a mattress. Satou et al. [54] presented vibration to the whole body with a frequency of 10 Hz while participants were in a sitting position, and reported that weakness levels in the alpha attenuation test were reduced by vibration presentation. Otsuki et al. [55] measured physiological responses to 26-Hz whole-body vibration (WBV) delivered to standing participants. The researchers reported an acute decrease in arteriosclerosis after WBV, although there was no difference in blood pressure or heart rate. In the above study, vibrations were presented to the entire body, but the effect of improving pain and mood by sequentially presenting vibrations to parts of the body has also been reported [56].

In several studies, vibration stimuli were presented with music stimulation to enhance the relaxation-inducing effects of the stimuli [53,56,57]. Yajima et al. [57] reported that simultaneous presentation of 54.5 Hz vibration stimuli to the lumbar area and music induced a decrease in heart rate and salivary amylase activity. These results indicate the suppression of sympathetic nervous system activity by the presentation of stimuli.

The current experiment focused on the vibration of the trunk and investigated which frequency of vibration was most effective for inducing relaxation.

3.7.2 Presentation stimulus and presentation method

Participants held a cushion speaker (Shima System Co., Ltd.) and a specific frequency of vibration was presented via the speaker. The speaker vibrated at low frequencies 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 for the speaker to vibrate. A sine wave was output using MATLAB (Mathworks Co., Ltd.), and vibration stimuli of 40 Hz, 55 Hz, 70 Hz, 85 Hz, and 100 Hz were presented. The frequency range was set to 40–100 Hz because (1) the cushion speaker could not output stable vibrations below 40 Hz, and (2) vibration above 100 Hz caused an unpleasant sensation in which the vibration was transmitted only to the skin surface.

The cushion speakers had the characteristic of easily amplifying high-frequency vibration. Therefore, to make the magnitude of vibration equal at each frequency, the acceleration was measured using a small six-axis MP-M6-02 / 500C-J motion sensor (Micro Stone Co., Ltd.). The root mean square value (RMS) of acceleration was calculated. Figure 3.6 shows the sensor attachment position in the cushion speaker. Five motion sensors were mounted at the center and 100 mm from the center to the left, right, top and bottom. The sampling frequency was 1,000 Hz, and the measurement was performed with the cushion speaker leaning vertically. RMS of the acceleration in the Az direction was measured while changing the volume output at five different frequencies, and the average of the five effective values of the acceleration for 1 minute (Az direction) was calculated. The volume output was then adjusted so that the RMS of the acceleration in the Az direction was 95 m/s^2 ± 5% in all frequency conditions.

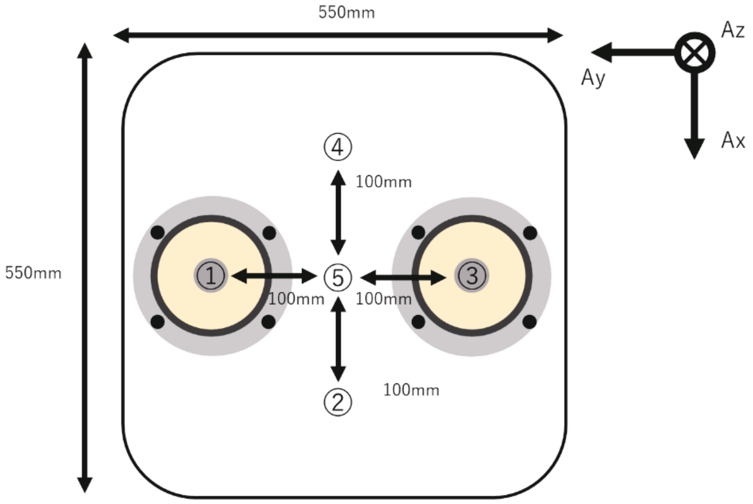

Figure 3.6 Sensor attachment position

The amplitude randomly changed to 0.25, 0.50, 0.75, and 1.00 times every 2.5 seconds to prevent participants becoming habituated to the stimuli. The vibration signal was sent from a laptop to the cushion speaker through a digital amplifier PDP-SAII (Shima System Co., Ltd.) and presented to participants. Participants wore headphones with a noise canceling function (WH-1000X M2, Sony Co., Ltd.) to reduce the noise caused by vibration.

3.7.3 Experimental procedure

A total of 20 participants (10 men and 10 women) were recruited. Participants were asked to hold cushion speakers and wear headphones while maintaining a sitting position (Figure 3.7). Similar to the paired comparison of other stimuli, the vibration of frequency A was presented for 1 minute, and the vibration of frequency B was presented for 1 minute. The evaluation was performed according to the paired comparison method (Ura’s variation method). Considering the order effect, the comparison was conducted 20 times in total. Participants rated their “feelings of comfort,” “feelings of relaxation,” and “preferences” on a 7-point scale (−3 to 3), as in the stimulus selection processes in the other experiments.

[redacted]

Figure 3.7 Vibration presentation

3.7.4 Results and discussion

The average preference and test results of the differences between stimuli are shown in Table 3.6. ANOVAs were performed, and significant main effects were confirmed for all terms: “feelings of comfort”; $F(4,294) = 33.98$, $p < 0.001$, “feelings of relaxation”; $F(4,294) = 43.90$, $p < 0.001$, and “preference”; $F(4,294) = 19.87$, $p < 0.001$. The rating of the 55 Hz vibration stimulus was significantly different to all of the other stimuli in the “feeling of relaxation.” Additionally, the vibration frequencies of 40 Hz and 55 Hz were significantly different from the other stimuli in “feelings of comfort,” and the average degree of preference was large. These frequencies are consistent with the relaxation frequencies reported in previous studies [53,57]. In contrast, 100 Hz vibration was the lowest for all sensory terms.

I speculated that these results were caused by the frequency characteristics of each part of the body. Miwa et al. [58] presented vibrations to the buttocks while participants were in a sitting position and gradually increased the vibration frequency. The results revealed that the internal organs vibrated at 6 to 8 Hz, the eyeball vibrated at 28 to 30 Hz, then the vibration descended along the spine at 40 to 60 Hz, the waist vibrated at 60 to 80 Hz, and the contact area vibrated at 80 Hz or higher. Additionally, vibrations above 100 Hz were perceived as skin sensations only. These findings indicated that high-frequency vibrations were transmitted only to the contact area, which participants considered uncomfortable. In addition, the frequency of 40–55 Hz vibration was transmitted to the trunk, and induced a strong feeling of relaxation.

These findings indicated that the vibration frequency of 55 Hz was the most relaxing stimulus tested.

Table 3.6 Average degree of preference and difference in degree of each stimulus

		Vibration Frequency [Hz]	Average degree of preference	Difference in average degree of preference				Y 0.05
				-No.2	- No.3	- No.4	- No.5	
Feelings of comfort	No.1	40	0.290	-0.255	0.460 *	0.395 *	0.850 *	0.287
	No.2	55	0.545		0.715 *	0.650 *	1.105 *	
	No.3	70	-0.170			-0.065	0.390 *	
	No.4	85	-0.105				0.455 *	
	No.5	100	-0.560					
Feeling of relaxation	No.1	40	0.280	-0.320 *	0.375 *	0.425 *	0.920 *	0.317
	No.2	55	0.600		0.695 *	0.745 *	1.240 *	
	No.3	70	-0.095			0.050	0.545 *	
	No.4	85	-0.145				0.495 *	
	No.5	100	-0.640					
Preference	No.1	40	0.165	-0.250	0.160	0.220	0.695 *	0.305
	No.2	55	0.415		0.410 *	0.470 *	0.945 *	
	No.3	70	0.005			0.060	0.535 *	
	No.4	85	-0.055				0.475 *	
	No.5	100	0.165					

3.8 Odor stimulation

3.8.1 Background

Aroma oils are widely considered to have stress-reducing, relaxation and sedative effects. Many previous studies have evaluated these effects using physiological and psychological reaction measurement [59-62]. Regarding citrus scents, Lehrner et al. [59] reported that the orange odor provided subjective relaxation and sedation. Watanabe et al. [60] reported that lavender oil and grapefruit oil increased work efficiency at visual display terminals and significantly reduced salivary cortisol levels (stress index) compared with unscented conditions. Kuroda et al. [61] revealed a significant increase in heart rate and HF because of the presentation of the scent of jasmine tea and lavender. Hashizume et al. [62] presented lavender oil, and reported that α-waves of the occipital area were increased by the aspiration of aroma. In addition, a relaxation-inducing effect of simultaneous presentation of thermal stimulation and odor stimulation has also been reported [2,3,12] as described in Chapter 1.

Lavender and citrus odors (such as orange and grapefruit) are widely used as relaxing odor stimuli. Previous studies investigating the preferences for these odors reported that lavender had large individual differences [63], whereas citrus scents were rated as the most preferred scents by Japanese university students [64]. Because the experimental participants in the current study were university students, this study focused on citrus odors, and sought to identify the most relaxing citrus odor using one paired comparison (Nakaya's variation method).

3.8.2 Presentation stimulus and presentation method

Three types of aroma oils (MUJI Co., Ltd.), grapefruit (*Citrus paradisi*), yuzu (*Citrus junos*), and sweet orange (*Citrus sinensis*), were selected as candidates for citrus odors. Three bottles with a diameter of 9.8 cm and a height of 12.2 cm were used to present the odor. A piece of Kimwipe (Nippon Paper Industries Co., Ltd) cut into eight equal parts was placed in a bottle, and 0.1 ml of each aroma oil was dropped onto the piece of Kimwipe using a micropipette (Figure 3.8). These bottles were placed approximately 10.0 cm from the nostrils of the participants, and comparisons were performed after opening the bottle lids. Because the sense of smell can rapidly become accustomed to an odor, instant coffee powder was used to reset the sense of smell.

Figure 3.8 The bottle and Kimwipe used to present the odor

3.8.3 Experimental procedure

A total of 20 participants without olfactory dysfunction (10 men and 10 women) were recruited. Two bottles with different odors were placed in front of the sitting participants. Participants were asked to sniff and compare the two scents according to a Scheffe’s paired comparison evaluation (Nakaya’s variation method). In the preliminary experiment, the odor stimuli were presented in order for 1 minute according to Scheffe’s paired comparison method (Ura’s variation method). However, many participants commented that it was difficult to compare the odor stimuli. Therefore, participants performed the evaluation by arbitrarily sniffing the two odors and a paired comparison was performed according to Nakaya’s variation method. Participants rated 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. After the evaluation, participants inhaled the smell of instant coffee to reset their sense of smell. This evaluation was repeated three times for all combinations (without considering the order effect).

3.8.4 Results and discussion

Table 3.7 shows the average preference and the test results of the difference between them. ANOVA revealed the significant main effect in all terms, “feelings of comfort”; $F(2,19) = 11.11$, $p < 0.001$, “feelings of relaxation”; $F(2,19) = 10.33$, $p < 0.001$, and “preference”; $F(2,19) = 17.59$, $p < 0.001$. In all evaluation terms, the odor of yuzu was rated the lowest, and a significant difference was observed between yuzu and the odors of grapefruit and sweet orange. Participants answered that they felt bitterness and astringency when the scent of yuzu was presented. The yuzu aroma oil contains more γ-terpinene and α-pinene (a wood-like aroma) compared with grapefruit and sweet orange. These odor components may have reduced the ratings of comfort and relaxation for the yuzu odor stimulus.

No significant differences were found in the evaluation results between grapefruit and sweet orange. Some participants reported that it was difficult to distinguish between grapefruit and sweet orange. A possible reason for this finding is that both odors contain limonene, which is the main component of odors in the citrus family. Regarding "feelings of relaxation," nine participants evaluated the grapefruit odor as more relaxing, and five participants evaluated the orange odor as more relaxing. Additionally, six participants rated grapefruit and sweet orange as having the same degree of relaxation. The odor of grapefruit was selected as the most relaxing stimulus, because there were more participants who rated grapefruit as more relaxing.

Table 3.7 Average degree of preference and difference in degree of each stimulus

		Odor	Average degree of preference	Difference in average degree of preference				Y (0.05)
				-No.2		- No.3		
Feelings of comfort	No.1	Grapefruit	0.367	1.033	*	0.067		
	No.2	Yuzu	-0.667			-0.967	*	0.623
	No.3	Sweet orange	0.300					
Feelings of relaxation	No.1	Grapefruit	0.300	0.833	*	0.067		
	No.2	Yuzu	-0.533			-0.767	*	0.517
	No.3	Sweet orange	0.233					
Preference	No.1	Grapefruit	0.367	1.133	*	-0.033		
	No.2	Yuzu	-0.767			-1.167	*	0.569
	No.3	Sweet orange	0.400					

3.9 Summary

This study identified the most relaxing stimulus for each sensory stimulus modality using Scheffe’s paired comparison method. Table 3.8 summarizes the relaxing stimuli selected and the presentation equipments.

- Thermal stimulation: A rubber mat was used to present the temperature of three conditions to the sole of the foot, and a temperature of 40 °C was selected as the most relaxing stimulus.
- Movie stimulation: Five types of movie were projected onto the screen, and the movie showing an underwater scene was selected as the most relaxing stimulus.
- Musical stimulus: Five piece of classical music were presented using via headphones, and Beethoven’s “Pathetique Piano Sonata No. 8 Op. 13-2” was selected as the most relaxing stimulus.
- Illumination stimulation: Five colors of illumination were presented to participants from above, and light blue illumination was selected as the most relaxing stimulus.
- Vibration stimulation: A cushion speaker presented vibration to the trunk in five different frequency conditions, and vibration with a frequency of 55 Hz was selected as the most relaxing stimulus.

・Odor stimulation: Three types of citrus odor were presented using a bottle filled with odor, and grapefruit odor was selected as the most relaxing stimulus.

The stimuli selected in this study were presented in the experiment in Chapter 4. Chapter 4 examined the relaxation-inducing effects of multi-sensory integration with thermal stimuli combined with other stimulus types. A stronger relaxation effect was expected to be induced by presenting a combination of stimuli with strong relaxation-inducing characteristics.

Table 3.8 Selected stimulus

Stimulus	Selected relaxing stimulus	Presentation equipment
Thermal	Thermal stimulation to the soles (40°C)	Silicon rubber heater (HAKKO FINE THERMO Co., Ltd.)
Movie	Underwater movie	Projector: EB-535W (EPSON Co., Ltd.)
Music	Beethoven - Pathetique Piano Sonata No.8 Op.13-2	Headphone: WH-1000X M2 (SONY Co., Ltd.)
Illumination	Light blue Illumination (50lx)	LED Cube (THOUSLITE Co., Ltd.)
Vibration	Vibration to trunk (55Hz)	Cushion speaker (Shima System Co., Ltd.)
Odor	Grapefruit	Odor-filled bottle

Chapter 4

Relaxation induced by comfortable thermal stimuli to the soles of the feet with simultaneous presentation of various sensory stimuli

4.1 Introduction

In this study, stimuli to other sensory organs that were expected to induce the feeling of relaxation simultaneously were presented with a thermal stimulus. music stimulus, movie stimulus, illumination stimulus, odor stimulus and vibration stimulus (applied to the trunk) selected in Chapter 3. Previous studies evaluated participant’s physiological and psychological responses when presenting stimuli to a single sensory modality. However, few studies have examined the combination thermal stimuli with stimulation of other sensory modalities [2,4,12,13]. Thus, it may be valuable to clarify the psychological and physiological responses when presenting other stimuli in combination with thermal stimulation. This study examined the differences in physiological responses to comfortable thermal stimulation applied to the soles of the feet simultaneously with stimulation in another sensory modality, and whether different combinations lead to different psychological and physiological states. The current study was designed to clarify which sensory stimuli besides thermal stimuli can enable multi-sensory integration to induce feelings of comfort and relaxation. Physiological responses of the autonomic nervous system and the central nervous system were measured as mentioned in Chapter 2. The relaxation-inducing effect of multisensory integration was verified by evaluating the physiological indices of the whole of body. Additionally, a sensory test of comfort and relaxation were performed along with the physiological responses to verify the subjective relaxation effect.

4.2 Method

4.2.1 Presentation stimuli

A pilot study was conducted in chapter 3, Scheffe's paired comparison method (Ura's variation, odor stimuli were evaluated using Nakaya's variation) revealed the most relaxing stimuli.

(a) Thermal stimulation

The thermal stimulation at a temperature of 40℃ was presented to the soles of the feet. The participants were asked to place their bare feet on the 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.

(b) Video stimulation

The video contained 30 underwater photos, each of which was displayed for 10 seconds (300 seconds in total). Under water movies was projected on a screen in front of the participants (1.5 m) using a projector (EB-535W, Epson Co., Ltd.).

(c) Music stimulation

“Pathetique Piano Sonata No.8 Op.13-2” as music stimulation was via headphones (WH-1000X M2, Sony Co., Ltd.). The first 5 minutes of the music file were presented, which was 5 minutes and 40 seconds long.

(d) Vibration stimulation

Light blue Illumination was presented using the LED cube (THOUSLITE Co., Ltd), which was able to present illumination in a range of colors. The LED cube was installed on the ceiling with a 2.0 meters square angle, and illumination was presented from above. The horizontal illuminance was set to 50 lx at a height of 1.5 meters.

(e) Illumination stimulation

Participants were asked to hold the cushion speaker (Shima System Co., Ltd.) that produced a vibration. This speaker vibrated at a low frequency to match the rhythm of the music. A sine wave was outputted using MATLAB (Mathworks Co., Ltd.). The vibration frequency in the main study was 55 Hz. 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-SAII digital amplifier (Shima System Co., Ltd.).

(f) Odor stimulation

Grapefruit odor was presented using an aroma shooter (Aroma Join Co., Ltd.). The odor was presented using a bottle in chapter 2, but it was difficult to present the odor continuously. Therefore, the presentation device was changed to an aroma shooter. This device presents an odor by injecting the odor stored in an internal cartridge and was aimed in a forward direction at the right side of the participant. Odor injection was performed at 10-second intervals to prevent participants from becoming used to the odor.

4.2.2 Physiological measurements

In this study, the physiological responses of the autonomic nervous system (ECG, respiration, pulse wave, peripheral blood flow and sweating) and the central nervous system (EEG and frontal cerebral blood flow) were measured as mentioned in Chater 2. In the measurement of the physiological response of the autonomic nervous system, all biological amplifiers were connected to MP150 and recorded. The sampling frequency was 1000 Hz. EEG and prefrontal cortex cerebral blood flow were recorded connected to the laptop using a separate system. The sampling frequency of EEG was 500 Hz, and the cerebral blood flow was recorded at 2 Hz.

(A) ECG

ECG electrodes were attached to the participants at the upper sternum and apical region via the chest bipolar induction method using a MP150 ECG100C amplifier system (BIOPAC Systems, Inc.). Instantaneous heart rate (IHR), CVRR, LF/HF, and HF were calculated from the R-R interval. IHR and CVRR were calculated in 1-minute windows. 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).

(B)Respiration

Respiration was measured 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.). The respiratory peak frequency (PF) and center of gravity frequency (GF) were calculated from the obtained waveforms. Since there was no difference between PF and GF in the current study, only PF was analyzed.

(c) Fingertip pulse wave

The fingertip pulse wave measured 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.). The pulse transit time (PTT) was calculated from the time difference between the rise point of the pulse wave waveform and the R wave of the ECG.

(d) Peripheral blood flow

A MoorVMS-LDF laser Doppler blood flow meter and a VT1T optical probe (Moor Instruments Co., Ltd.) were used to measure peripheral blood flow. The sensor probe was attached to the third finger of the participant’s left hand. Blood perfusion units (BPU) were calculated from this sensor. I calculated the section average for each minute from the obtained waveform to use as an index of blood flow.

(e) Sweating

A SKN-2000 (SKINOS Co., Ltd.) unit was used to measure the amount of sweating. The sensor probe was attached to the fourth finger of the left hand to measure mental sweating. From the obtained signal, the section average for each minute was calculated and used this as an index of sweating amount.

(f) EEG

EEG was measured using Polymate AP-1000 (Miyuki Giken Co., Ltd.). EEG electrodes were attached to Pz and A1 according to the international 10-20 electrode system. α-wave activity was calculated by dividing the α-wave power spectrum by the sum of the θ-wave, α-wave, and β-wave power spectra. The whole activity of the brain was evaluated from the α-wave content.

(g) Cerebral blood flow in the prefrontal cortex

Cerebral blood flow in the prefrontal cortex was estimated using NIRS, with Hb-132 (Astem Co., Ltd.). The amount of oxy-Hb was calculated relative to a pre-rest reference point. The Hb 132 had five-channel, and the channels were arranged at 35-mm intervals on the left and right sides. Channel 3 was located at the center of the prefrontal cortex and was set to Fpz according to the international 10-20 electrode system. Channels 1 and 2 were attached over the left frontal lobe and Channels 4 and 5 were attached over the right frontal lobe.

In this study, 10 physiological indices were calculated from biological signals. These indicators were used to evaluate of relaxation-inducing effect. In the relaxed state, CVRR, HF, PTT, and BPU α-wave content increase, and the IHR, LF/HF, Respiration PF, Sweating rate and oxy-Hb in prefrontal cortex decrease.

4.2.3 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. Participants also participated experiment of chapter 3. Additionally, the participants had no autonomic nervous system dysfunction and did not take medications that affect the autonomic nervous system.

The experimental the experimental protocol is shown in Figure 4.1, and experimental environment is shown in Figure 4.2. Each trial comprised two time periods: Cognitive load task (180 seconds), and Stimulus presentation (300 seconds). Thermal stimulation was constantly presented to the soles of the feet during the trials. Physiological responses were measured throughout each trial. Each participant participated in six trials, one for each of the presentation patterns. Each set of six tests was performed on the same day, and the experiment was performed twice (2 days in total). The data 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 angle was reported by Fujimaki et al. to be comfortable for participants [65].

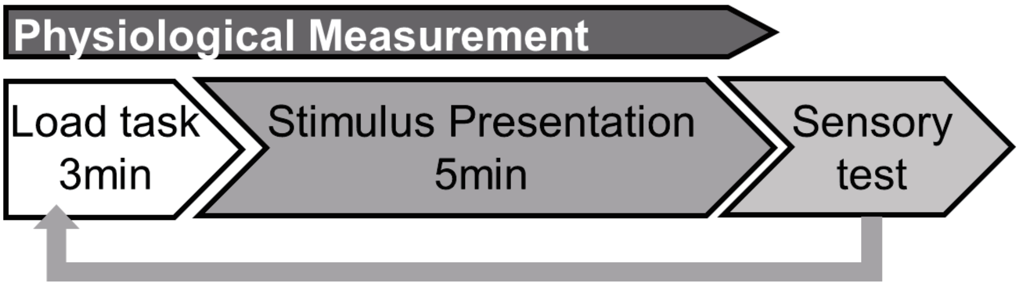

Figure 4.1 Experimental protocol

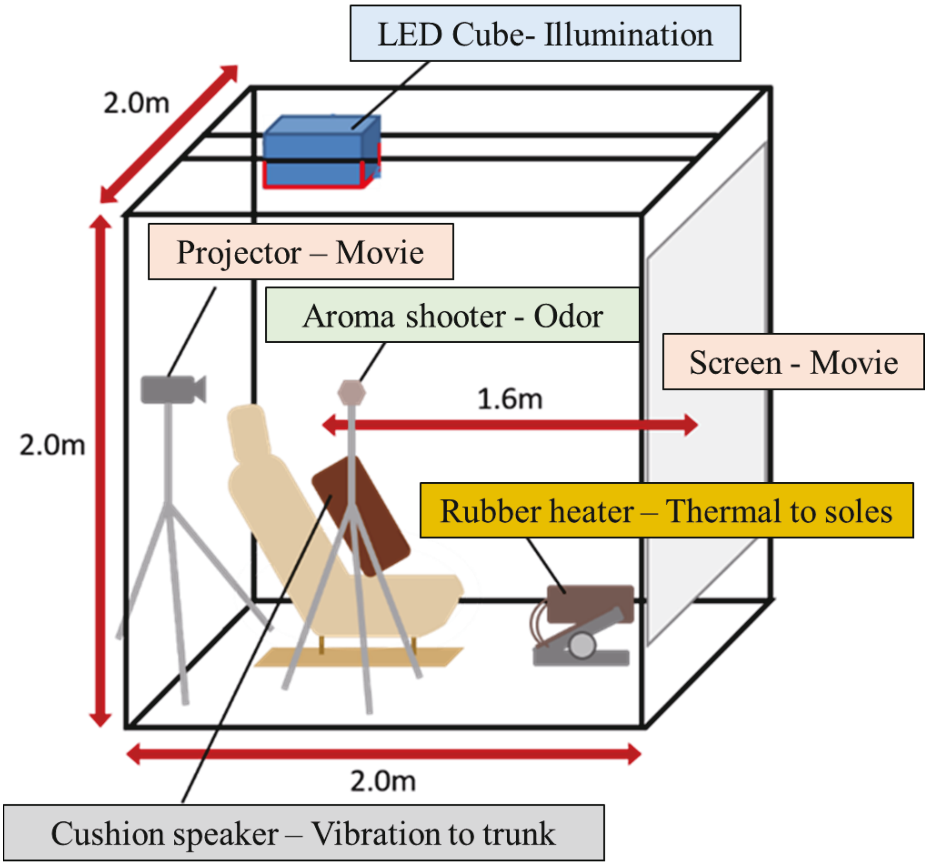

Figure 4.2 Experimental environment

4.2.4 Advanced trail making test

The participants performed the Advanced Trail Making Test (ATMT) as a cognitive load task in each trial to control initial conditions. The ATMT is a cognitive load task in which participants were instructed to use a mouse to sequentially click numbers displayed on the screen (Figure 4.3). The numbers were from 20 to 75, and 25 numbers were displayed each time. The screen switches each time a number was clicked, and the arrangement of the displayed numbers changes randomly. When the number reaches 75, the task restarts at 20.

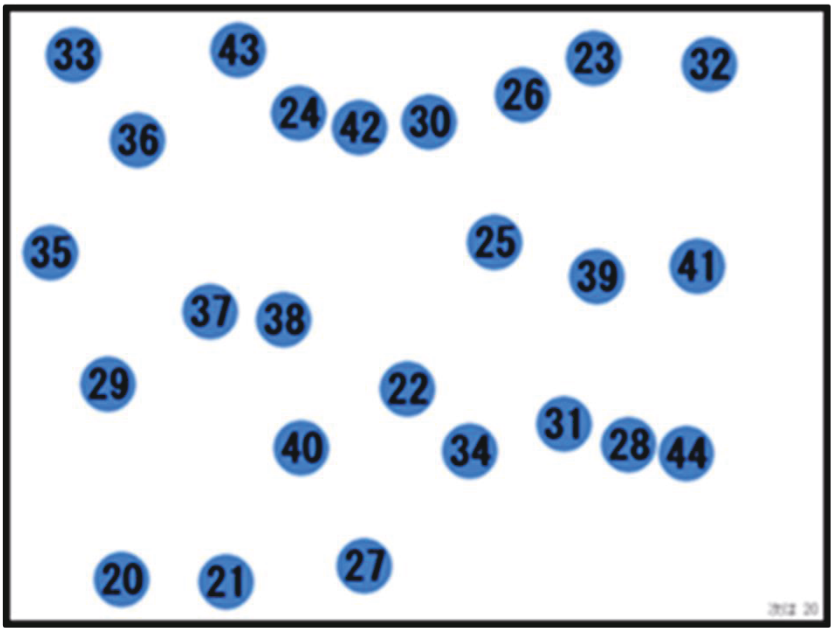

Figure 4.3 An example of ATMT displayed on the screen

4.2.5 Sensory test

A sensory test was performed after each trial. The participants were asked about their “feelings of comfort” (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. Participants were asked about their respective states before and after stimulus presentation after each trial.

4.2.6 Statistical analysis

A two-way ANOVA was performed to verify the statistical significance of the two main effects, stimulus and time course, and the interaction between them. Given the robustness of ANOVA, it was assumed that the scores for each sensory test and biological indices follow a normal distribution. Because there is no non-parametric test applied to two-way ANOVA, parametric test was conducted in this paper. Additionally, Tukey’s test was used for multiple comparisons.

4.3 Results of sensory test

Figure 4.4 – 4.7 show the mean sensory scores obtained from 10 participants. A two-way ANOVA was performed for the mean value of each evaluation term (factor 1: six levels, stimulation condition; factor 2: two levels, before-after).There were significant main effect of factor 2 (before-after) for all evaluation terms, “comfort – discomfort”; $F(1,108) = 31.56$, $p < 0.001$, $\eta^2_p = .13$, “arousal – sedation”; $F(1,108) = 128.24$, $p < 0.001$, $\eta^2_p = .33$, “feeling of relaxation”; $F(1,108) = 100.72$, $p < 0.001$, $\eta^2_p = .29$, and “fatigue state”; $F(1,108) = 35.33$, $p < 0.001$, $\eta^2_p = .08$. Regarding “comfort-discomfort”, a significant factor 1 × factor 2 interaction was confirmed, $F(5,108) = 2.40$, $p = 0.042$, $\eta^2_p = .04$. Additionally, multiple comparisons using Tukey’s test revealed significant differences between the presentation stimuli and before-after each. In the comparison between before and after, the scores for “feeling of comfort” and “feeling of relaxation” increased significantly after presentation, and scores of arousal and fatigue state decreased significantly ($p < 0.05$). In the comparison between presentation stimuli, I confirmed that “music + thermal” stimulation scores tended to be significantly higher than those for other stimuli in terms of the “feeling of comfort” and the “feeling of relaxation”. Based on these results indicated that all of the presented stimulus modalities induced feelings of relaxation and sedation, and that the “music + thermal” condition was subjectively evaluated as the most relaxing.

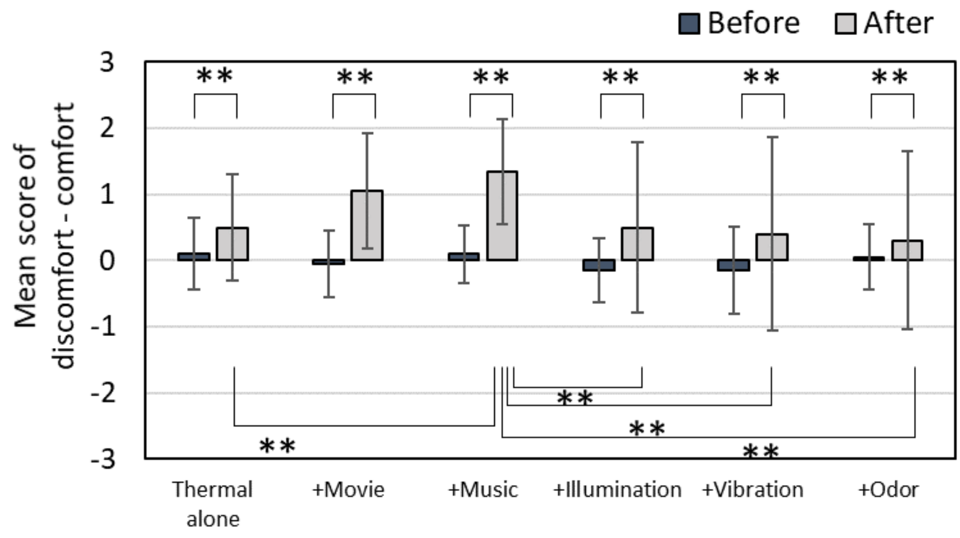

Figure 4.4 Mean scores for “feelings of comfort” (**$p < 0.01$, *$p < 0.05$)

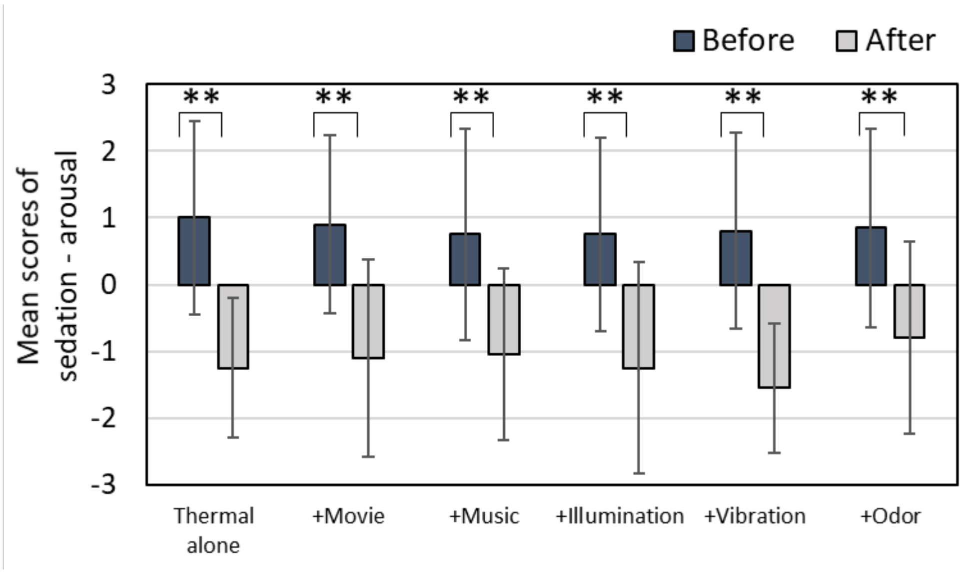

Figure 4.5 Mean scores for “arousal – sedation” (**$p < 0.01$, *$p < 0.05$)

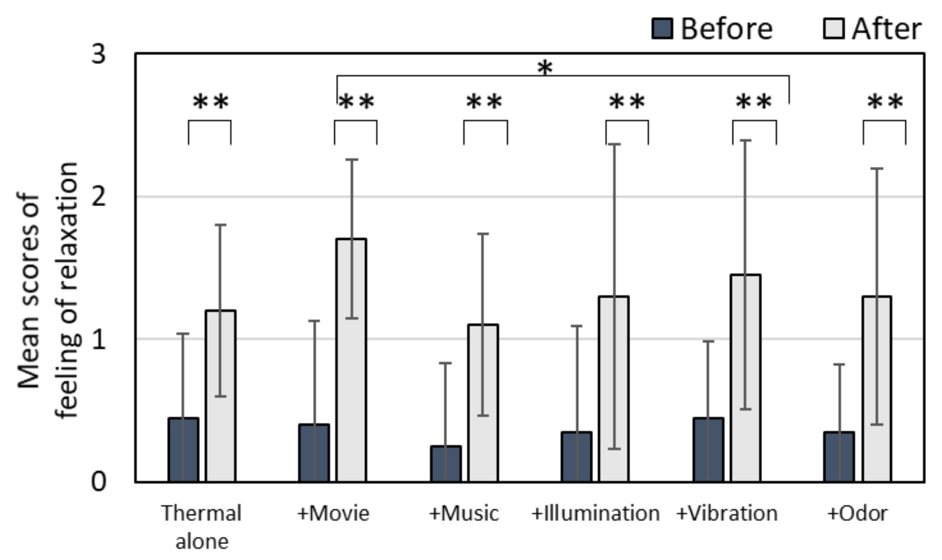

Figure 4.6 Mean scores for “feeling of relaxation” (**$p < 0.01$, *$p < 0.05$)

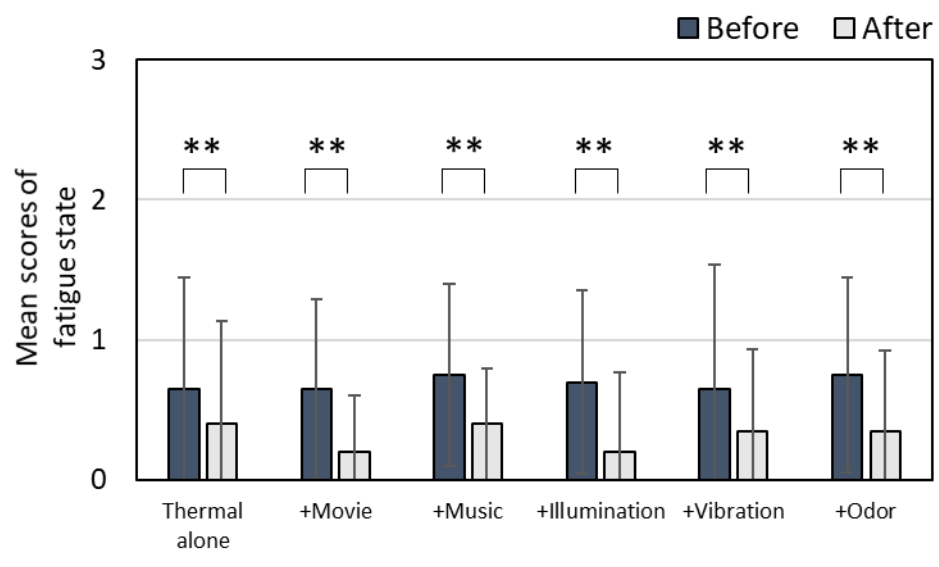

Figure 4.7 Mean scores for “fatigue state” (**$p < 0.01$, *$p < 0.05$)

4.4 Results of physiological measurements

4.4.1 Results of the two-way ANOVA

Two-way ANOVAs were performed for each index for the different stimuli (6 levels) and elapsed time factors (7 levels for IHR ratio, Δ Sweating rate, Δ BPU and Δ oxy-Hb for each channel, 8 levels for CVRR, PF, PTT and α-wave content, 6 levels for LF/HF and HF). Table 4.1 shows a summary of the results of two-way ANOVA. Additionally, multiple comparisons using Tukey's tests were carried out 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 two-way ANOVA and the multiple comparisons.

Table 4.1 Summary of the two-way ANOVA (**$p < 0.01$, *$p < 0.05$, † $p<0.10$)

Physiological indices	Main effect of the stimulus					Main effect of the time					Interaction					Residual
	df	F	η^2_p	p		df	F	η^2_p	p		df	F	η^2_p	p		
IHR ratio	5	2.33	0.041	0.058	†	6	0.55	0.010	0.768		30	1.19	0.024	0.236		378
CVRR	5	1.14	0.006	0.353		7	5.66	0.164	0.000	**	35	0.86	0.022	0.693		432
LF/HF	5	1.47	0.013	0.219		5	1.08	0.013	0.382		25	1.31	0.031	0.154		324
HF	5	1.87	0.007	0.119		5	3.34	0.036	0.012	*	25	0.86	0.004	0.665		324
Peak Frequency	5	2.98	0.020	0.021	*	7	14.04	0.140	0.000	**	35	1.54	0.040	0.030	*	432
PTT	5	0.85	0.010	0.521		7	0.08	0.000	0.999		35	1.21	0.010	0.204		432
ΔSweating rate	5	0.28	0.005	0.922		6	1.58	0.034	0.171		30	0.72	0.009	0.863		378
ΔBPU	5	1.45	0.054	0.224		6	0.75	0.008	0.612		30	1.23	0.027	0.194		378
α-wave content	5	3.58	0.028	0.008	**	7	11.73	0.237	0.000	**	35	1.79	0.023	0.005	**	432
1ch Δoxy-Hb	5	0.97	0.043	0.445		6	5.32	0.066	0.000	**	30	0.75	0.022	0.830		336
2ch Δoxy-Hb	5	0.70	0.024	0.628		6	7.90	0.115	0.000	**	30	0.53	0.012	0.979		336
3ch Δoxy-Hb	5	0.85	0.022	0.523		6	3.71	0.074	0.004	**	30	0.63	0.015	0.932		336
4ch Δoxy-Hb	5	0.87	0.026	0.510		6	3.16	0.064	0.011	*	30	0.65	0.016	0.921		336
5ch Δoxy-Hb	5	0.58	0.020	0.718		6	1.62	0.036	0.161		30	0.60	0.015	0.955		336

Note: ΔOxy-Hb has a small residual because there is a lack of data for one participant.

4.4.2 ECG

Figure 4.8 - 4.11 show the mean scores for the four indices calculated from RRI. 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) IHR

Figure 4.8 shows the average IHR ratio per minutes. The elapsed time on the x-axis represents the end time of the calculation section for 1 minute (i.e., the calculation interval 0–1 minute is expressed as 1 minute). The two-way ANOVA was performed, and found that the main effect of stimulus factor for IHR ratio approached significance, $F(6,378) = 2.33$, $p = 0.053$, $\eta^2_p = .04$. 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 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.

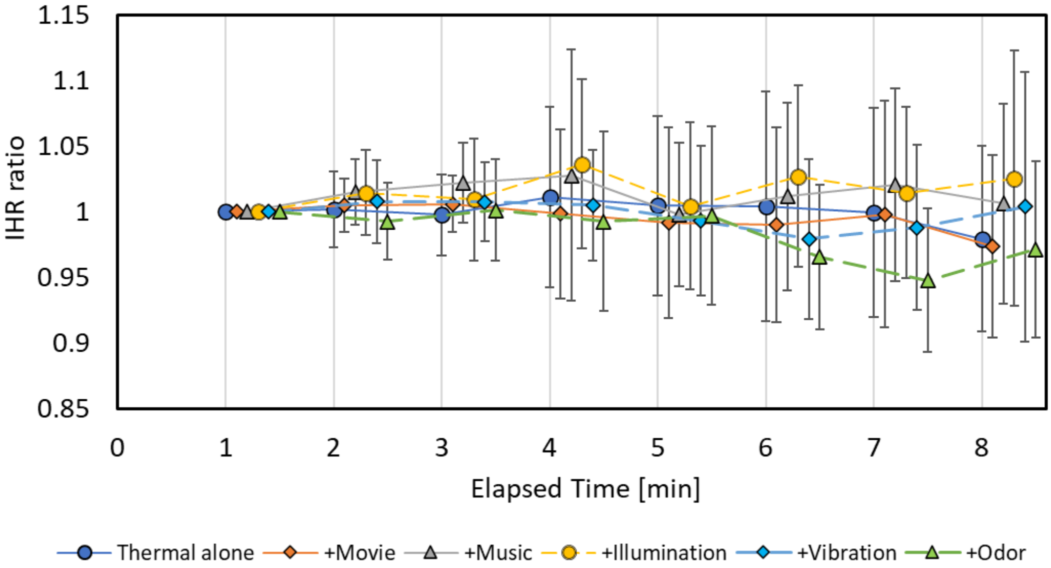

Figure 4.8 Mean scores for IHR ratio

(b)CVRR

Figure 4.9 shows the average CVRR per minutes. The two-way ANOVA revealed the significant main effect of the time factor, $F(7,432) = 5.66$, $p < 0.001$, $\eta^2_p = .16$. The CVRR data were similar regardless of the type of stimulus. There were significant differences 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 ($p < 0.05$). Moreover, 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 were 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.

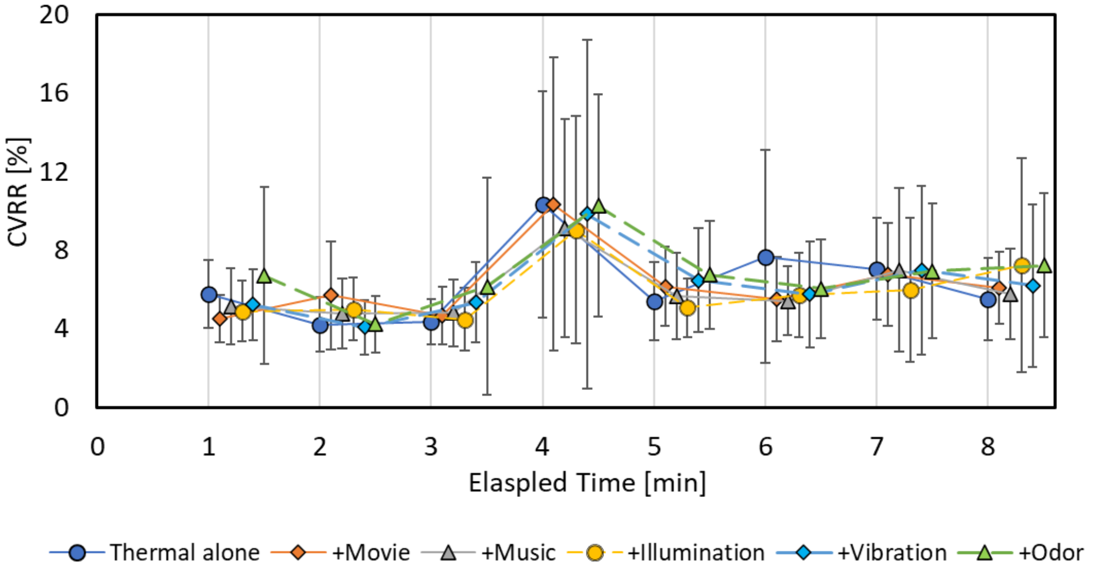

Figure 4.9 Mean scores for CVRR

(c) LF/HF

Figure 4.10 shows the mean scores for 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 that those for the other stimuli ($p < 0.05$). This indicated that the stimuli increased sympathetic nerve activity, as well as the IHR.

(d) HF

Figure 4.11 shows the mean scores for HF. The two-way ANOVA revealed the significant main effect of the time factor, $F(5,324) = 3.34$, $p = 0.012$, $\eta^2_p = .04$. 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, there was no significant differences between any stimuli and the thermal stimulation alone, except for the “illumination + thermal” trials.

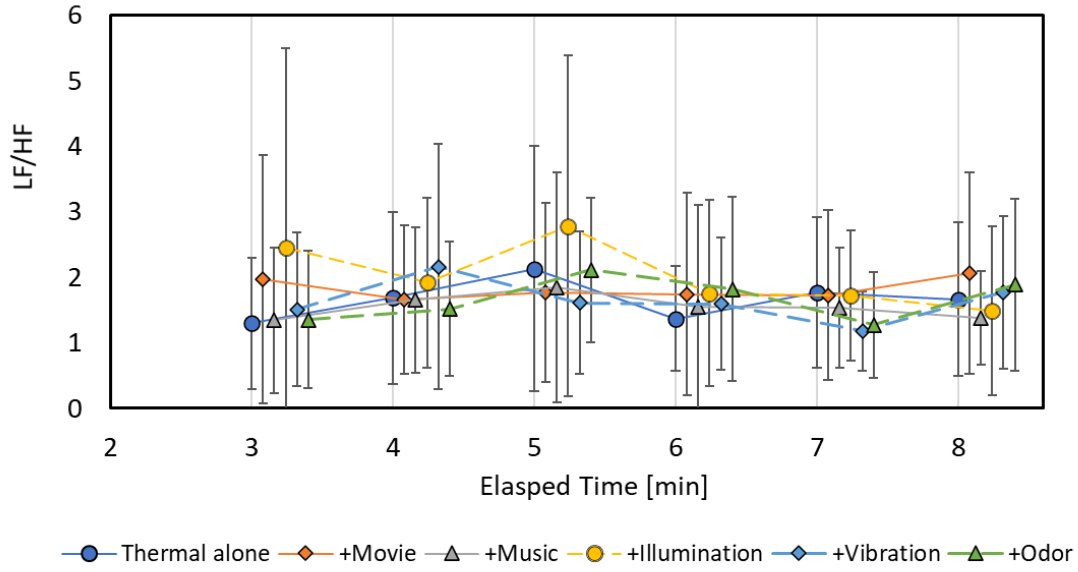

Figure 4.10 Mean scores for LF/HF

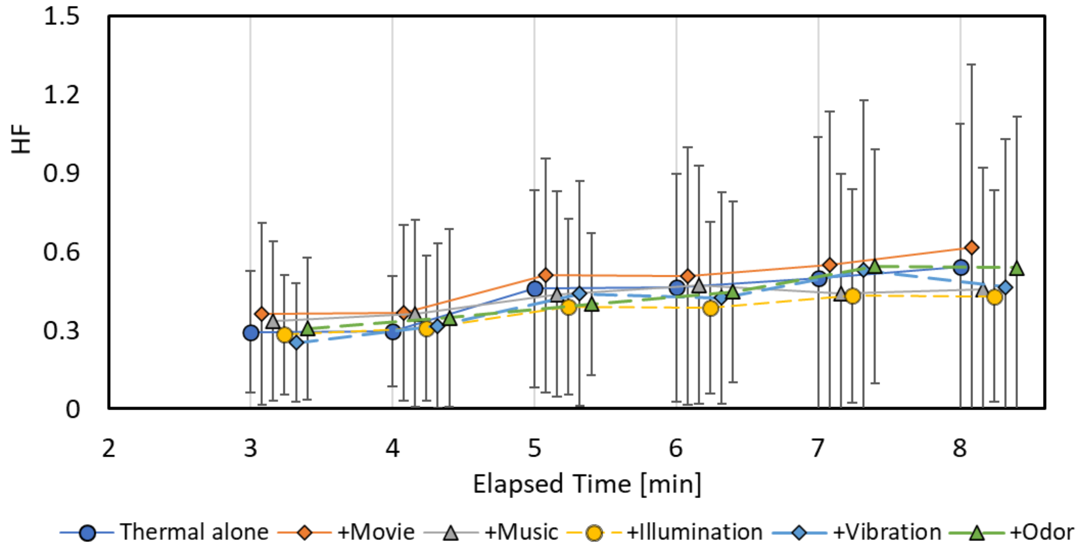

Figure 4.11 Mean scores for HF

4.4.3 Respiration

Figure 4.12 shows the mean scores for Respiratory PF per minute. The two-way ANOVA and multiple comparisons using Tukey's test were performed under the same conditions as the CVRR analyses. The main effect of time was significant, $F(7,432) = 14.04$, $p < 0.001$, $\eta^2_p = .14$, and the main factor of stimulation was significant, $F(5,432) = 2.98$, $p = 0.021$, $\eta^2_p = .02$. The interaction was also significant, $F(35,432)=1.54$, $p=0.030$, $\eta^2_p = .04$. Additionally, the PF 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 PF values, and there was a significant difference between respiration in these trials and that with thermal stimulation alone ($p < 0.05$). The PF 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" , the PF 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.

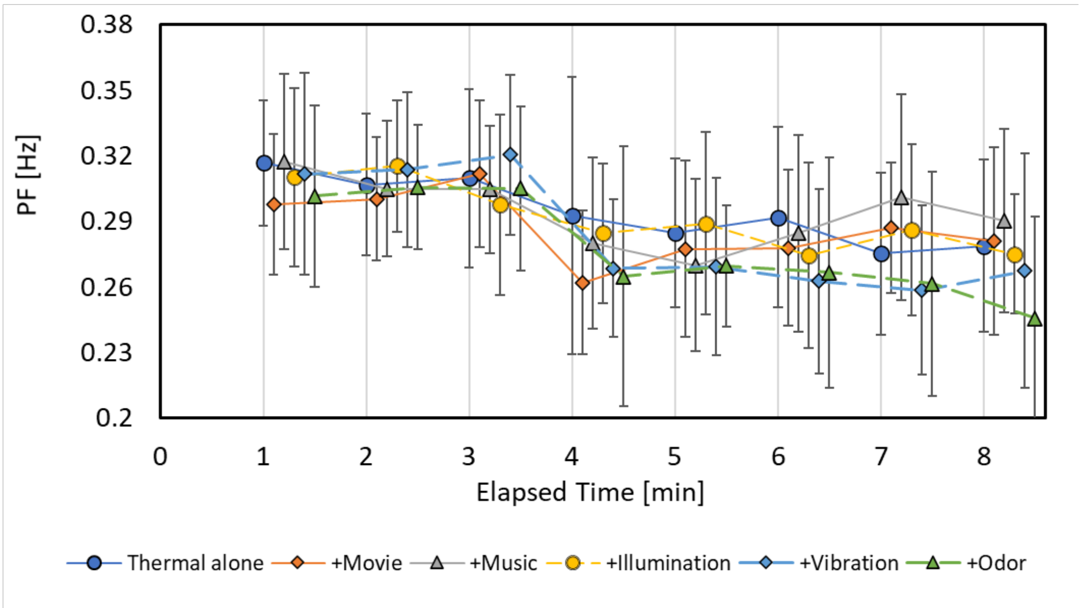

Figure 4.12 Mean scores for PF

4.4.4 Fingertip pulse wave

Figure 4.13 shows the average PTT per minute. The 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 were 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.

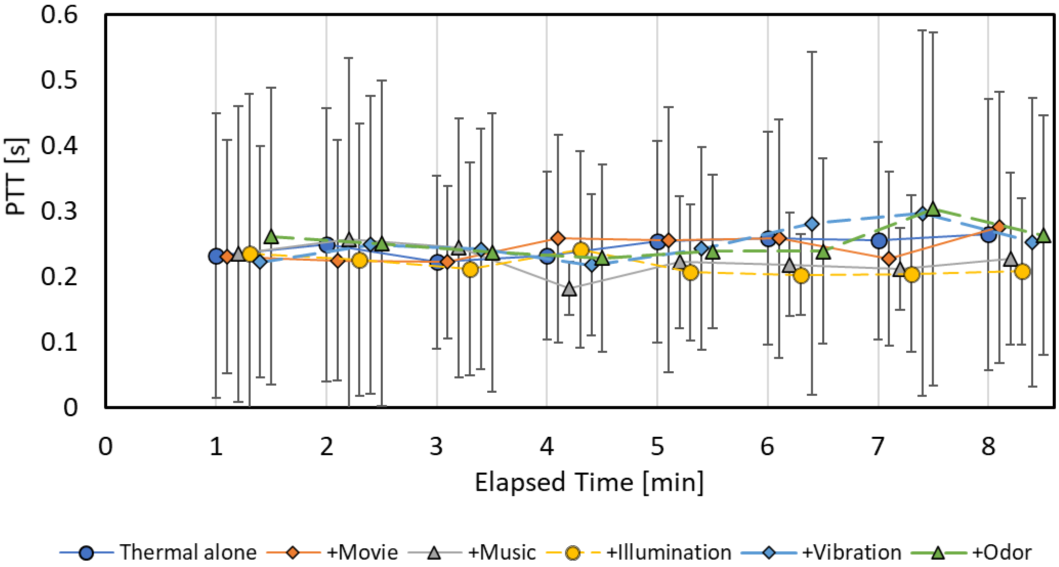

Figure 4.13 Mean scores for PTT

4.4.5 Sweating rate and peripheral blood flow

Figures 4.14 and 4.15 show the average amount of changes in sweating rate 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 at 5–7 minutes and “odor + thermal” trial at 5–8 minutes was significantly smaller than that in the “thermal alone” trial ($p < 0.05$).

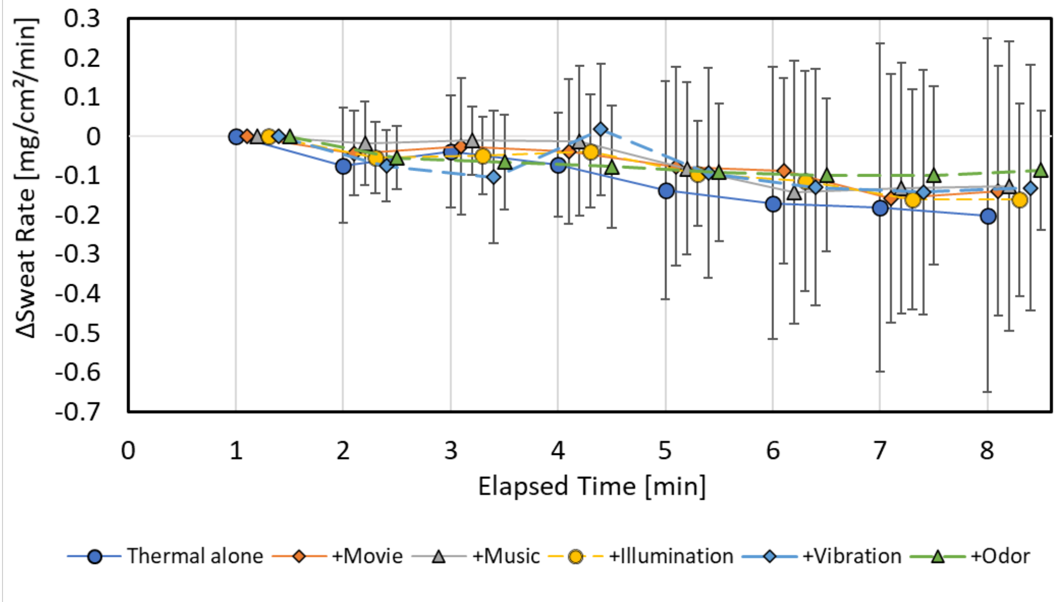

Figure 4.14 Mean scores for Δ Sweating rate

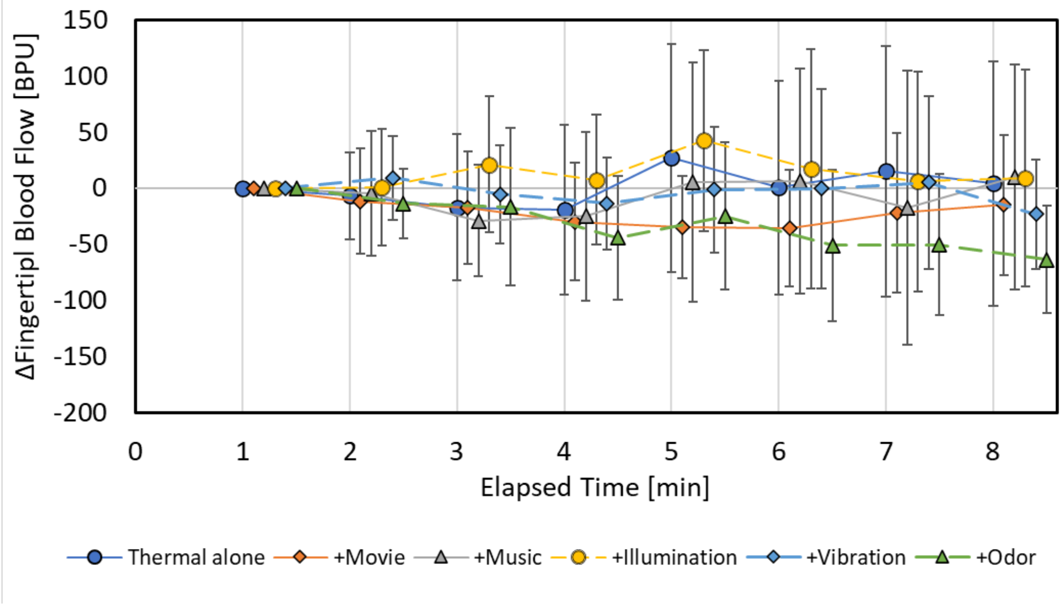

Figure 4.15 Mean scores for Δ Fingertip blood flow

4.4.6 EEG

Figure 4.16 shows the average EEG α-wave activity, which was calculated every minute. The two-way ANOVA and multiple comparisons using Tukey's test were performed under the same conditions similarly other physiological indices. The main effect of time was significant, $F(7,432) = 11.73$, $p < 0.001$, $\eta^2_p = .24$, and the main factor of stimulation was significant, $F(5,432) = 3.58$, $p = 0.008$, $\eta^2_p = .03$. The interaction was also significant, $F(35,432) = 1.79$, $p = 0.005$, $\eta^2_p = .02$. EEG α-wave activity was significantly increased in all stimulation conditions compared with during the cognitive load task at 1-3 minutes ($p < 0.05$) for all stimuli. During stimulus presentation, α-wave activity in the "movie + thermal" at 4-6 minutes and "illumination + thermal" at 4-5 minutes were significantly small compared with the other conditions ($p < 0.05$); however, this difference was smaller in the final (8 min). Regarding the differences between the stimulation trials at each time point, the "odor + thermal" and "vibration + thermal" were larger than the only thermal stimulation at 6 minutes ($p < 0.05$). Additionally, at 7 minutes, stimuli other than "music + thermal" were associated with higher α-wave activity than "movie + thermal" stimulation ($p < 0.05$), and at 8 minutes, thermal stimulation alone induced higher α-wave activity than the "illumination + thermal" and "movie + thermal" trials ($p < 0.05$). These findings indicate that the movie/illumination stimuli, including visual stimulation, tended to induce less α-wave activity, possibly because of the occurrence of α-attenuation. Conversely, vibration and odor stimuli tended to induce larger α-wave activity.

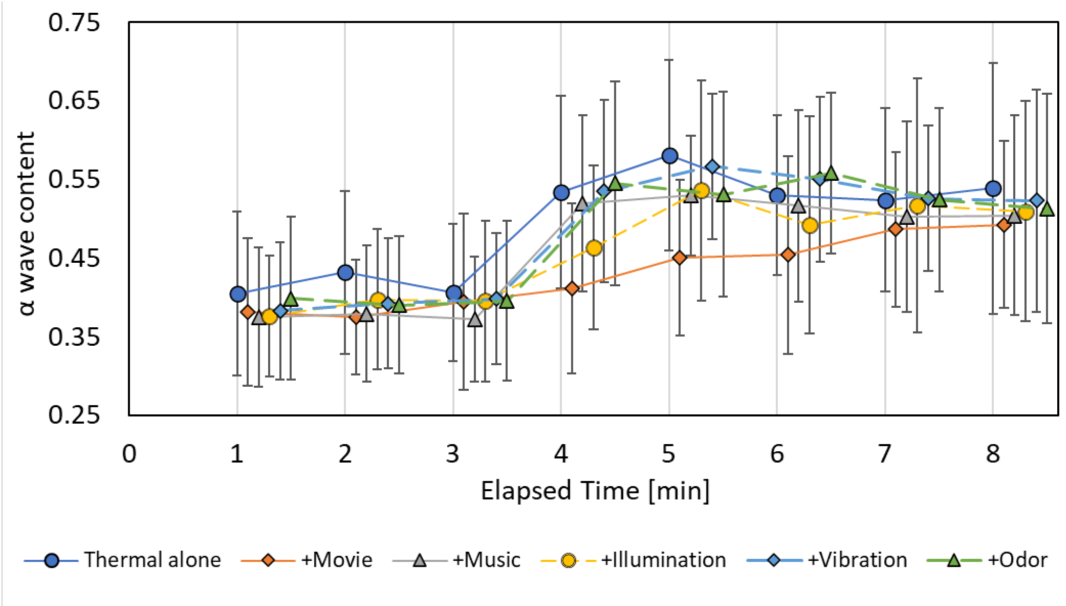

Figure 4.16 Mean scores for α-wave content

4.4.7 Cerebral blood flow in prefrontal cortex

Figure 4.17 – 4.21 show the mean scores for Δ oxy-Hb on all channels from nine participants. One participant's data was removed because of missing data on both measurement days. The average oxy-Hb in each minute was calculated, and the difference from the oxy-Hb amount from 0–1 minute is shown in below. A two-way ANOVA were performed to examine the mean value of change in oxy-Hb in all channels for the stimuli factor (6 levels) and elapsed time factor (7 levels, elapsed time excluding 1 minute data). The ANOVA revealed a main effect of elapsed time factor in all channels except for channel 5, channel 1; $F(6,336) = 5.32$, $p < 0.001$, $\eta^2_p = .07$, channel 2; $F(6,336) = 7.90$, $p < 0.001$, $\eta^2_p = .16$, channel 3; $F(6,336) = 3.71$, $p = 0.004$, $\eta^2_p = .07$, channel

4; $F(6,336) = 3.16$, $p = 0.011$, $\eta^2_p = .06$, channel 5; $F(6,336) = 1.62$, $p = 0.16$, $\eta^2_p = .04$, but no significant interaction.

Multiple comparisons (Tukey's test) were also conducted for the elapsed time in each stimulus presentation condition, and for the stimuli at each elapsed time point. The results revealed that the thermal stimulation alone at 5-8 minutes were significantly lower than during the cognitive load task (3 minute) in all channels.

The "movie + thermal" stimulation at 5-8 minutes were significantly lower than during the cognitive load task (3 minute) in all channels. Additionally, comparing during stimulus presentation, oxy-Hb was significantly lower in the latter half of stimulus presentation (7-8 minutes) than in the first half of stimulus presentation (4-5 minutes), which was common to all channels. Regarding differences between stimuli, "movie + thermal" stimulation at 7-8 minutes in channel 1 were significantly smaller than other stimuli other than thermal stimulation. The channel 1 was attached at left frontal lobe, and the decrease in oxy-Hb in the left frontal lobe by movie presentation was consistent with previous study [26]. In channel 3 and 4, oxy-Hb of "movie + thermal" were significantly lower than for thermal stimulation alone at 7 minute ($p < 0.05$).

Regarding "music + thermal" stimulation, oxy-Hb at 4-8 minutes in channels 2-4 and at 5-6 minutes in channels 1 and 5 were significantly lower smaller during the load task (2-3minutes). The decrease in oxy-Hb on the side of the frontal region tended to be small (channels 1 and 5). Additionally, focusing on oxy-Hb at 4 minutes in channel 2 and 3, oxy-Hb of “music + thermal” stimulation was significantly lower than thermal alone, “movie + thermal” and “odor + vibration” stimulation. These findings indicate that “music + thermal” reduced cerebral blood flow faster than other stimuli. However, no significant difference was confirmed for oxy-Hb of “music + thermal” during stimulus presentation (5-8 minutes).

Regarding the “illumination + thermal” trials, oxy-Hb at 4-8 minutes in channels 2-4 were significantly lower than during the cognitive load task at 2-3 minutes (p < 0.05), however, no significant difference was confirmed in channel 1 compared to during workload. In channel 5, only oxy-Hb at 5 minutes had significant difference between the during load task (2-3 minutes). No significant difference was confirmed during stimulus presentation (4-8 minutes) for all channels, additionally, oxy-Hb at 6 minutes was significantly larger than that thermal alone in channels 2 and 3. The “illumination + thermal” tended to have a smaller decrease in oxy-Hb than other stimuli.

The “vibration + thermal” significantly decreased oxy-Hb at 5-8 minutes compared with during the cognitive load task (2-3 minutes) in channels 1 and 2 (p < 0.05). On the other hand, there was no significant difference between channel 4 and channel 5 during workload and stimulus presentation. Compared with thermal alone, the 6-minute oxy-Hb of channel 1 and channel 2 was significantly higher. As a tendency common to all channels, the decrease in oxy-Hb was gradual.

The oxy-Hb of “odor + thermal” stimulation at 7-8 minutes had significantly lower value compared to 2-5 minutes in channels 2-5. In channel 1, significant differences were confirmed between the during presentation stimulus (5-8 minutes) and during load task (3 minutes). Except for channel 1, oxy-Hb at 7 minutes on all channels was significantly smaller than other stimuli. These tendencies indicated that “odor + thermal” trial slowly decreased oxy-Hb more than other stimuli.

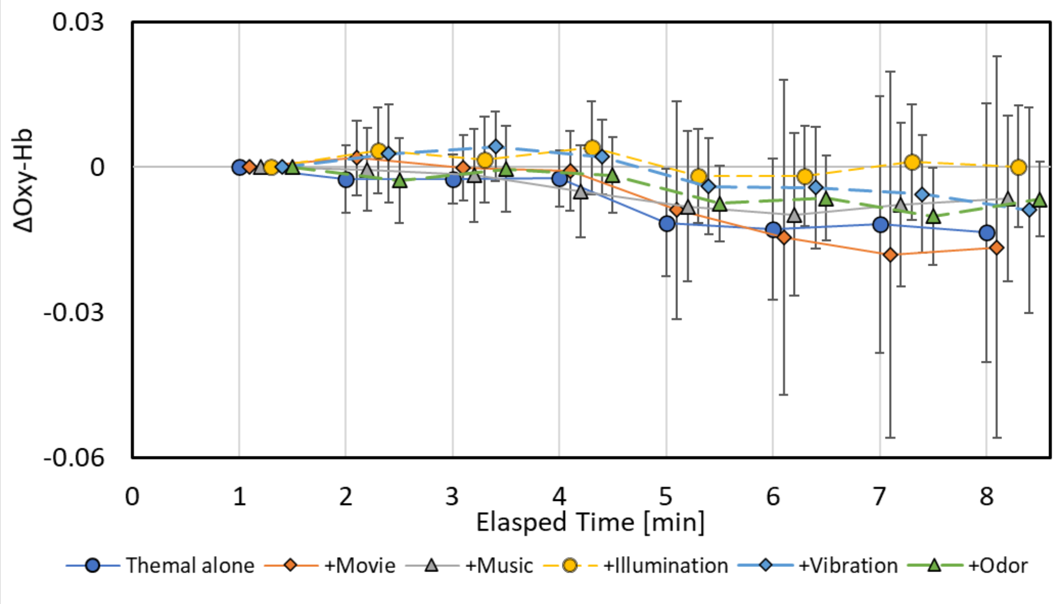

Figure 4.17 Mean scores for 1ch Δ oxy-Hb

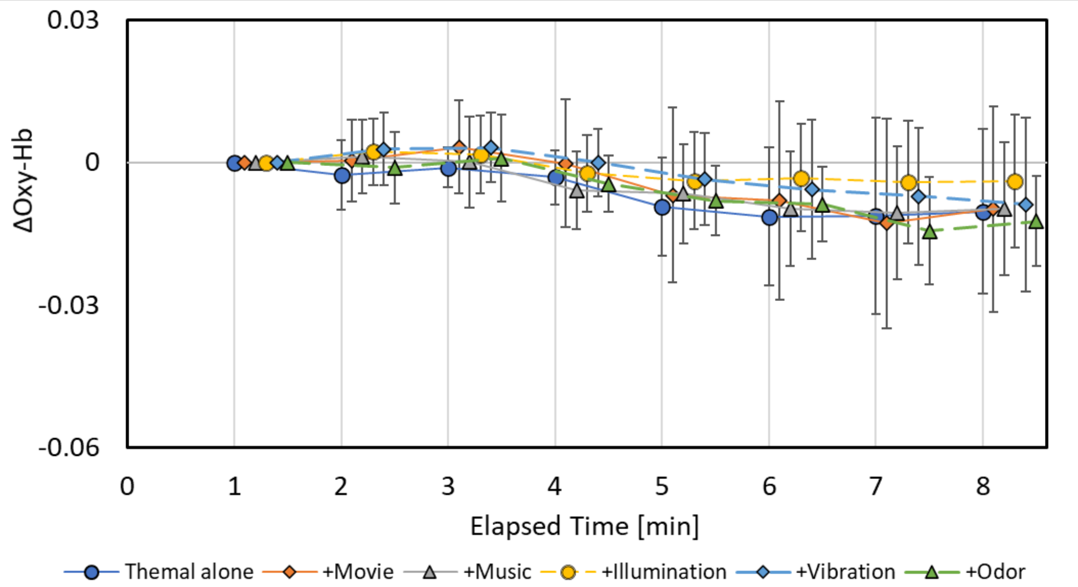

Figure 4.18 Mean scores for 2ch Δ oxy-Hb

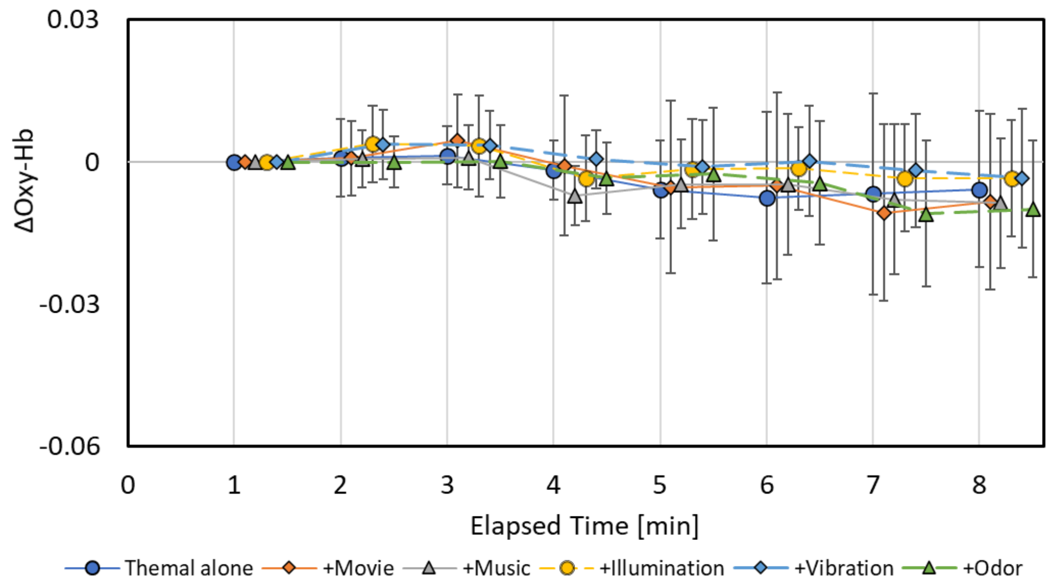

Figure 4.19 Mean scores for 3ch Δ oxy-Hb

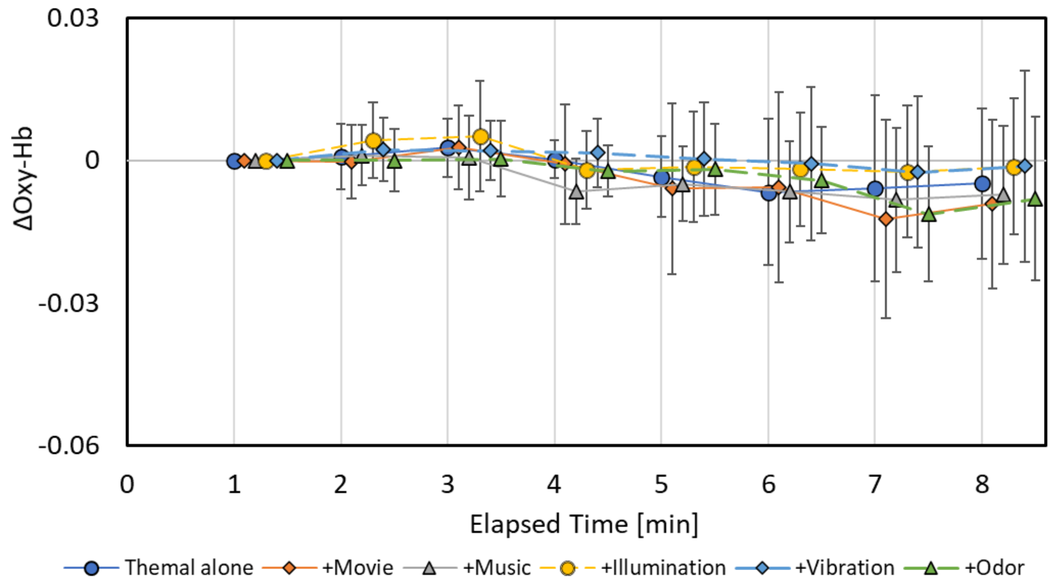

Figure 4.20 Mean scores for 4ch Δ oxy-Hb

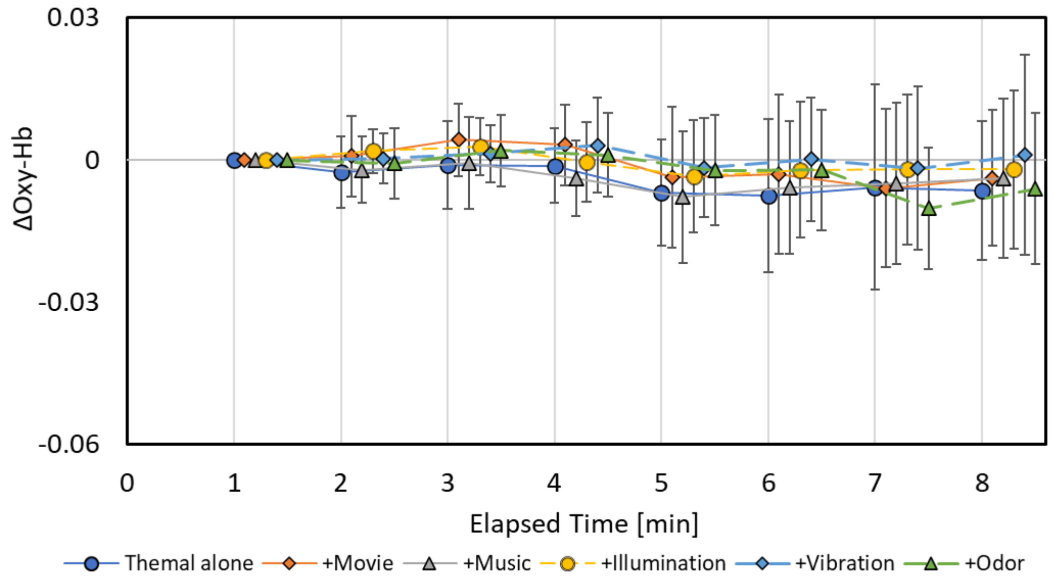

Figure 4.21 Mean scores for 5ch Δ oxy-Hb

4.6 Discussion

For all conditions, stimulus presentation led to an increase in CVRR, HF and α-wave, a decrease in respiratory PF and cerebral blood flow in prefrontal cortex. This indicates that the stimuli induced relaxation. Regarding the IHR, PTT, and pulse wave index, the tendency of change and the differences in latency were confirmed for each stimulus. Additionally, the position of the frontal lobe where cerebral blood flow decreased depended on the presentation stimulus. In the following section, the physiological and psychological response data are integrated and examined to verify whether the combined presentation of two stimuli induced relaxation. In addition, section 4.6.6 summarizes the differences between stimuli during stimulus presentation and identifies stimuli with a high relaxation-inducing effect in multisensory integration with thermal stimulation.

4.6.1 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. Regarding the central nervous system, the level of EEG α-wave activity was relatively low compared with the other stimulation conditions, likely because of α-attenuation. However, cerebral blood flow was substantially and slowly reduced in these conditions compared with the other stimulation conditions especially the left side of prefrontal cortex. In total, it was speculated that while the “movie + thermal” combination has a relaxing-inducing effect and that the latency of the physiological response differed depending on the physiological indices.

4.6.2 Music + thermal stimulation

The “music + thermal” stimulation was the most positively evaluated stimulus in the sensory test. The IHR and respiratory PF 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. [45] 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 PF increased over time. Thus, the parasympathetic hyperactivity elicited by this stimulus had a short duration. Focusing on brain activity, decreased cerebral blood flow and increased EEG α-wave activity were confirmed. The activation of EEG alpha waves by “music + thermal” presentation was consistent with previous study [13]. Additionally, immediately after the stimulus presentation (4 minutes), cerebral blood flow in the center of the frontal lobe (channels 3 and 4) was significantly lower compared with the other stimulation conditions. The results did not reveal any significant differences between the thermal stimulation alone condition in α-wave activity or cerebral blood flow, except at 4 minutes for oxy-Hb levels at channels 3 and 4. The short latency and duration of physiological responses are characteristic of "music + thermal" stimulation in both the autonomic nervous system and the central nervous system. The above results suggested that the “music + thermal” stimulation can induce relaxation in a short period of time.

4.6.3 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. I attributed 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. This tendency was similar in EEG, α-wave content slowly increased. On the other hand, the decrease in cerebral blood flow in the prefrontal cortex were smaller than those of other stimuli. The above results suggested that “illumination + thermal” stimulation can induce relaxation as the participants become accustomed to the blue illumination.

4.6.4 Vibration + thermal stimulation

The “vibration + thermal” stimulation received a slightly lower subjective evaluation. The IHR (6 minutes) and respiratory PF (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 latency of the physiological responses was long. Additionally, EEG α-wave activity significantly increased with a peak at 5 minutes, and significantly decreased cerebral blood flow on the left side of the prefrontal cortex. However, the decrease in cerebral blood flow was small, and there were no significant differences in right side of frontal cortex between the during the cognitive load task. Some participants reported that they felt strange when the vibration was presented, as in the vibration presentation. The small reduction in cerebral blood flow was attributed to this subjective impression. From above results, it was concluded that the "vibration + thermal" stimulation induced relaxation by being presented simultaneously with thermal stimuli, although the subjective feeling of relaxation was low.

4.6.5 Odor + thermal stimulation

For each evaluation term of the sensory test, the “odor + thermal” stimulation did not exhibit a significant difference from other stimuli. However, in terms of physiological responses, this stimulation elicited the largest increase in parasympathetic nerve activity and a suppression of brain activity. The IHR and respiratory PF 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. These results are consistent with previous studies on “foot bath + odor” presentation [2,4,12]. It was considered that “odor + thermal” stimulation elicits a slow physiological 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 the “movie + thermal” trials, which indicates activation of sympathetic nerves in peripheral body regions. EEG α-wave activity increased with a peak at 6 minutes, and cerebral blood flow decreased, with a minimum value at 7 minutes. Because the orbitofrontal cortex (OFC) of the frontal lobe responds to the inhalation of odors, it was speculated that cerebral blood flow decreased because of the presentation of a relaxing odor. These trends in physiological responses are consistent with previous studies of the effects of relaxing odor presentation [61,62]. It was concluded that “odor + thermal” stimulation remarkedly led to an increase in parasympathetic nerve activity and a suppression of brain activity, and slowly induced relaxation.

4.6.6 Comparison of physiological indices between combination of stimuli during presentation stimulation

Regarding the comparison of physiological indices between the stimuli, the “odor + thermal” and “vibration + thermal” combination were significantly enhanced parasympathetic nerves and suppressed brain activity compared to the combination of other stimuli. The IHR for “odor + thermal” was significantly lower at 7 minutes than that for the other stimuli, and the PF for “odor + thermal” and “vibration + thermal” were significantly higher than other stimuli at 7 minutes. Moreover. the PTT in the “vibration + thermal” and “odor + thermal” trials were significantly larger than that for the other stimuli at 7 minutes. These results indicate increase parasympathetic activity, additionally, the significant differences were confirmed around 7 minutes (4 minutes from the presentation of the stimulus). Regarding the brain activity, the α-wave content for “odor + thermal” and “vibration + thermal” were larger than the other stimuli at 6 minutes. The oxy-Hb for “Odor + thermal” at 7 minutes on 2-5 channels was significantly smaller than other stimuli. On the other hand, the decrease in oxy-Hb for “vibration + thermal” was gradual. Summarizing these results, the odor and vibration had strongly relaxation-inducing effects by multisensory integration with thermal stimuli.

The presented stimuli could be classified into two groups: group1 (movie / music / illumination) and group2 (thermal / odor / vibration). The stimulus of group1 was characterized as a stimulus that involves judgment and cognition. The stimulus of group2 was characterized by a stimulus that directly affects the human body, mainly judging the strength of the stimulus. In multisensory integration with thermal stimulation, the combination of stimuli that directly act on the human body had strong relaxation-inducing effect.

4.6.7 Summary of discussion

Table 4.2 summarizes the results and discussion of the current study. From above findings indicate that all stimuli activated parasympathetic nerve activity and suppressed brain activity. As a characteristic stimulus, "odor + thermal" had a long latency of physiological responses and a high relaxation-inducing effect, and "music + thermal" stimulation had a short latency and duration of physiological reaction. Previous studies have reported that the combination of these stimuli has a relaxing-promoting effects [23,12,13], and similar results were obtained in this study. Moreover, the "movie + thermal" stimulation induced relaxation and was characterized in that the latency of the physiological response differs depending on the physiological indices. Regarding "illumination + thermal" and "vibration + thermal" combination, participants complained of discomfort immediately after the presentation of the stimulus. Thus, it is necessary to reexamine the method of presenting the stimulus. On the other hand, since the activation of parasympathetic nerves and the suppression of brain activity were confirmed over time, it was speculated that these stimuli could induce relaxation as the participants became accustomed to the stimuli.

Among the combinations of stimuli, "odor + thermal" and "vibration + thermal” stimulation had the highest physical relaxation-inducing effect. These stimuli significantly enhanced parasympathetic nervous system activity and suppressed brain activity than in other stimuli. In this study, stimuli were classified into cognitive stimuli (movie/ music/ lighting) and stimuli that act directly on the body (thermal / odor / vibration). It was speculated that the combination of the same groups had a high relaxation-inducing effect by multisensory integration.

I expected that all combinations of thermal and other sensory stimuli would induce relaxation more than thermal stimuli alone. However, I 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. It was speculated that the matching between these stimuli and the thermal stimulus was poor. The relaxation inducement effect by presenting warm-colored movie / illumination stimuli together with thermal stimuli should be verified.

Table 4.2 Summary of results and discussion

Stimulus	Sensory Test Compared with Thermal	Autonomic Nevous System	Central Nevous System	Relaxation-Inducing Effects
+ Movie	N.S.	PTT and HF increased (4min) PF showed the lowest value (4min) IHR showed the lowest value (8min)	Lower α-wave content oxy-Hb decreased (7min)	Induced Relaxation Latency depends on physiological index
+ Music	The most positivly evaluated "comfort - discomfort" : **	HR and PF decreased (5min) and increased over time HF gradually increased	α-wave content increased (5 min) oxy-Hb decreased (4min)	Quickly induced relaxation and short duration
+ Illumination	N.S.	IHR and LF/HF increased immidiatelly HF and CVRR gradually increased	Lower α-wave content oxy-Hb decreased slightly	Induced relaxation Gradually enhance parasympathetic activity
+ Vibration	N.S.	IHR and PF (6-7 min) PTT showed the highest value (7min)	α-wave content increased (5 min) oxy-Hb decreased slightly	Slowly relaxation inducement Highely phisiological relaxation-inducing effect
+ Odor	N.S.	IHR and PF decreased (7-8 min) PTT showed the highest value (7min)	α-wave content increased (6 min) oxy-Hb gradually decreased	Significantly induced relaxation Long latency of physiological responses

4.7 Summary

This chapter aims to examine the relaxation-inducing effects of simultaneous thermal stimulation of the feet with stimuli targeting other sensory modalities, including movie, music, illumination, vibrations to the trunk and odor. All stimuli were able to activate parasympathetic nervous and suppress brain activity. Here, the relaxation-inducing effects of thermal stimuli plus stimuli targeted at other sensory organs was characterized, as well as the differences in the latency and duration of the physiological responses to each stimulus. In particular, the “odor + thermal” stimulation significantly induced relaxation, and the “music + thermal” stimulation quickly induced relaxation. The combination of stimuli that directly act on the human body (such as odor and vibration) had strong relaxation-inducing effects in multisensory integration with thermal stimuli.

Chapter 5

Conclusions

・Conclusions

The purpose of this study was to verify the relaxation-inducing effects of multisensory integration involving thermal stimulation. This study focused on the degree to which thermal stimulation presented to the soles of the feet combined with other sensory stimuli could induce relaxation. As relaxation-inducing stimuli, movie, music, illumination, vibration, and odor stimuli were each presented simultaneously with a thermal stimulus.

In Chapter 2, methods for evaluating relaxation effects using physiological response measurements were described. To objectively and quantitatively evaluate the relaxation-inducing effect, it was important to measure changes in physiological condition caused by the presentation of stimuli. In this study, the physiological responses of the autonomic nervous system and the central nervous system were measured, and the relaxation-inducing effect was evaluated from multiple physiological indices.

In Chapter 3, Scheffe’s paired comparison method was performed to identify the most relaxing stimuli for each sensory modality. In this section, thermal stimulation to the soles at 40 °C, a movie showing an underwater scene, classical music (Beethoven - “Pathetique Piano Sonata No. 8 Op. 13-2”), light blue illumination, 55-Hz vibrations to the trunk, and grapefruit odor were selected the most relaxing stimuli.

In Chapter 4, the relaxing stimuli identified in Chapter 3 were simultaneously presented with thermal stimulation to the soles, and the relaxation-inducing effects were verified by measuring physiological responses and sensory tests. The results revealed that all stimulus combinations induced parasympathetic activation and suppressed brain activity. Additionally, the relaxation-inducing effects of thermal stimuli with other sensory stimuli was characterized, as well as differences in the latency and duration of the physiological responses to each stimulus combination. In particular, the “odor + thermal” stimulation significantly induced relaxation, and the latency of physiological responses was relatively long. The “music + thermal” stimulation condition induced relaxation in a short period of time.

The presented stimuli could be classified into (1) cognitive stimuli (movie / music / illumination) and (2) stimuli that directly act on the body (thermal/ odor/ vibration). Focusing on the difference in each physiological index between the stimuli during the presentation of the stimulus, the combination of the thermal stimulus and the stimulus in category (2) significantly enhanced parasympathetic nervous system activity and suppressed brain activity compared with other stimulus combinations. This result suggests that the combination of stimuli that act directly on the body has a strong effect of inducing relaxation by multisensory integration.

The current findings suggest possible approaches for promoting relaxation in humans through the design of high-comfort indoor and in-vehicle spaces. For instance, “music + thermal” stimulation could be used to quickly induce a relaxation state, which could then be maintained for a long duration using “odor + thermal” stimulation. By presenting a combination of different stimuli according to user’s condition, a relaxed state could be induced. In future, it will be possible to design next-generation smart houses and in-vehicle environments to maximize comfort by clarifying the relaxation-inducing effects of multisensory integration.

This study focused on the relaxation-inducing effects of multisensory integration of thermal stimulation and the stimulation of other sensory organs. Future research on multisensory integration should examine this issue more comprehensively. Specifically, it may be helpful for future studies to investigate (1) the effect of matching the impressions of the sensory stimuli, (2) multisensory integration of stimuli between groups of stimuli classified in this study, (3) the effect of presenting more sensory stimuli, and (4) the enhancement of sensations other than relaxation. Additionally, the physiological mechanisms of sensory enhancement via multisensory integration should be clarified.

Regarding the matching of impressions between different sensory stimuli, it is expected that a stronger relaxation effect may be obtained when stimuli match the user’s impressions of the stimuli. For instance, in this study, cool-colored visual stimuli (light blue illumination / underwater movies) were presented with thermal stimulation. It was assumed that the relaxation-inducing effect was weaker than other stimuli because of the poor match between cool-colored stimuli and thermal stimulation. In future, I hope to verify the relaxation-inducing effect of presenting warm-colored visual stimuli (sunset and fireplace movies/orange-based illumination) together with thermal stimulation. Such impression concordance may occur not only between thermal and visual stimuli, but also between stimuli involving other sensory organs.

In the current study, stimuli were classified as cognitive stimuli and stimuli that act on the body. The current study examined multisensory integration by combining stimuli that directly affect the body. However, the effects of multisensory integration by combining cognitive stimuli should also be verified. For instance, the effects of combining music and video are widely known, and previous studies have also reported that the multisensory integration of illumination and music enhanced the impression of music [6]. With an extremely large number of combinations of stimuli, it is expected that the effect of multisensory integration based on stimulus classification will be verified in future research.

In the current study, the combination of only two stimuli based on a thermal stimulus was verified because the number of potential combinations of stimuli is enormous. Although some previous studies have tested combinations of two stimuli, few studies have examined combinations of three or more stimuli. It may be valuable to verify whether increasing the number of presented stimuli is more or less effective for inducing relaxation. However, verification of the effects of presenting three or more types of sensory stimuli may be difficult in terms of which stimuli are presented and how to evaluate them. Long-term research is required to clarify this issue.

Additionally, the study of multisensory integration is likely to be applied not only to relaxation but also to various types of sensory enhancement.

For instance, a combination of sensory stimuli could be used to induce excitement or improve the ability to concentrate in the workplace.

Research on multisensory integration has many aspects, and there is a diverse range of potential future research directions. In addition, the psychological and physiological mechanisms of the effects of multisensory integration remain to be clarified. Finally, I hope that further research on multisensory integration will inform the development of methods to improve the experience of comfort in people’s daily lives.

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1. Seiya Fujiwara, Minami Sasakura, Haruki Oita, Mayumi Uemae, Hiroaki Yoshida, Takashi Matsuoka, Yumi Shibagaki and Masayoshi Kamijo; Central Nervous System Responses to Comfortable Thermal Stimuli to the Soles of the Feet with Simultaneous Presentation of Other Sensory Stimuli, International Journal of Affective Engineering; 20(1), pp.11-20, 2021.
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Table Excerpt of the physiological indices result of participant 1

	Elapsed Time [min]	IHR	CVRR	Respiratory PF [Hz]	PTT [s]	Blood Flow [BPU]	Sweating Rate [mg/cm²/min]	αwave content	1ch oxy-Hb	2ch oxy-Hb	3ch oxy-Hb	4ch oxy-Hb	5ch oxy-Hb
Thermal alone	1	77.12	3.43	0.294	0.206	89.80	0.40	0.29	0.011	-0.005	-0.006	-0.001	-0.019
	2	77.75	3.10	0.301	0.208	72.37	0.14	0.33	0.013	-0.006	-0.003	-0.001	-0.019
	3	77.28	3.94	0.334	0.209	61.32	0.11	0.25	0.012	-0.005	-0.003	-0.002	-0.017
	4	73.73	19.10	0.233	0.216	75.91	0.13	0.34	0.018	-0.004	0.003	0.002	-0.011
	5	77.28	5.44	0.252	0.220	129.50	0.11	0.54	0.017	-0.001	0.003	0.007	-0.007
	6	74.54	21.03	0.244	0.209	83.39	0.12	0.42	0.017	0.001	0.018	0.013	-0.002
	7	76.10	5.87	0.217	0.212	114.35	0.12	0.42	0.035	0.018	0.022	0.019	0.005
	8	74.67	4.97	0.235	0.206	50.69	0.13	0.37	0.014	0.003	0.013	0.009	-0.006
Movie + Thermal	1	74.88	3.82	0.294	0.194	30.79	0.21	0.27	0.013	0.009	0.016	0.017	-0.016
	2	75.56	4.14	0.279	0.205	28.93	0.12	0.29	0.012	0.006	0.014	0.014	-0.020
	3	74.18	3.99	0.320	0.202	30.82	0.10	0.25	0.013	0.009	0.017	0.016	-0.016
	4	69.53	27.50	0.235	0.284	40.06	0.10	0.37	0.024	0.006	0.016	0.016	-0.011
	5	70.48	4.50	0.256	0.183	16.28	0.10	0.37	0.004	0.001	0.012	0.013	-0.021
	6	69.01	4.89	0.221	0.199	36.03	0.10	0.30	0.006	0.005	0.019	0.018	-0.014
	7	70.76	7.83	0.256	0.199	35.49	0.10	0.44	0.011	-0.002	0.007	0.010	-0.014
	8	68.42	5.27	0.258	0.241	24.90	0.09	0.34	0.001	-0.006	0.007	0.010	-0.025
Music + Thermal	1	74.77	9.62	0.304	0.191	45.66	0.26	0.24	-0.029	-0.005	-0.010	-0.014	0.004
	2	74.71	4.36	0.342	0.194	45.44	0.12	0.29	-0.028	-0.005	-0.009	-0.013	0.008
	3	76.41	4.51	0.320	0.203	52.08	0.11	0.29	-0.025	-0.001	-0.005	-0.012	0.009
	4	75.63	22.19	0.241	0.214	44.13	0.11	0.42	-0.027	-0.006	-0.006	-0.012	0.010
	5	74.49	4.55	0.233	0.212	52.99	0.09	0.45	-0.030	-0.008	-0.001	-0.011	0.012
	6	77.27	3.63	0.325	0.219	120.99	0.10	0.59	-0.021	0.004	0.020	0.002	0.027
	7	76.41	15.58	0.342	0.219	119.67	0.11	0.50	-0.018	0.004	0.014	-0.001	0.029
	8	72.61	4.92	0.305	0.194	60.64	0.11	0.46	-0.029	-0.003	-0.004	-0.010	0.015
Illumination + Thermal	1	75.85	3.90	0.342	0.203	103.59	0.10	0.29	-0.017	0.003	-0.009	-0.014	-0.008
	2	73.89	4.63	0.330	0.185	173.88	0.10	0.40	-0.014	0.009	0.000	-0.010	-0.001
	3	75.92	3.80	0.325	0.191	262.46	0.11	0.28	-0.014	0.011	0.005	-0.006	0.000
	4	74.07	23.36	0.261	0.211	213.37	0.13	0.40	0.003	0.010	0.001	-0.007	0.008
	5	75.39	4.09	0.275	0.196	260.36	0.13	0.55	-0.011	0.016	0.014	0.003	0.007
	6	75.99	4.09	0.261	0.203	278.87	0.14	0.50	-0.013	0.011	0.004	-0.001	0.006
	7	75.96	10.97	0.275	0.185	165.42	0.13	0.48	-0.010	0.013	0.006	0.002	0.007
	8	76.82	4.52	0.266	0.192	221.95	0.11	0.52	-0.006	0.019	0.013	0.005	0.013
Vibration + Thermal	1	77.63	3.81	0.310	0.201	102.88	0.17	0.29	-0.026	0.002	-0.021	-0.028	-0.006
	2	76.62	4.61	0.333	0.197	101.81	0.09	0.33	-0.022	0.009	-0.012	-0.022	0.001
	3	77.01	9.62	0.327	0.202	90.19	0.09	0.31	-0.020	0.009	-0.011	-0.022	0.002
	4	75.58	32.50	0.227	0.244	76.50	0.10	0.39	-0.018	0.007	-0.015	-0.018	0.008
	5	78.23	10.04	0.261	0.215	69.27	0.08	0.48	-0.025	0.009	-0.017	-0.017	0.004
	6	77.63	9.98	0.290	0.210	150.40	0.07	0.56	-0.021	0.012	-0.018	-0.015	0.005
	7	75.89	18.55	0.237	0.209	147.55	0.10	0.45	-0.016	0.016	-0.014	-0.008	0.013
	8	75.95	3.83	0.261	0.210	92.43	0.10	0.45	-0.016	0.013	-0.018	-0.003	0.018
Odor + Thermal	1	78.36	19.02	0.276	0.208	56.96	0.34	0.26	0.008	-0.019	-0.008	0.007	-0.001
	2	77.84	3.54	0.323	0.205	47.42	0.13	0.30	0.011	-0.018	-0.004	0.012	0.002
	3	77.56	21.05	0.325	0.210	41.85	0.12	0.26	0.012	-0.016	-0.001	0.013	0.007
	4	73.51	20.02	0.290	0.214	56.51	0.13	0.48	0.011	-0.022	-0.001	0.011	0.002
	5	76.98	5.39	0.290	0.211	58.25	0.13	0.40	0.010	-0.018	0.013	0.017	0.008
	6	74.66	4.65	0.279	0.217	82.59	0.11	0.50	0.010	-0.018	0.005	0.014	0.006
	7	74.70	11.08	0.240	0.198	43.92	0.11	0.47	0.009	-0.028	-0.009	0.004	-0.001
	8	71.05	5.29	0.256	0.178	26.15	0.11	0.38	0.001	-0.032	-0.011	0.001	-0.007

	Elapsed Time [min]	LF	LF/HF	HF
Thermal alone	4	1.63	1.22	1.33
	5	3.64	1.99	1.83
	6	2.12	1.29	1.64
	7	3.25	1.99	1.63
	8	3.80	2.62	1.45
Movie + Thermal	4	0.87	0.66	1.32
	5	1.34	0.89	1.51
	6	0.93	0.44	2.11
	7	2.86	1.20	2.39
	8	5.80	2.60	2.23
Music + Thermal	4	1.11	1.12	0.99
	5	1.01	1.16	0.87
	6	0.80	0.96	0.84
	7	0.76	0.97	0.78
	8	1.44	1.82	0.79
Illumination + Thermal	4	1.06	1.44	0.73
	5	1.39	1.95	0.71
	6	0.89	1.13	0.79
	7	0.88	0.97	0.90
	8	0.99	0.82	1.22
Vibration + Thermal	4	0.78	0.84	0.93
	5	0.97	1.13	0.86
	6	0.83	0.82	1.01
	7	1.15	1.06	1.09
	8	2.32	2.28	1.02
Odor + Thermal	4	1.42	1.13	1.26
	5	2.30	1.90	1.21
	6	2.10	1.31	1.60
	7	1.46	0.86	1.71
	8	4.10	1.93	2.12

Note: The indicators in the left -side table were calculated in the 1-minute window, the indicators in the right-side table were calculated in the 3-minute

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