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博士（人間科学）

濡れおよび蒸れ知覚に関わる神経基盤の探索

Research on The Neural Basis of Wet and Humid Sensations

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Chapter ONE

1. Background

Thermoregulation is one of the essential functions of homeostasis. The goal of thermoregulation is to maintain the core body temperature, achieved through behavioral and autonomic thermoregulation mechanisms. For thermoregulation, environmental awareness is essential. An increase in relative humidity increases the rate of thermal discomfort (Thom, 1959). Individuals often experience discomfort and exertion in hot and humid environments, and their physical performance decreases during exercise (Armstrong et al., 2007). Sensing environmental humidity and skin surface wetness is also crucial for behavioral thermoregulation. Although several studies have been conducted, the mechanisms underlying humid and wet sensations in humans remain unclear. The neural pathways and physiological responses involved in the detection and response to humidity and wetness must be fully characterized. Identifying these mechanisms may have important implications for understanding thermoregulation.

Heat-related illnesses, such as heat exhaustion and heat stroke, are significant public health concerns, particularly at high temperatures and humidity levels (Bouchama & Knochel, 2002). Sweat rate increases with increasing environmental temperature and relative humidity, whereas the amount of evaporation decreases (Zhang

& Tamura, 2014). Previous studies have suggested that the evaporation rate of sweat decreases when environmental humidity and/or skin surface wetness increases (Candas et al., 1979; Nadel & Stolwijk, 1973). Therefore, it is essential to perceive wetting of the skin surface and remove it to increase the efficiency of sweat evaporation. Previously, studies examined the role of thermal and tactile sensations in the perception of wetness by presenting each stimulus separately (Filingeri et al., 2014). Some researchers have demonstrated that thermal reception is involved in the wet sensation (Filingeri et al., 2014; Typolt & Filingeri, 2020).

By elucidating the mechanisms underlying wet sensation, we hope to contribute to a better understanding of thermoregulation and inform the development of more effective interventions for heat-related illnesses. The present study is unique in its focus on the neural and physiological mechanisms involved in these sensations. The research is expected to impact various fields, including materials science, product design, and occupational health and safety, by exploring the factors and mechanisms involved in wet and humid sensations.

The remainder of this paper is organized as follows. Chapter Two critically reviews the literature on the mechanisms underlying humid and wet sensations in humans. Chapter Three highlights the aims and hypotheses of the study. Chapters Four and Five report the findings of the experiments. Chapter Four presents the experimental results on humid sensation, exploring how humans sense humidity in their environments. Chapter Five reports the effects of the experiment on wet sensation, which investigates how humans perceive the wetness of a substance including that on their skin. In Chapter Six, the results of the experiments along with the implications and limitations of the findings are emphasized. Finally, conclusions based on the conducted experiments are presented, and proposals for future research are suggested.

The dissertation aims to advance our understanding of the mechanisms underlying the human perception of humid and wet sensations, which have important implications for thermoregulation and overall well-being.

Chapter TWO

2. Review of Literature

2.1. Thermoregulation

The body temperature of homeotherms, including humans, consists of core temperature, which is the temperature at which vital organs such as the brain, heart, liver, and kidneys exist, and a shell temperature, which is the temperature at which other body parts exist. The primary purpose of thermoregulation is to maintain a constant core temperature. In humans, the core temperature is maintained at approximately 37°C (Sund-Levander et al., 2002). In contrast, the shell temperature largely fluctuates under the influence of environmental temperature and thermoregulation (Chen et al., 2011; Choi & Loftness, 2012; Ji et al., 2017; Y. Liu et al., 2013). Thermoregulation is a critical process that enables the core temperature to remain constant despite fluctuations in the environmental temperature. Maintenance of the core body temperature is essential for the maintenance of bodily functions, including enzyme activity, metabolism, and immune function reactions. Thermoregulation can be broadly classified into behavioral and autonomic thermoregulation. Behavioral thermoregulation refers to the selection of a preferable thermal environment based on movement and/or behavior. Autonomic thermoregulation is achieved by the effector organs of thermoregulation, which are involved in either heat production or dissipation.

2.2. Behavioral thermoregulation

Behavioral thermoregulation denotes thermoregulation achieved by various physical behaviors. Such behaviors contribute to the prevention of possible temperature changes, that is seeking warmer or cooler environments. Behavioral thermoregulation selects an optimal environment to maintain the core temperature. It is reported that, in humans, an increase in mean skin temperature plays a key role in activating behavioral thermoregulation when the ambient temperature rises (Vargas, Slyer, et al., 2018). Schlader et al. suggested that a change in skin temperature is a vital thermal input that initiates behavioral thermoregulation (Schlader et al., 2009). Thermal input to the skin plays an essential role, and the ambient environment is monitored through the skin to determine appropriate behavior.

Behavioral thermoregulation may not be appropriate in infants and the elderly because of changes in sensory nerves or underdeveloped motor function (such as reduced thermal sensation and the inability to act on themselves). A previous study on mouse lemurs reported that aged animals prefer higher ambient temperatures throughout the day than adult animals (Aujard et al., 2006). Thermal sensation is a critical factor for maintaining body temperature homeostasis. Understanding age-related changes in thermal sensation and thermoregulatory behavior will lead to a better understanding of the central mechanisms of behavioral thermoregulation.

2.3. Thermal sensation

The thermal sensation is a physiological response to changes in environmental temperature. Sensing ambient temperature is essential for autonomic and behavioral thermoregulation in homeotherms, including humans. Afferents, that increase their firing frequency in response to temperature changes are called thermosensitive neurons. Ion channels responding to a specific temperature range and those expressed in thermosensitive neurons have been identified (Schepers & Ringkamp, 2010). Sensory nerves on the skin contain several types of thermoreceptors called transient receptor potential (TRP) channels, which respond to different temperature ranges (Flockerzi & Nilius, 2007). The receptors send signals to the brain, which interprets the information and generates thermal sensations. When thermoreceptors in the skin detect a temperature change, they transmit signals through the nerves to the spinal cord and then to the thalamus via the spinothalamic tract, transmitting the temperature sensation to consciousness.

Thermosensitive neurons have been identified as core body temperature sensors and are known to change their firing frequency in response to alterations in brain temperature (Nakayama et al., 1961; Kobayashi, 1986; Tan et al., 2016). Heating the preoptic area and anterior hypothalamus causes a cutaneous vasodilatory response (Kanosue et al., 1994). Optogenetic excitation of warm-sensitive neurons in the hypothalamus causes a rapid decrease in body temperature (Tan et al., 2016).

2.4. Thermal comfort

Thermal comfort describes an individual's subjective state of mind that expresses satisfaction with the thermal environment. Various factors influence thermal comfort, including ambient temperature, humidity, and airflow (Cosma & Simha, 2018; Ugursal, 2010; Uğursal & Culp, 2013). High humidity diminishes thermal comfort (Buonocore et al., 2018; Jing et al., 2013) and decreases sweating efficiency (Libert et al., 1976). The body temperature of homeotherms is determined by the balance between heat transfer to and from the external environment, including heat production and loss. Thermal comfort is provided by the body temperature approaching a regulated state, while thermal discomfort is caused by the body temperature deviating from the regulated state (Nagashima et al., 2018). Core and skin temperatures are afferent inputs to the thermoregulatory central nervous system, and Frank has suggested that they contribute to thermal comfort in equal ratios (Frank et al., 1999). Nakamura et al. (Nakamura et al., 2008) reported that thermal comfort in response to local thermal stimuli varies by body region, with the face and abdomen exhibiting different trends than other regions.

2.5. Humid sensation

Humidity is one of the senses that often comes to our attention in our daily lives. Ambient humidity affects comfort levels and thermoregulation (Jing Feng & Teruko, 2014). The humidity level in an environment is often evaluated based on relative humidity. High relative humidity can cause discomfort because of the reduced ability of sweat to evaporate from the skin (Libert et al., 1976). In contrast, low relative humidity can cause dryness of the skin and respiratory system (Barreca & Shimshack, 2012).

A previous study reported no difference in the subjective humid sensation when randomly exposed to four different relative humidity levels between 10%–70% at a constant ambient temperature (Andersen et al., 1973). Tamura suggested that with ambient temperatures below 25°C, an increase in relative humidity is not perceived

(Tamura & Koshiba, 1995). However, in a study where office work was done in various humidity settings, weariness considerably rises at high relative humidity levels (Tsutsumi et al., 2007). As mentioned above, there have been discussions about the humid sensation, and a unified opinion is yet to be reached.

2.6. Wet sensation

The wet sensation is one of the most critical functions of organisms. In Drosophila, channels in neurons in the antennae act as hygroreceptors, suggesting the possibility of accurate perception of environmental moisture (L. Liu et al., 2007; Montell, 2008). Wet sensation is an important function in humans as it involves thermal comfort and behavioral thermoregulation (Schlader et al., 2010). It has been suggested that humans do not possess receptors that respond specifically to moisture (Filingeri et al., 2014; Filingeri, Fournet, et al., 2015; Filingeri, Redortier, et al., 2015; Shibahara & Sato, 2016). From the specific receptors involved in wet sensation to the transmission of information to the brain, most of the neural basis of the phenomenon remains unclear. It has been hypothesized that the input of cold and mechanical stimuli produces a wet sensation (Filingeri et al., 2014; Merrick et al., 2021). Moreover, it is assumed that temperature and pressure information is transmitted and integrated by different nerve fibers to identify the state of the skin surface. Other research suggests that a wet sensation may be an independent perceptual quantity that is separate from the properties of the material being touched (Bergmann Tiest et al., 2012). Despite many studies that have aimed to clarify the mechanisms involved in wet sensation, the central mechanisms that shape wet sensation still need to be elucidated.

Chapter THREE

3. Aims and Hypotheses

3.1. Study aims

The present study aimed to investigate the mechanisms involved in humid and wet sensations, and identify the neural bases for these sensations. As indicated in the introduction section (Chapter One), tactile and thermal stimuli are necessary to form a wet sensation. However, the contribution of these two stimuli to wet sensations and how they are integrated remain to be resolved. Therefore, the present study has two major research objectives: 1) to explore the mechanism of sensory formation related to the humid sensation (Aim1) and 2) to clarify the contribution of mechanical and thermal sensations and define the characteristics of the wet sensation (Aim 2).

To achieve Aim 1, we focused on enhancing humid sensation by wearing a face mask. We investigated the effects of exercise high-temperature and high-humidity conditions on humid sensation. To achieve Aim 2, we presented "wet" stimuli without temperature change and searched for the threshold stimulus amount for the perception of wetness. We also combined thermal and wet stimuli to investigate the influence of thermal sensations on wet sensations.

3.2. Working hypotheses

In the study, the following two hypotheses were tested.

Hypothesis 1) The thermal sensation in the nasal mucosal cavity is vital for humid sensation. In addition, the temperature change in the nasal mucosa due to the moist conditions of inhalation enables the perception of the humidity of the environment. We, we hypothesized that wearing a face mask would elevate the humid sensation and increase physical and psychological fatigue.

Hypothesis 2) As previously hypothesized, tactile and temperature sensations involve the formation of wet sensation. In addition, we hypothesized that even if the temperature is constant, an increase in the water content of the touched material increases the wet sensation. Furthermore, the intensity of the wet sensation is modified and altered by the temperature sensation.

Chapter FOUR

4. Humid sensation with wearing surgical masks

4.1. Introduction

Face masks have been used for various purposes. In some work environments, masks must be worn for protection from harmful substances, such as gas and dust, in industrial fields (Lawrence et al., 2006) or infectious substances, such as bacteria and viruses, in medical fields (Wllleke, 1993). However, because of the recent increase in the risk of viral infections (e.g., influenza, SARDS, MARDS, and COVID-19), wearing masks seem to have become a lifestyle choice in ordinary people. Leung et al. reported (Leung et al., 2020) that surgical masks reduce the transmission of human COVID-19 and influenza viruses. In addition, the importance of surgical masks in preventing respiratory infections from spreading in the entire community was suggested (Cheng et al., 2020). Surgical masks are meant for healthcare workers; however, this evidence may have facilitated the use of surgical masks among familiar people.

In 2020, the Ministry of Environment and the Ministry of Health, Labor and Welfare in Japan announced the risk of heat stroke due to wearing hygiene masks during intense work or exercise in hot and humid conditions. They encouraged taking off masks in such conditions (Ministry of Health, n.d.). However, the mechanism for the risk of heat stroke has not been identified. Moreover, it remains unclear whether mild-intensity work and/or exercise could bear such risk. One possible mechanism underlying the risk of heat stroke may be increased respiratory resistance, which causes by an increase in the work of respiratory muscles and the oxygen demand. Wearing masks may also increase respiratory dead space, thereby increasing the inspiratory CO_2 level. One report showed no apparent effect of surgical masks on cardiopulmonary functions during vigorous exercise (Shaw et al., 2020); however, Fikenzer et al. suggested an increase in respiratory resistance (Fikenzer et al., 2020a). Other possible mechanisms may be changes in the thermal and humidity environment of the upper airway (Scarano et al., 2020), which suppress dry and evaporative heat loss. In addition, the changes may also affect thirst and subsequent drinking behavior, resulting in the risk of heat stroke. However, we do not know if wearing surgical masks alters the local environment of the upper airway and affects heat loss and thirst during mild exercise.

When evaluating the influence of wearing masks on exercise, thermal and humid sensations on the face should be considered. Scarano et al. (Scarano et al., 2020) reported increased facial temperature and humidity with breathlessness and discomfort when subjects wore N95 masks. It was reported that the face is more sensitive to heat than other body sites (Cotter & Taylor, 2005). Armada-da-Silva, Woods, & Jones

(Armada-da-Silva et al., 2004) showed that fatigue increases with facial skin temperature. Therefore, we may have misinterpreted the augmented hot sensation and/or fatigue for the risk of heat stroke.

The present study aimed to test the hypotheses that i) the risk of heat stroke increases by wearing surgical masks during mild exercise in hot and humid conditions and ii) wearing surgical masks augments thermal sensation and fatigue during mild exercise. Moreover, we aimed to clarify the mechanisms for the possible risk of heat stroke. Therefore, participants conducted treadmill exercises of mild intensity for 30 min in hot (ambient temperature (T_a) of 35°C) and humid (65% relative humidity; RH) conditions while wearing or not wearing a surgical mask. We also measured the temperature and humidity under the mask and assessed the physiological and psychological responses during the exercise.

The studies that comprise Chapter Four were described with modifications of our previous study (Kato et al., 2021).

4.2. Materials and Methods

4.2.1. *Participants*

Twelve healthy volunteers (8 males and 4 females; age, 23 ± 3 years; height, 170 ± 6 cm; and body weight, 63.61 ± 10.53 kg, mean ± standard deviation [SD]) participated in the present study. They were non-smokers and had no clinical history of cardiovascular, metabolic, or respiratory diseases, and were not involved in exercise training. Participants were instructed to refrain from heavy exercise and consumption of a high-protein diet, alcohol, and caffeine from one day before the experiment. The experimental protocol was approved by the Ethical Committee of Human Research, Waseda University (2020-098), and was conducted in accordance with the Declaration of Helsinki (1983). Participants provided written informed consent before the start of the experiments.

4.2.2. *Experimental protocol*

The experiment consisted of two trials, which were separated by at least a two-day interval and finished within a month. In both trials, participants conducted the same treadmill exercise. However, participants wore a mask in one trial and no mask in the other (mask and control trials, respectively). On the day of each trial, participants had two rice balls (420 kcal) with > 500 mL of water 3 h before the exercise. In each trial, they arrived at the laboratory and rested on a chair for 30 min while drinking 300 mL of water. They urinated, and the nude body weight was measured (DP-7900PS-S, Yamato Scale, Akashi, Japan). They changed to a T-shirt, short pants, athletic shoes, and ankle-length socks. Participants rested for another 30 min in an environmental chamber

(Espec, Osaka, Japan) maintained at T_a of 35°C and RH of 65% with a ventilating wind speed of 0.5 m/s. The wet bulb globe temperature (WBGT) (PARSONS, 2006) was continuously monitored with a WBGT thermometer fixed at a height of 1.5 m above the floor, which ranged from 30.0-32.1°C (30.9°C in average, HI-2000SD, Custom, Tokyo, Japan). The setting was chosen to mimic the environmental condition of the daytime in the middle of summer (July to September) in Tokyo, Japan (*Japan Meteorological Agency*, n.d.), in which a number of people suffer from heat stroke (*Heat Illness Prevention Information Provided by MoE*, n.d.). Heart rates (HR) were monitored by electrocardiography (BSM-2401, Nihon Koden, Tokyo, Japan). Rectal temperature (T_{rec}) was measured with a thermistor probe (401J, Nikkiso-Thermo, Musashino, Japan) placed 13 cm from the anus, and recorded every 30 s with a data-logger (N543, Nikkiso-Thermo, Musashino, Japan). Ear canal temperature (T_{ear}) was assessed using the infrared sensor placed in the ear canal (Vit Thermo VTB-01, Vitarate, Tokyo, Japan). The ear was covered with a medical film (Tegaderm, 3M Company, Saint Paul, USA) to keep the stable position of the sensor in the ear canal and avoid cooling the sensor by the ventilating wind. Temperature and relative humidity at the perioral area of the face (T_{face} and RH_{face}, respectively), anterior chest, and lateral planes of the upper arm, thigh, and lower leg were measured with a temperature/humidity logger (DS1923 iButton

Hygrochron, Maxim Integrated, San Jose, USA) every 30 s. The temperature/humidity loggers were placed on the skin. The temperature sensor was located at the bottom of the logger, measuring the skin surface temperature. The humidity sensor was located at the top of the logger, estimating air humidity ca. 1 cm above the skin surface.

Participants moved on a treadmill (TRM731, Precor, Woodinville, USA) and stood still for 10 min, during which baseline data were obtained. Before the start of the baseline measurement, participants wore a surgical mask in the mask trial. The surgical mask had a size of 175 x 95 mm and was made of three layers of non-woven polypropylene fabric (Level 3 of ASTM-F2100-11, respiratory resistance of < 6 mmH_2O/cm^2, Maruoh, Fuji, Japan). The mask was placed such that the gap between the mask and the face was reduced and the temperature/humidity logger was covered. The participants ran on the treadmill for 30 min at a speed of 6 km/h and a slope of 5% at T_a of 35°C and 65% RH. The exercise intensity corresponds to a light jogging level or moderate manual labor (4.5 metabolic equivalents) (AINSWORTH et al., 2000). The slope was adopted to lessen the variation of relative exercise intensity among participants due to changes in the step length and frequency (Padulo et al., 2012). Participants rested for 1 min after running for 10 and 20 min. During the resting periods, participants reported their psychological responses as described below. Participants' nude body weight was measured again at the end of the experiment. The reduction of body weight was estimated as the water loss during the exercise, which originated from sweating and respiration.

Participants rated their thermal sensation, thermal discomfort, the humid sensation of the face and whole body, physical fatigue, and thirst sensation separately by drawing a cross line on a visual analog scale (VAS). The rating was conducted before the running and at 10, 20, and 30 min. The scale had a 150 mm length, on which “nothing at all” was labeled 25 mm from the left, and “extreme that I have ever had” was labeled 25 mm from the right.

4.2.3. ***Statistical analysis***

The sample size was determined using G * Power 3.1.9.7 (Faul et al., 2007). For the assessment of physiological variables, an effect size f of 0.25, the α error probability of 0.05, the number of groups of 2, and a power of 0.8 was determined, and sample size 9 was estimated. For the assessment of psychological variables, an effect size f of 0.25, the α error probability of 0.05, the number of groups of 2, and a power of 0.8 were determined, and a sample size of 12 was estimated. We estimated that the required number of participants was more than 12 in each trial in the present study. These were calculated by adopting the values of the parameters based on our previous human studies evaluating the physiological and psychological responses during exercise in heat (Tokizawa et al., 2014).

Mean skin temperature (mean T_{skin}) was calculated using the Ramanathan's formula (RAMANATHAN, 1964): 0.3•(skin temperature at the chest + that at the arm) + 0.2•(that at the thigh + that at the leg). The data during the one-min resting periods were excluded and averaged every 5 min. Body weight before and after the exercise was compared using the paired t-test. To compare HR, T_{rec}, T_{face}, and RH_{face} between two trials, a two-way analysis of variance for repeated measurement was conducted after verifying their normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene's test). A post-hoc test was conducted by the Bonferroni method. The comparison of thermal sensation, thermal discomfort, and humid sensation of the face and whole body, physical fatigue, and thirst sensation in the baseline period and during exercise between two trials was conducted by Friedman's test. Wilcoxon signed-rank test was conducted as the post-hoc test. The null hypothesis was rejected at $P < 0.05$. R was used for all statistical analyses (R Core Team, 2019). Data are presented as means ± standard deviation (SD).

4.3. Results

In both control and mask trials, the body weight at the end of the exercise did not change from that before the exercise (control trial; P = 0.917, 63.5 ± 11.0 and 63.0 ± 10.9 kg; and mask trial; P = 0.927, 63.5 ± 10.7 and 63.1 ± 10.7 kg before and after the exercise, respectively). Baseline HR, T_{rec}, and T_{ear} were 89 ± 15 beats/min, 37.1 ± 0.4°C, and 37.3 ± 0.3°C for the control trial and 91 ± 15 bpm, 37.1 ± 0.4°C, and 37.3 ± 0.3°C for the mask trial, respectively.

Figure 1 illustrates HR in the control and mask trials. HR continued to increase during the exercise ($F_{(1, 6)} = 71.11$, $P < 0.001$, 169 ± 15 and 171 ± 14 beats/min at 30 min in the control and mask trials, respectively); however, no significant difference was observed between the two trials.

T_{rec}, T_{ear}, and mean T_{skin} in the control and mask trials are shown in Figures 2A, B, and C, respectively). T_{rec} increased at 25-30 min in both trials ($F_{(1, 6)} = 13.58$, $P < 0.05$; 38.0 ± 0.5 and 38.1 ± 0.4°C at 30 min, respectively); however, there were no significant differences between the two trials. T_{ear} increased at 20-30 min in the two trials ($F_{(1, 6)} = 34.89$, $P < 0.05$; 38.5 ± 0.4 and 38.4 ± 0.3°C at 30 min, respectively) without any significant difference. Mean T_{skin} in the control and mask trials increased during 10-30 min ($F_{(1, 6)} = 66.84$, $P < 0.001$; 37.0 ± 0.3 and 37.0 ± 0.4°C at 30 min, respectively), but no significant differences were observed between the two trials.

Figures 3A and B show T_{face} and RH_{face} in the control and mask trials, respectively. The baseline T_{face} was not different between the control and mask trials (P = 0.11; 36.1 ± 0.6 and 36.5 ± 0.4°C, respectively). T_{face} in the control trial became higher than the baseline at 15-30 min ($F_{(1, 6)}$ = 17.02, P < 0.001; 37.5 ± 0.5°C at 30 min) and at 25-30 min in the mask trial (P < 0.05; 37.3 ± 0.5°C at 30 min), but there were no significant differences between the two trials.

The baseline RH_{face} in the mask trial was higher than that in the control trial ($F_{(1, 6)}$ = 797.60, P < 0.001; 67.0 ± 3.4 and 79.9 ± 2.3% in the control and mask trials, respectively). The value in the control trial remained unchanged during the exercise period (P = 1.00; 69.0 ± 2.8% at 30 min). However, RH_{face} in the mask trial became greater than the baseline at 30 min ($F_{(1, 6)}$ = 5.54, P = 0.04; 84.3 ± 4.3% at 30 min), and significant differences in RH_{face} (P < 0.001) were observed between the two trials during the exercise. The relative humidity in the chest increased from the baseline at 15-30 min in the control trial and 10-30 min in the mask trial ($F_{(1, 6)}$ = 13.39, p < 0.05; 83.4 ± 5.8% and 82.4 ± 4.8% at 30 min, respectively). Baseline values of relative humidity in the arm, thigh, and leg were not different between the two trials and remained unchanged during the exercise.

Thermal sensation, humid sensation, and thermal discomfort of the face are illustrated in Figures 4A, B, and C, respectively. The baseline value of each perception was not different between the control and mask trials ($p = 0.36$, 0.10, and 0.22, respectively). The thermal sensation, humid sensation, and thermal discomfort of the face became higher than the baseline at 10, 20, and 30 min in the control and mask trials ($p < 0.05$). There were no differences in the thermal discomfort of the face between the two trials during the exercise ($p = 0.052$ at 30 min). Thermal sensation and humid sensation of the face in the mask trial were higher than those in the control trial at 30 min ($p = 0.04$ and 0.02, respectively).

The thermal sensation, humidity sensation, and thermal discomfort of the whole body are illustrated in Figures 4D, E, and F, respectively. The baseline value of thermal sensation and humid sensation of the whole body was not different between the two trials ($p = 0.78$ and 0.81, respectively). The all-rating values increased ($P < 0.05$) from the baseline at 10, 20, and 30 min. There were no differences in the humid sensation of the whole body between the two trials during exercise ($p = 0.07$). The thermal sensation of the whole body in the mask trial is higher than that in the control trial at 20 and 30 min ($p = 0.01$ and 0.008, respectively). Thermal discomfort of the whole body in the mask trial is greater than that in the control trial at the baseline period and 20 min ($p = 0.03$ and 0.02, respectively).

Figure 5A shows the rating of fatigue in the two trials. The baseline value was not different between the two trials. The rating during the exercise increased from the baseline at 10, 20, and 30 min in both trials ($P < 0.05$), and there were no significant differences between the trials. The rating of thirst is shown in Figure 5B, and the baseline value was not different between the two trials. The rating during the exercise increased from the baseline at 30 min in the control ($P < 0.01$) and at 10, 20, and 30 min in the mask trial ($p < 0.05$), but no significant differences were observed between the two trials.

4.4. Discussion

In the present study, we examined whether wearing surgical masks increases the risk of heat stroke during mild treadmill exercise in hot and humid conditions. In addition, the influence of wearing a mask on the micro-environment (i.e., temperature and humidity) under the mask was evaluated, which may affect physiological and psychological responses to the exercise.

The Japanese government warned about the risk of heat stroke induced by intense work and/or exercise while wearing masks in hot and humid conditions (*Point of Heat Exhaustion Prevention Behavior in "New Lifestyle,"* 2020); however, there was no information regarding the specific workload and/or environmental condition. Most cases of exertional heat stroke occur during mild-intensity work or exercise (Miyake et al., 2010). Thus, we raised a fundamental question, do we need to take off masks even when conducting a mild-intensity exercise or working in hot and humid conditions?

Factors inducing exertional heat stroke could be divided into 1) environmental conditions including ambient temperature, humidity, radiation, clothes, etc.; 2) relative workload for individuals; and 3) physical conditions such as hydration state and heat tolerance. At the WBGT level in the present study, the American Society of Sports Medicine recommends that all work and sports activities should be prohibited (*ACSM Guidelines for Heat and Humidity*, n.d.; Asayama, 2009). These experimental conditions might clarify whether surgical mask augments the risk of heat stroke during work and/or exercise in the hot and humid condition that we usually have in summer.

4.4.1. *Changes in skin temperature and humidity under the surgical mask*

In the U.S., commercially available surgical masks are cleared by the U.S. Food and Drug Administration (*Face Masks, Including Surgical Masks, and Respirators for COVID-19 | FDA*, n.d.). These surgical masks, made of non-woven fibrous filters with triple layers, were used in the present study (Chua et al., 2020). During the baseline period, there was no difference in T_{face} between the control and mask trials (Figure 3A). Scarano et al. assessed the perioral skin temperature before and after wearing surgical mask among resting subjects in a condition of 22-24°C ambient temperature and 50%

relative humidity, and reported no difference in the skin temperature, similar to the present study (Scarano et al., 2020). In a normal ambient condition, the temperature of the expiratory air reaches the level of the body temperature (Berry, 1914). However, the warm expiratory air did affect the perioral skin temperature under the mask. These results may suggest that, in the resting condition, the expiratory air rapidly diffuses to the environment through the mask. Different from T_{face}, the RH_{face} in the mask trial was higher than that in the control trial at rest. Courtney and Bax reported that surgical masks increase the relative humidity of the inspiratory air, which may indicate that humid air space was built under the mask (Courtney & Bax, 2021). It was reported that expiratory air has a relative humidity of 78%, which is close to the level of the baseline in the mask trial (Berry, 1914), or the fibers of the mask might absorb the expiratory water, adding water constantly to the inspiratory air.

During the exercise, T_{face} increased without any difference between the two trials. The increase was linearly linked with T_{rec}, T_{ear}, and mean T_{skin} (Figure 2). Therefore, the increase in T_{face} may simply reflect the increase in body temperature. RH_{face} in the mask trial remained greater than that in the control trial. RH_{face} in both trials remained unchanged from the respective baseline value, except for the increase in the mask trial at 30 min. These results may suggest that the influence of wearing a surgical mask on the humidity of the expiratory and inspiratory air was not changed by the exercise.

4.4.2. *The influence of wearing a surgical mask on the cardiac and thermal load*

The baseline heart rates were similar in the two trials. Thus, the surgical mask had no influence on heart rates at rest, as previously reported (Fikenzer et al., 2020b). HR gradually increased during the exercise (Figure 1), and there were no significant differences between the two trials. During continuous exercise, heart rates increased with the changes in the relative intensity for individuals, body temperature, and hydration state (Peçanha et al., 2017; Ekelund, 1966; Wingo et al., 2012). Since body weight remained unchanged in each trial, the hydration state also remained unchanged. T_{rec} and mean T_{skin} increased with time, but no differences between the two trials were observed. These results suggest that HR might have increased under the influence of body temperature. Wearing a mask may increase the respiratory resistance, which increases the work of respiratory muscles and metabolic demand. It was reported that the humidity in the respiratory air does not affect respiratory resistance (Roberge et al., 2010). Fikenzer et al. reported that surgical mask decreases forced vital capacity and forced expiratory volume (Fikenzer et al., 2020b), which may indicate the increase in respiratory resistance. However, they also showed that surgical mask did not affect cardiopulmonary function as well as arterial O_2 and PO_2 tensions, even during the maximum oxygen uptake test. These results suggest that wearing a surgical mask may increase workload during mild exercise.

There may be two possible influences of wearing a surgical mask on thermoregulation. First, the mask may suppress heat loss from the covered skin area of the face. Second, it may promote evaporative heat loss from the airways. It was reported that the respiration of high-humidity air decreases heat transfer from the body (Bilgili et al., 2019). White and Cabanac assessed the relationship between respiratory heat loss and core body temperature during exercise, in which subjects inhaled air of low or high humidity (White & Cabanac, 1995). The study showed that the inhalation of humid air induced a greater increase in tympanic temperature (reflecting brain temperature) relative to esophageal temperature (reflecting body trunk temperature), suggesting the involvement of the airways as a measure of the cooling of the brain. However, we found no differences in T_{rec}, also reflecting the trunk temperature, T_{ear}, mean T_{skin}, and T_{face} (Figures 2 and 3). A previous study conducted in a cool and dry condition also reported that surgical mask had no influence on core body temperature during exercise (Roberge et al., 2012). The results may suggest that surgical masks do not suppress heat loss from the skin and airways during mild exercise in a hot and humid condition. In the present study, the humidity of the perioral skin (i.e., RH_{face}) was high enough. Therefore, if we repeated the study under hot and dry conditions, we might have found smaller heat loss from the airway in the mask trial, as speculated by the increase in T_{ear}.

4.4.3. *The influence of wearing a surgical mask on the psychological responses*

Thermal discomfort of the face, humidity sensation of the whole body, fatigue, and thirst sensation increased during the exercise in both trials (Figures 4 and 5). We did not find any difference in T_{face} and mean T_{skin} between the two trials (Figure 3A). However, the thermal sensation of the face and whole body and thermal discomfort of the face became greater during exercise in the mask trial (Figures 4A, D, and C). Nakamura et al. reported that, in a hot environment, topical warming of the face increases both thermal discomfort of the local skin as well as that of the whole body (Nakamura et al., 2008). Therefore, T_{face} was not a factor modulating the thermal perceptions in the mask trial. It is speculated that sensation on the skin is a factor augmenting thermal discomfort in a hot environment (Vargas et al., 2020a). Greater humidity and humid sensation of the face (Figures 3B and 4B) may be involved in the mechanism.

It was reported that, during exercise in a cool and dry environment, topical warming of the face decreased work output for the given perception of effort (Schlader et al., 2011). However, a previous study showed that wearing a surgical mask has no effects on the rating of perceived exertion and time to exhaustion during exercise (Shaw et al., 2020). Moreover, people are more reluctant to wear a mask when the conditions are warm and humid (Nielsen et al., 1987). Wearing a mask may augment thermal discomfort probably due to greater humidity inside; however, may not affect perceived exertion during exercise.

In the future, we need to clarify if the influence of time length or work intensity of exercise affects physiological and psychological responses. Recently, Morris et al. (Morris et al., 2020) showed that prolonged facemask use resulted in dyspnea without affecting moto-cognitive performance. Thus, the time length may be a strong factor augmenting the influence of wearing a mask on thermal perception, fatigue, and other psychological responses. Moreover, when the experiment was conducted in mild heat and/or dry conditions, the micro-environment in the mask may have been largely different from the ambient air, clarifying the influence on the psychological responses.

4.5. Conclusion

In conclusion, we did not find any influence of wearing a surgical mask on cardiac and thermal responses during mild exercise in a hot and humid environment.

Therefore, surgical masks per se could not be a factor augmenting the risk of heat stroke in such work/exercise and environmental conditions. Moreover, a greater increase in humidity under the mask was observed; however, the increase did not affect the fatigue and thirst sensation.

Chapter FIVE

5. The interaction between wet and thermal sensation in the skin

5.1. Introduction

Wet sensations are closely related to daily life and survival in humans. The sensations play an important role in the assessment of the external environment and thermoregulatory responses. Wet sensation augments thermal discomfort (Kolka et al., 1998) and induces subsequent thermoregulatory behavior, such as escaping from the environment and changing or removing clothes (Vargas, Chapman, et al., 2018; Vargas et al., 2020b).

Despite the obvious wet sensations that humans experience in daily life, there is no clear evidence of the presence of a specific sensor to detect dampness of the skin and/or contact material in human beings to date. Bentley (Bentley, 1900) showed that, more than 100 years ago, the wet sensation of the finger could be synthesized even when the finger was covered with a thin rubber sheath and immersed in a liquid (i.e., the finger was not actually wet). The strength of the wet sensation was augmented by a liquid with a lower temperature and higher specific gravity. Furthermore, he concluded that the sensation of wetness could be attributed to temperature and pressure stimuli to the skin. Interestingly, he suggested that a wet sensation does not require touching wet material. However, the individual roles of temperature and pressure in the sensation of wetness and the interaction between the two factors are not fully understood.

Numerous behavioral studies have also shown that factors involved in thermal and mechanical stimuli affect the sensation of wetness (Bergmann Tiest et al., 2012; Filingeri et al., 2014; Merrick et al., 2021; Raccuglia et al., 2018; Shibahara & Sato, 2016). Bergmann Tiest et al. (Bergmann Tiest et al., 2012) further classified the factors inducing the sensation of wetness into four categories. When touching wet thin-layered materials (e.g., clothing fabric), thermal and mechanical stimuli, respectively, are induced by evaporative heat loss from the skin and stickiness. When touching large-volume materials (e.g., liquid in glass), thermal and mechanical stimuli, respectively, are induced by thermal conductance and pressure. They also suggested that discriminating the wetness of thin materials is largely induced by stickiness, which is modulated by the method of touching (static or dynamic) and the nature of the material. In their experiment, the factor of temperature, including the influence of evaporative heat loss, was not controlled; however, they suggested the influence of hand temperature on discrimination.

Yamakawa and Isaji (Yamakawa & Isaji, 1987) reported that cold sensations and/or a decrease in skin temperature during contact with wet materials are related to wet sensations. Another study showed that a warm stimulus at 35°C lessened the wet sensation on the finger pad and forearm (Filingeri et al., 2014). Fillingeri et al. showed that a wet sensation is induced by touching cold but dry material (Filingeri et al., 2013), and augmented cold sensation caused by a greater cooling rate of the local skin are a factor inducing this sensation (Raccuglia et al., 2018). Thus, the cold sensation is one of the essential factors generating wet sensation (Filingeri & Havenith, 2015). They also reported greater inter-individual differences in wet sensation, although the mechanism remains unclear.

In the present study, we aimed to evaluate the influence of temperature on the sensation of wetness when touching the thin wet paper. We also examined whether the sensation of wetness was blunted when factors related to thermal and wet stimuli decreased. In the first experiment, a change in wet sensation among papers moistened with different water contents was evaluated during static touch with the ventral tip of the right index finger. The stimulus temperature for the fingers was maintained using a temperature-controlled Peltier apparatus. In the second experiment, the thermal and wet sensations of the finger and their interaction were evaluated during the static touch of saturated paper. We hypothesized that i) wet sensation is augmented with the increase in water content when skin temperature is maintained at the level of “neither cold nor warm," and ii) thermal sensation is a determinant of wetness, which may be a reason for the inter-individual difference in wet sensation.

5.2. Materials and Methods

5.2.1. *Participants*

Twenty-seven right-handed, non-smoking volunteers (14 males and 13 females; age, 25 ± 5 years; mean ± standard deviation [SD]) participated in the present study. They were healthy and had no history of neurological or psychiatric illness. All participants provided written informed consent for the experiment, which was approved by the Human Research Ethics Committee of the Faculty of Human Sciences of Waseda University (2020-098). The experiments were conducted in accordance with the Declaration of Helsinki (1983).

5.2.2. *Experimental protocols*

Thermal and wet stimuli were applied to the skin surface of the ventral tip of the left index finger. Thermal stimulation was provided using a Peltier apparatus covered with a thin circular copper board (3 cm diameter; Intercross 2000, Tokyo, Japan). The surface temperature was controlled at the target temperature and continuously monitored (LabVIEW 2013; National Instruments, Texas, USA). Wet stimulation was applied with cellulose fiber filter paper (2 cm × 2 cm; Whatman paper grade 4; 92 g/m^2, 205 µm thickness; Advantec, Tokyo, Japan) containing distilled water in a definite volume, which was placed on the Peltier apparatus. The surface of the Peltier apparatus was filmed with a thin polyvinylidene chloride, which prevents the spreading of water on the filter paper to the surface.

The participants sat on a chair in front of a desk whose height was adjusted to the level of the elbow. The left forearm was loosely fixed to the desk, covered with a cardboard box, and blinded to the participants. A Peltier apparatus with the wet paper was placed on a rubber board on a desk. The thermal and wet stimuli were provided by asking participants to gently place their left index finger pad on the apparatus with wet paper.

5.2.3. *Experimental procedure*

Each participant had at least two experimental trials (Experiments 1 and 2) separated by at least one day. The order of the two experiments was randomly chosen. The participants arrived at the laboratory at 10:00 am. After changing into T-shirts and short pants, they entered the environmental chamber at an ambient temperature of 28°C with 50% relative humidity. They rested on a chair for 1 h drinking 300 ml water.

5.2.3.1. *Experiment 1*

This experiment assessed the wetness of moist paper with different water contents at 30°C. The temperature was determined based on averaged hand temperature at an ambient temperature of 27°C which was previously reported (Webb, 1992), and the averaged index fingertip temperature obtained from our previous studies under the same ambient condition. The trial consisted of 30 repeated 45-s sessions, each of which consisted of 5-s preparation, 15-s stimulation, and 25-s recovery in sequence (Fig. 6). Before starting the trial, the participants placed their finger on a Peltier apparatus maintained at 30°C for more than 3 min. In the 5-s preparation period, a researcher placed the wet paper on the Peltier apparatus. The water content of the paper for each session was selected from either 0.00, 3.75, 7.50, 11.25, 15.00, or 18.75 $\mu g/cm^2$ (i.e., water content per area), corresponding to 0.00, 0.18, 0.37, 0.55, 0.73 and 0.91 $\mu g/mm^3$ (i.e., water content per volume). Participants placed their finger on the Peltier apparatus for the 15-s stimulation period and reported whether they felt a wet sensation in the last 5 s. The surface temperature of the paper reached the target temperature of 30°C within 5 s after placing the paper on the Peltier. Participants were instructed not to move their finger during the stimulation period. During the 25-s recovery period, the participants removed their fingers and gently touched a dry towel. The paper was removed from the Peltier apparatus during this period. During the remainder of the period (20 s at least), the participants placed their fingers on the 30°C apparatus. In addition, a researcher verified that participants felt “neither cold nor warm” and “not wet” at the end of each session. Five sessions for each water content were conducted, and the order of the sessions was randomized.

5.2.3.2. *Experiment 2*

This experiment evaluated the influence of stimulation temperature on wet sensation. The trial comprised 25 repeated 45-s sessions, each involving 5-s preparation, 15-s stimulation, and 25-s recovery in sequence. In this trial, two Peltier apparatuses were prepared. One was for the thermal stimulus, and the other for recovery. The water content of the paper was constant at 18.75 $\mu g/cm^2$ (0.91 $\mu g/mm^3$). In each session, a stimulation temperature was selected from either 20°C, 25°C, 30°C, 35°C, or 40°C, which was applied through the wet paper. Five sessions for each temperature were performed in a randomized order. The temperature for the recovery was maintained at 30°C without filter paper on the Peltier apparatus. Before starting the trial, the participants placed their fingers on a Peltier apparatus maintained at 30°C for more than 3 min. During the 5-s preparation, the paper was placed on the Peltier apparatus, which was set at the desired temperature. The participants then placed their fingers on the apparatus for 15 s. In the last 5 s of the stimulation period, participants separately reported subjective thermal and wet sensations by marking their rating on a visual analog scale, which had a 15 cm line on which “very hot” or “very wet” was indicated

2.5 cm from the right end, and “very cold” or “dry” was indicated 2.5 cm from the left. The midpoint of the line indicating thermal sensation denoted “neither hot nor cold.” The sensations were quantified as the length (in mm) from the “very cold” or “dry” point to the marked point (perceived rate of thermal and wet sensations, respectively). The sensations were quantified as the length in mm from the “very cold” or “dry” point to the marked point (perceived rate of thermal and wet sensations, respectively). The sensation was expressed as a negative value if the marked point was left to the “very cold” or “dry” point. After the stimulation, the participants placed their finger on the Peltier apparatus for recovery after gently touching a dry towel. A researcher verified that participants felt “neither cold nor warm” and “not wet” at the end of each session.

We did not assess water loss in the wet filter paper at the time of measurement; however, the loss was less than 10% from the initial weight in the preliminary finding. The thermal gradient between the Peltier and the paper surfaces was less than 0.5°C.

5.2.4. *Statistical analysis*

The sample size was determined using G*Power 3.1.9.6 (Erdfelder et al., 2009; Faul et al., 2007). For the assessment of the wet sensation in Experiment 1, an effect size f of 0.25, the α error probability of 0.05, a group number of 1, and a power of 0.8 were determined, and a sample size of 24 was estimated. To assess the thermal and wet sensations in Experiment 2, an effect size f of 0.25, the α error probability of 0.05, a group number of 1, and a power of 0.8 were determined, and a sample size of 25 was estimated. In Experiment 1, the ratio of feeling wet for each water content was calculated in each participant (i.e., number of participants experiencing wet sensation out of 5 sessions for each water content, %). The ratio was averaged for all participants (percentage of participants experiencing wet sensation for each water content). For the correlation analysis between temperature and wetness in Experiment 2, a correlation p of 0.25, the α error probability of 0.05, a power of 0.8, and a sample size of 29 were estimated. Therefore, we estimated the required number of participants was greater than 29 in the present study.

Friedman's test was conducted to compare the percentage of participants experiencing wet sensation among the six different water contents in Experiment 1 and the perceived rate of a thermal and wet sensation among the five different thermal stimuli in Experiment 2. Post-hoc tests were conducted using the Wilcoxon signed-rank test when a significant difference was observed. In Experiment 2, Spearman's rank correlation test was conducted to assess the relationship between the stimulating temperature and the percentage rate of thermal and wet sensations. Sex differences for the percentage of experiencing wet sensation (Experiment 1) and the perceived rate of thermal and wet sensation (Experiment 2) were tested using the Kruskal-Wallis test. The null hypothesis was rejected at $P < 0.05$. R was used for statistical analyses (Ihaka & Gentleman, 1996; R Core Team, 2021). Data are presented as the mean ± SD.

5.3. Results

5.3.1. *Experiment 1*

Figure 7 illustrates the percentage rate of the wet sensation for the paper with water contents of 0.00, 3.75, 7.50, 11.25, 15.00 and 18.75 μg/cm^2 (19.2 ± 21.1%, 39.1 ± 28.5%, 46.6 ± 26.6%, 68.1 ± 25.5%, 76.2 ± 27.7%, 79.2 ± 27.4%, respectively). The percentage rate of wet sensation was greater than that of 0.00 μg/cm^2 at 3.75 μg/cm^2 ($P < 0.05$). The percentage rates of 11.25, 15.00, and 18.75 μg/cm^2 were significantly greater than those of 3.75 ($P < 0.01$) and 7.5 μg/cm^2 ($P < 0.005$). However, there were no differences among the water contents of 11.25, 15.00, and 18.75 μg/cm^2.

5.3.2. *Experiment 2*

Figure 8 shows the perceived rate of thermal sensation (A) and wet sensation at a given temperature on the finger pad (B). The rate of thermal sensation at T_{stim} of 25, 30, 35, and 40°C was greater than that at 20°C ($P < 0.001$; 11.4 ± 10.7 mm at 20°C, 27.6 ± 10.5 mm at 25°C, 47.6 ± 7.8 mm at 30°C, 65.2 ± 7.8 mm at 35°C, 78.7 ± 8.3 mm at 40°C, respectively). In addition, there were significant differences between the rate of thermal sensation of T_{stim} at 25–40°C, 30–40°C, and 35–40°C ($P < 0.001$ each). The perceived rate of wet sensation at T_{stim} of 25°C, 30°C, 35°C, and 40°C was lower than that at T_{stim} of 20°C ($P < 0.05$). In addition, the rate at T_{stim} of 30°C, 35°C, and 40°C was lower than the value at T_{stim} of 25°C ($P < 0.05$ each; 72.6 ± 16.8 mm at 20°C, 45.6 ± 14.8 mm at 30°C, 45.0 ± 14.3 mm at 35°C, 48.0 ± 20.3 mm at 40°C, respectively). There were no significant differences in the rate of a wet sensation among those at the T_{stim} of 30°C, 35°C, and 40°C.

Figure 9 shows the relationship between the perceived rate of thermal sensation and wetness. Each datum denotes the average perceived rate of thermal and wet sensations for the session of each thermal stimulus (i.e., 20°C, 25°C, 30°C, 35°C, or 40°C) of each participant in Experiment 2. The data group for Fig. 9A collected from the perceived rating of thermal sensation shows less than 50 mm in the visual analog scale (i.e., feeling cold), those for Fig. 9B shows equal to or greater than 50 mm in the visual analog scale (i.e., feeling not cold nor warm or feeling warm or hot). A significant correlation was observed between perceived thermal sensation and wet sensation in the data group shown in Fig. 9A (Rho = -0.532, $P < 0.001$) but not in the group shown in Fig. 9B (Rho = -0.01, $P = 0.938$).

5.3.3. ***Sex difference***

Although the sample size was insufficient to assess the influence of sex differences, no difference in the percentage of participants feeling a wet sensation on the wet paper was identified between male and female participants ($P = 0.50$; Experiment 1). Moreover, the influence of the stimulating temperature on wet sensation when touching the wet paper was not significantly different between male and female participants ($P = 0.50$; Experiment 2).

5.4. Discussion

This study investigated the mechanism involved in the sensation of wetness in the ventral tip of the index finger. In the first experiment involving a static touch of wet paper with six different water contents at 30°C, participants were asked to discriminate if the paper was wet. Participants could discriminate wetness more consistently as the water content increased. In the second experiment, stimulating the finger at six different temperatures and touching water-saturated paper induced different perceived rates of wetness. Stimulating temperatures lower than the conditioning temperature of 30°C (the level of normal skin temperature) induced a greater wet sensation. However, a stimulating temperature above the conditioning temperature did not correlate with a wet sensation.

Most studies investigating wet sensations have used clothing fabrics as wet materials because the sensation is closely related to clothing comfort (Ackerley et al., 2012; Filingeri et al., 2014; Shibahara & Sato, 2016; Sukigara & Niwa, 1997; Yokura & Sukigara, 2010). For similar reasons, these studies selected the skin of the torso, arms, and legs to examine the sensation of wetness. In older studies, as well as more recent studies (Bentley, 1900; Filingeri et al., 2014; Merrick et al., 2021), factors associated with thermal and mechanical sensations are thought to play an essential role in the wet sensation. More significant differences in tactile (McGlone & Reilly, 2010) and thermal sensations (Gerrett et al., 2014; Ouzzahra et al., 2012) among body sites have been reported. Tactile sensation assessed by the two-point discrimination test indicated that the fingertip, lips, and tongue were the most sensitive body sites (*Neuroanatomy through Clinical Cases*, n.d.). Nakamura et al. (Nakamura et al., 2006) reported that change in the local skin temperature during the application of both cold and heat stimuli was the greatest in the extremities compared with other body sites. Therefore, regional differences in wet sensation (McGlone & Reilly, 2010; Sukigara & Niwa, 1997) may reflect tactile and thermal sensations, at least in part. Thus, we assessed the sensation of wetness in the fingertip, assuming that the area reflects the influence of thermal and mechanical sensations.

In both Experiments 1 and 2, we minimized the influence of mechanical sensation in the following manner. First, the wet sensation was assessed during static touch maintained for 15 s. Second, the thin filter paper was used as the wet material, decreasing the friction between the skin and the paper. In addition, using thin filter paper, we added the desired volume of water with equal distribution. There was a slight temperature gradient between the paper's surface and the skin surface in each experimental session.

In Experiment 1, we assessed the sensation of wetness among papers with six different water saturation values. The Peltier apparatus and paper temperatures were maintained at 30°C throughout the sessions. Further, before starting the experiment, we verified that participants felt “neither cold nor warm” when touching the Peltier apparatus. The degree of evaporation might have varied between different water contents, and evaporation from the skin surface might have induced a cold sensation. This might have resulted in the difference in the percentage of participants feeling the wet sensation. However, the fingertip was kept dry after each stimulation. Therefore, we assumed that the influence associated with the cold sensation on the wet sensation was minimal in this experimental paradigm.

We assessed wet sensation from the filter papers with different water contents by evaluating the ratio of participants experiencing wet sensation at their left index fingertips. Previous studies have evaluated the wet sensation for various materials with different water contents. In one procedure, the participants had to touch two objects of the same material with different water contents using their right and left hands separately and determine the water contents of the materials (Bergmann Tiest et al., 2012). The results suggest the difference in sensitivity of wet sensation between the two hands. We found differences in some participants in the present experimental condition. However, we did not find apparent differences between the dominant and non-dominant hands. Thus, we have no specific reason for using this study's left (non-dominant) index finger. Another procedure involved asking participants whether a wet sensation was felt when touching wet materials before the threshold water content was determined (Merrick et al., 2021). However, as shown in Experiment 1 (Fig. 7), touching wet paper with water content did not always induce a wet sensation, even in the same participant. The percentage of participants experiencing wet sensation increased with even a slight increase in water content; however, the ratio plateaued at the level of 11.25 μg/cm^2 of water (68.1 ± 25.5%, Fig. 7). Participants reported wet sensation even at the level of 0.00 μg/cm^2 of water (complete dryness, 19.2 ± 21.1%). Although the fingertip was dried with a dry towel at the end of each session, the influence of the previous session (i.e., touching wet paper) might have affected the results.

Interestingly, even at 18.75 µg/cm^2 of water, the ratio did not reach 100% in all participants. In a study by Merrick et al. (Merrick et al., 2021) that investigated the static touch of diaper material, the threshold water content required to experience a wet sensation was found to be 14.58 µl/cm^2 at 29°C. This study showed a much lower detection level of water content (3.75 µl/cm^2). Within a small range of water content (0-11.25 µl/cm^2), the level of discrimination was 3.75 µl/cm^2 or less. This difference might reflect the water content of the contacting surface to the skin because the diaper material consisted of layers with different levels of water absorption.

Experiment 2 assessed the magnitudes of the thermal and wet sensations. The cut-off point for the maximum water content was determined based on the preliminary finding of the maximum level at which the filter paper could absorb water, and all participants could feel wetness. The percentage of participants experiencing wet sensation at 30°C plateaued in Experiment 1 (about 75%, Fig. 7). The influence of temperature on wet sensations can be categorized into two factors: direct temperature and the temperature change at the skin surface (Merrick et al., 2021). A temperature change is induced when we touch a material that is a different temperature or wet material from which the water has evaporated. Therefore, the wet sensation was assessed at 10–15 s after the finger was placed on the Peltier apparatus. We assumed that the influence of temperature on wet sensation was assessed in this study. The surface temperature of the fingertip changed for approximately 5 s and the thermal sensation of cold increased with the reduction in the stimulating temperature (Fig. 8A). Notably, a thermal sensation of 50 mm in the visual analog scale (not cold or warm/hot point) was observed at stimulus temperature of 30°C, which was the conditioning temperature in the present study. In addition, when the stimulation temperature was below 30°C, the wet sensation decreased as the stimulation temperature increased. However, the wet sensation reached a plateau at a stimulation temperature above 30°C. These results suggest that a thermal stimulus less than a conditioning temperature of 30°C is a determining factor of the magnitude of wet sensation, which remains consistent with the previous literature (Filingeri et al., 2014; Merrick et al., 2021). On the contrary, a stimulus above 30°C did not correlate with wet sensation.

We wondered how thermal stimuli less than the level of conditioning temperature (i.e., the level less than the normal skin temperature of the index finger) would increase the sensation of wetness. One possible mechanism is the influence of temperature per se, which stimulates thermal receptors on sensory A∂ and C fibers, such as TRPM8 channels (Venkatachalam & Montell, 2007). Another reason is the involvement of thermal sensations evoked in the brain, such as in the primary and secondary sensory cortex and insula (Aizawa et al., 2019). Therefore, we analyzed the relationship between thermal sensation and wet sensation (Fig. 8). Although we plotted every data point obtained from all the participants, we found interesting results. When the thermal sensation estimated with the visual analog scale was < 50 mm (indicating “cold sensation”), there was a strong negative correlation ($P<0.001$) between the thermal sensation and wet sensation (Fig. 8A). However, no significant correlation was observed in the data when the thermal sensation estimated with the visual analog scale was ≥ 50 mm (Fig. 8B). These results suggest that cold sensation increases the sensation of wetness in the brain as previously reported (Raccuglia et al., 2018). However, how wet and hot sensations coexist when mechanical sensation is reduced remains unclear. To clarify the influence of thermal sensation, we need a quantitative assessment of thermal sensation using functional magnetic resonance imaging and electroencephalography in the future. Moreover, the reason for intra- and inter-individual differences in wet sensation, as observed in this and other studies, may reflect that wet sensation is generated by subjective feelings such as thermal feeling in the brain.

5.5. Conclusion

We assessed the wet sensation of thin filter paper when the water content and temperature were modulated, and the mechanical sensation was minimized. We found a smaller threshold water content and discrimination level for wet sensations when the temperature of the paper was maintained at 30°C. We speculate that wetness can be felt even when thermal and mechanical stimuli to the skin are limited. The effect of temperature on wet sensation was limited to < 30°C. Moreover, we speculate that the thermal sensation of the skin plays a crucial role in generating a wet sensation. While cold sensations may play an essential role in this mechanism, warm sensations may have no influence. Further studies are required to investigate these theories further.

Chapter SIX

6. General Discussion and Conclusion

6.1. General Discussion

The study included in the dissertation investigated the factors contributing to humans' humid and wet sensations. The new findings add to previous studies on the relationship between wet and thermal sensations (especially warm sensations). Study 1 examined the impact of facemasks on humid sensation, thermal sensation, and thermoregulation. Study 2 focused on the effects of mechanical and thermal stimuli on wet sensations.

In Study 1 (Chapter Four), it is noteworthy that there was no change in either core body or skin temperature. According to the findings, Study 1's increased local facial humidity was the cause of the expansion of humidity and temperature sensation on the face and the entire body. A previous study has suggested that TRPM8, a thermoreceptor molecule, is abundant in the nasal mucosal epithelium and is involved in regulating mucus production (S.-C. Liu et al., 2017). The posterior nasal cavity temperature is approximately 34°C regardless of the inspiratory air temperature. The anterior nasal cavity may have a heating function to maintain this temperature (Keck et al., 2000). As changes in relative humidity significantly influence temperature changes in the mucosa, this property is expected to play a role in the function of the nasal cavity as a humidity sensor. The studies also indicate that the nasal cavity is involved in the humidity-sensing function.

Study 2 (Chapter Five) demonstrated that subjects could sense differences in minute amounts of water (3.75 $\mu l/cm^2$) at their fingertips. According to a previous study (Merrick et al., 2021), the stimulus for wetness is perceived at a higher threshold than the small amount generated by the current result. At the fingertips, the results suggest that it is possible to distinguish static wet stimuli using filter paper finely. Furthermore, the results suggest that the wet sensation is enhanced by a cold sensation but not affected by a warm sensation (Figure 9A, B). These results suggest that wet sensation is not a simple effect of temperature but is expected to have an independent relationship with cold sensation. The idea is consistent with previous studies (Filingeri et al., 2014; Merrick et al., 2021) proving that cold stimuli enhance the wet sensation.

The increase in relative humidity of the inhaled air may be the main factor in the mask-induced rise in humid sensation in Study 1. Slight differences in water content are also perceptible, as suggested in Study 2. The amount of water content in the mask increased due to sweating, which may have increased the wet sensation on the face. However, the skin temperature and thermal comfort on the face did not change, suggesting that the elevation in humid sensation was due to an increase in the intake air's relative humidity rather than the mask's wetness.

The following are possible mechanisms by which an increase in the relative humidity of the inhaled air causes the formation of the humid sensation. 1) As the relative humidity of inhalation increases, the water vapor pressure difference between the nasal epithelium and air decreases. 2) Water evaporation from the nasal cavity epithelium decreases, resulting in a reduction in temperature change. 3) This decrease in temperature change is sensed as a humid sensation. Study 2 suggests that cold sensation enhances wet sensation (Figure 9). Fillingeri *et al*. also has suggested that wet sensation is enhanced by evaporation (Filingeri et al., 2014). In Study 1, the change in cold sensation associated with evaporation was perceived as a change in wetness in the nasal cavity, which may play an essential role in sensing the humidity of the environment.

The results of Studies 1 and 2 suggest that TRPM8, a cold-sensing receptor molecule, may be an essential factor in the perception of wetness. Future studies should explore the detailed mechanisms underlying the involvement of cold sensation in wet sensation and clarify the neural circuits, neural substrates, and central regions responsible for wet and humid sensations.

6.2. Conclusion

In the study, we investigated the mechanisms underlying wet and humid sensation formation. Here we conclude the following about the mechanisms of humid and wet sensations.

i) An increase in local humidity on the face enhances the thermal and humid sensations on the face. It was concluded that the change in local humidity in the nasal cavity caused by respiration changed the thermal sensation, which in turn caused an increase in the humid sensation.

ii) The wet sensation is caused by mechanical stimuli independent of thermal sensation, and minute changes in water content are perceived. Furthermore, a wet sensation is enhanced by an increase in cold sensation, whereas a warm sensation does not affect the magnitude of the wet sensation.

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8. Figure legends

Figure 1. Heart rates (HR) during the 30-min exercise in the control and mask trials. Values are presented as means ± SD. †, Significant difference from the baseline value in the control trial, $P < 0.001$. §, Significant difference from the baseline value in the mask trial, $P < 0.001$.

Figure 2. Rectal temperature, ear canal temperature, and mean skin temperature in the control and mask trials (T_{rec}, A; T_{ear}, B; and mean T_{skin}, C; respectively). Values are presented as means ± SD. †, Significant difference from the baseline value in the control trial, $P < 0.05$. §, Significant difference from the baseline value in the mask trial, $P < 0.05$.

Figure 3. Skin temperature and relative humidity of the face (T_{face}, A; and RH_{face}, B; respectively) in the control and mask trials.

Values are presented as means ± SD. *, Significant difference between the control and mask trials, $P<0.05$. †, Significant difference from the baseline value in the control trial, $P < 0.05$. §, Significant difference from the baseline value in the mask trial, $P < 0.05$.

Figure 4. Thermal and humidity sensation and thermal discomfort of the face (A, B and C, respectively) and whole body (D, E and F, respectively) in the control and mask trials.

Values are presented as means ± SE. †, Significant difference from the baseline value in the control trial, $P < 0.05$. §, Significant difference from the baseline value in the mask trial, $P < 0.05$.

Figure 5. Fatigue (A) and thirst (B) in the control and mask trials.

Values are presented as means ± SE. †, Significant difference from the baseline value in the control trial, $P < 0.05$. §, Significant difference from the baseline value in the mask trial, $P < 0.05$.

Figure 6. Thirty and 25 sessions were performed in Experiments 1 and 2, respectively. Each session consisted of a 5-s preparation period (placement of the paper on the Peltier apparatus), 15-s temperature stimulation period, and 25-s recovery period. In Experiment 1, the Peltier apparatus was maintained at 30°C throughout. In Experiment 2, the Peltier apparatus was maintained at 30°C during preparation and recovery.

Figure 7. Percentage of participants experiencing wet sensation in the index finger when touching paper saturated by six different water contents

Water content is denoted in both per area and volume (value in parenthesis) of the filter paper. Values are presented as mean ± SD. *, Significant difference from the value of water content of 0 $\mu g/cm^2$, $P < 0.05$; †, 3.75 $\mu g/cm^2$, $P < 0.05$; and ‡, 7.50 $\mu g/cm^2$, $P < 0.05$.

Figure 8. Perceived rate of thermal and wet sensation of the index finger when touching paper at five different temperatures

Values are presented as mean ± SD. *, Significant difference from stimulation at 20°C; †, 25°C, $P < 0.05$; ‡, 30°C, $P < 0.05$; §, 35°C, respectively.

Figure 9. Relationship between the perceived rate of thermal sensation and wet sensation

Each data point denotes the average perceived rate of thermal and wet sensations for either thermal stimulus (i.e., 20, 25, 30, 35, or 40°C) for each participant in Experiment 2. The relationship was separately illustrated for the data in which participants reported thermal sensations of < 50 mm on the visual analog scale (i.e., cold sensation; A) and ≥

50 mm (i.e., nothing or warm sensation; B). The correlation coefficient (Rho) and P-value are shown. Significance was observed in the data group in which thermal sensation was < 50 mm on the visual analog scale (Rho = -0.532, $P < 0.001$) but not in the group in which thermal sensation was ≥ 50 mm on the visual analog scale (Rho = -0.01, $P = 0.938$).

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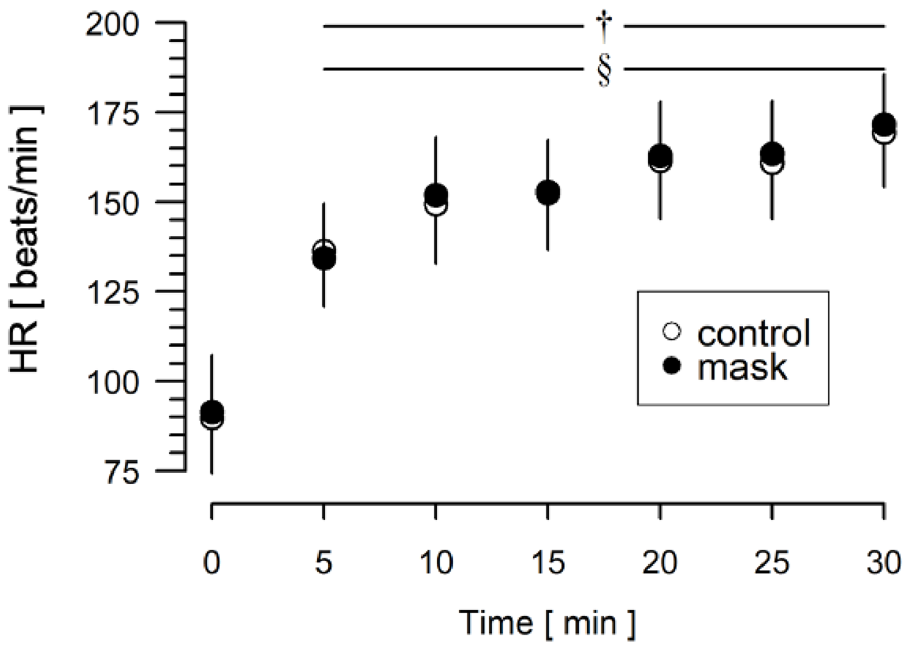

200
175
150
125
100
75
HR [beats/min]
†
§
control
mask
0
5
10
15
20
25
30
Time [min]

Figure 1

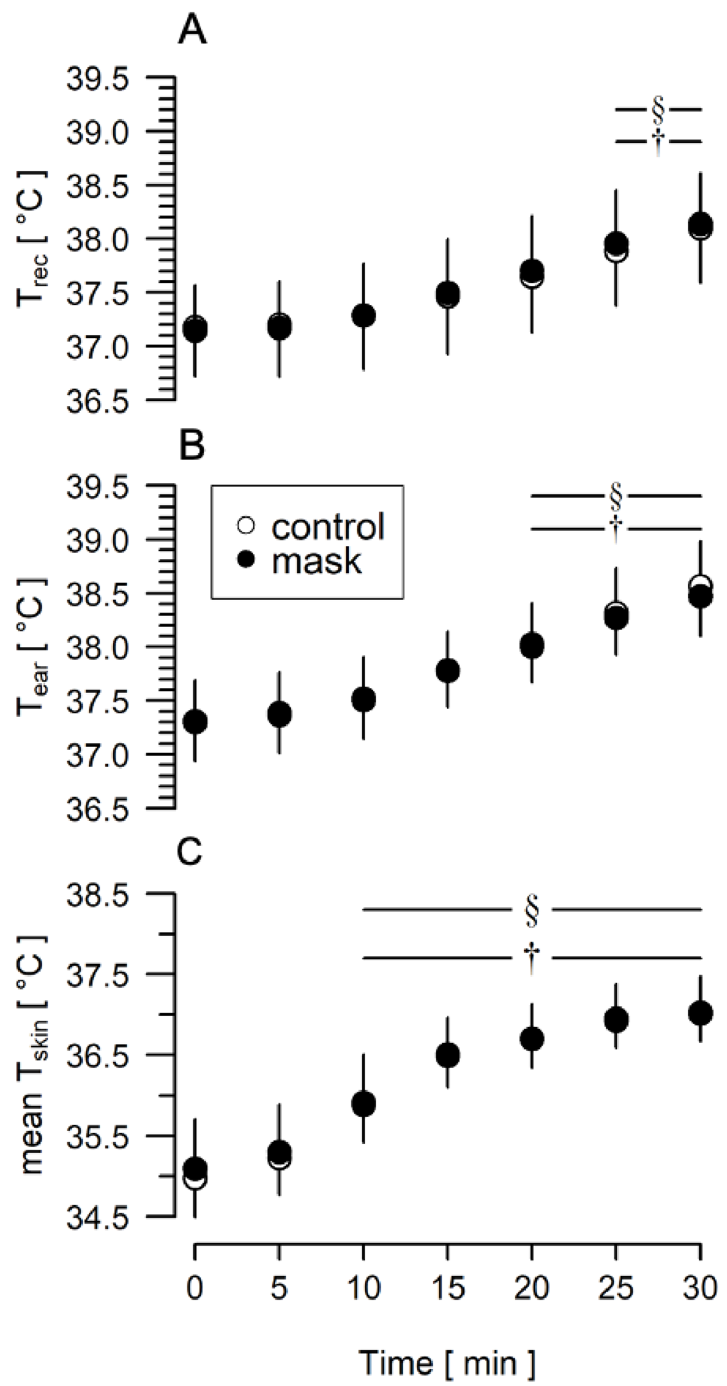
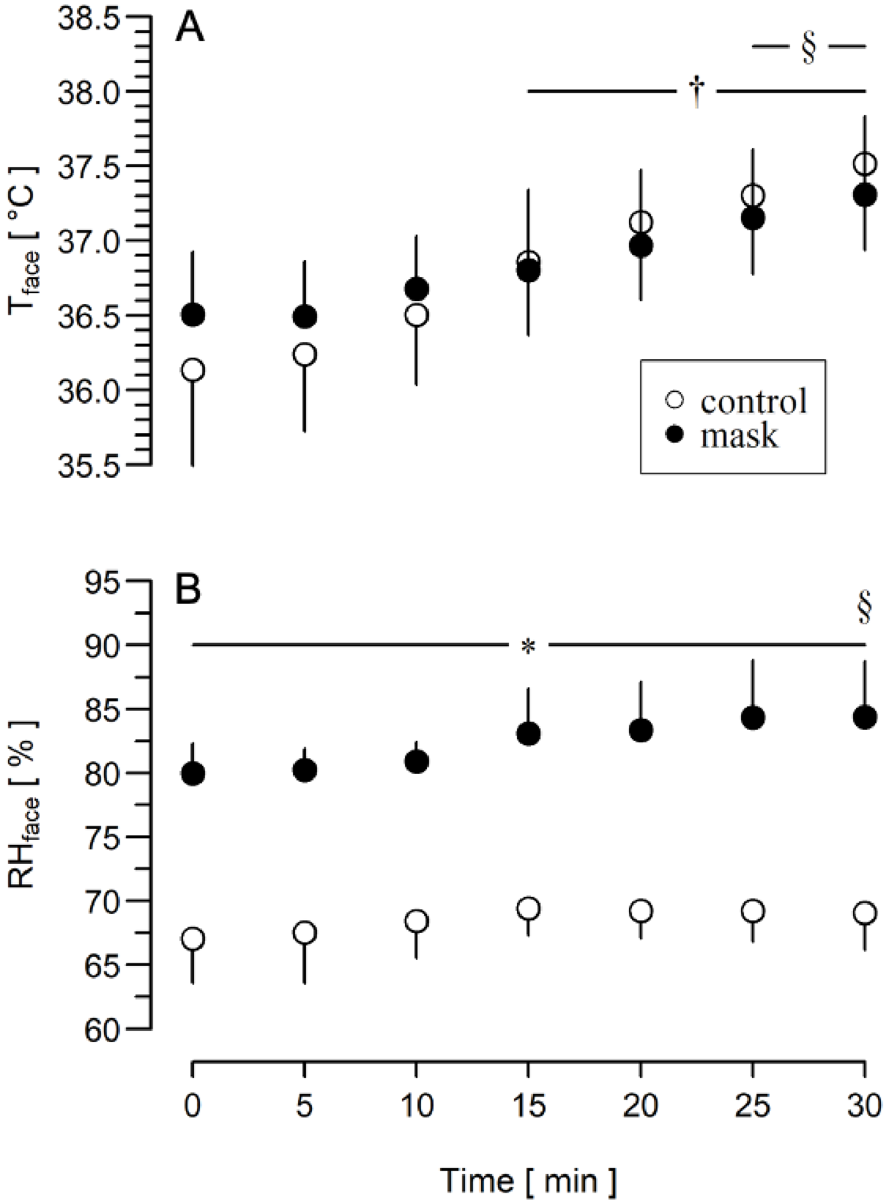

A
39.5
39.0
38.5
38.0
37.5
37.0
36.5
T_rec [°C]
§
†
B
control
mask
T_ear [°C]
C
38.5
37.5
36.5
35.5
34.5
mean T_skin [°C]
0
5
10
15
20
25
30
Time [min]

Figure 2



A
B
38.5
38.0
37.5
37.0
36.5
36.0
35.5
T_face [°C]
§
†
control
mask
95
90
85
80
75
70
65
60
RH_face [%]
*
§
0
5
10
15
20
25
30
Time [min]

Figure 3

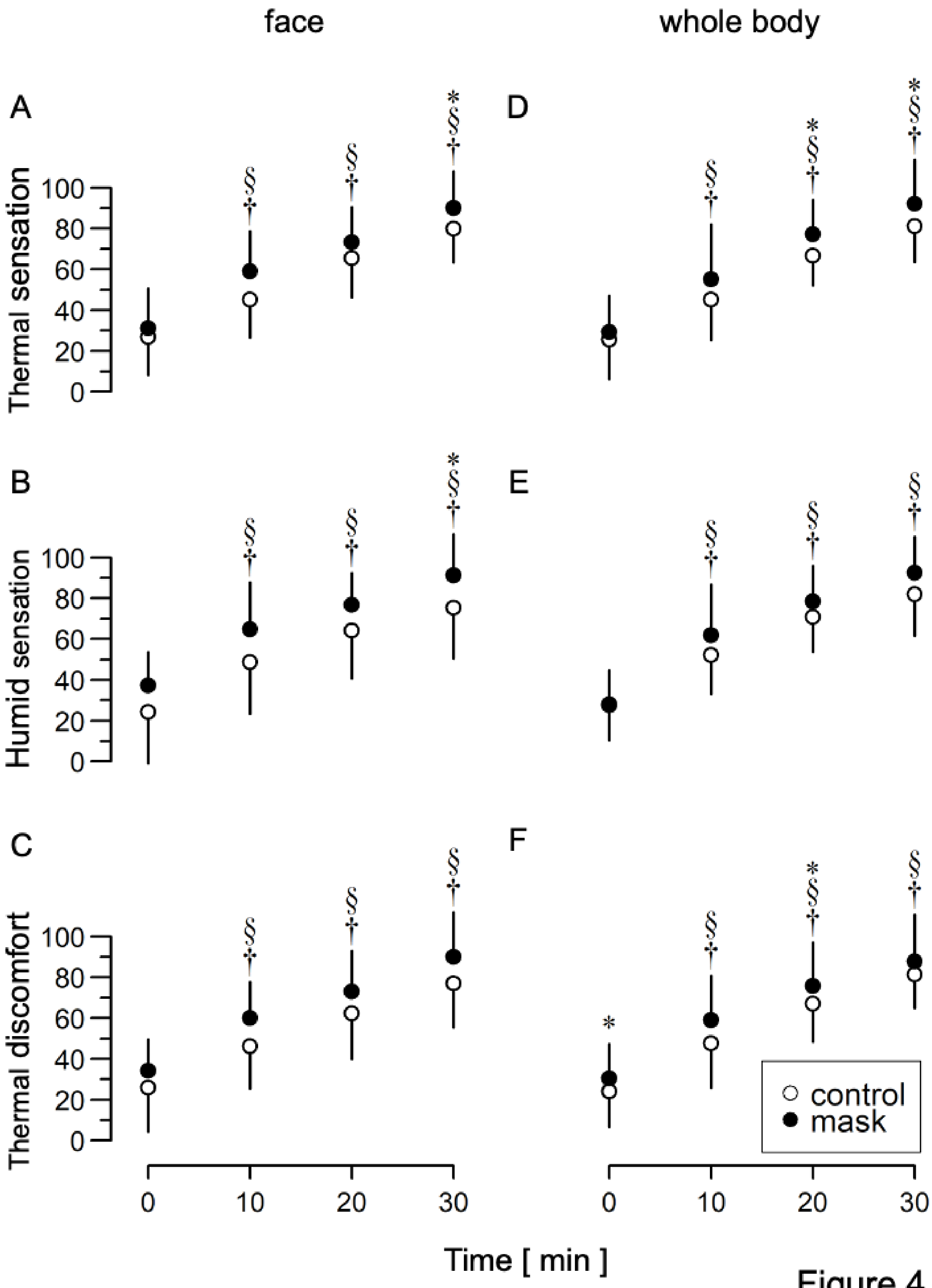

face
whole body
A
D
B
E
C
F
Thermal sensation
Humid sensation
Thermal discomfort
100
80
60
40
20
0
0
10
20
30
Time [min]
control
mask

Figure 4

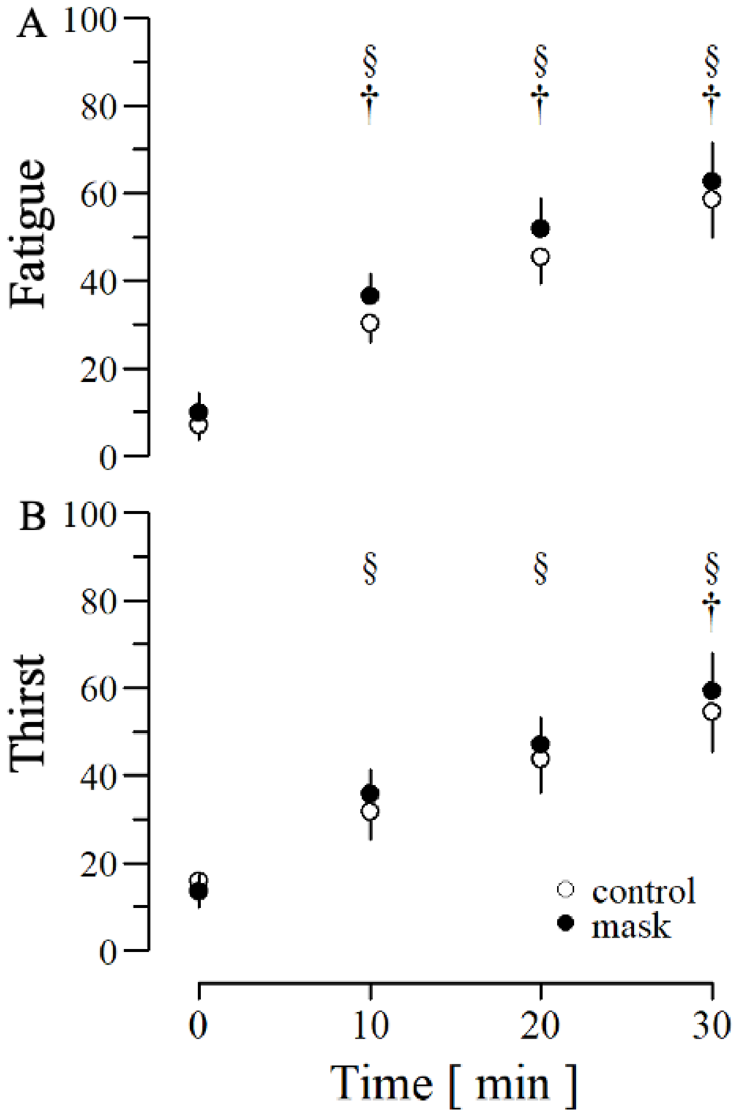

A
100
80
60
40
20
0
Fatigue
§
†
B
Thirst
○ control
● mask
0
10
20
30
Time [min]

Figure 5

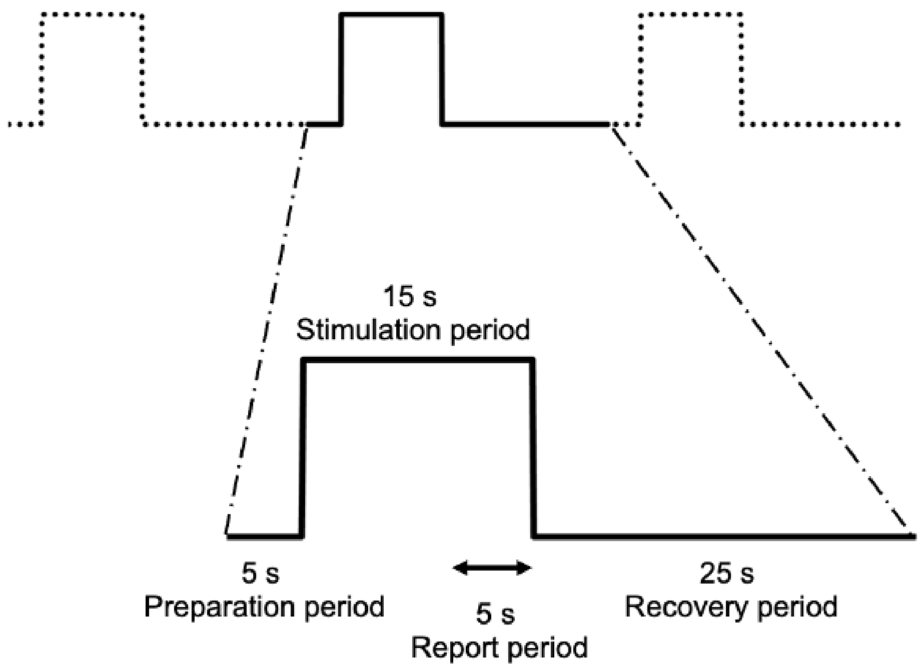
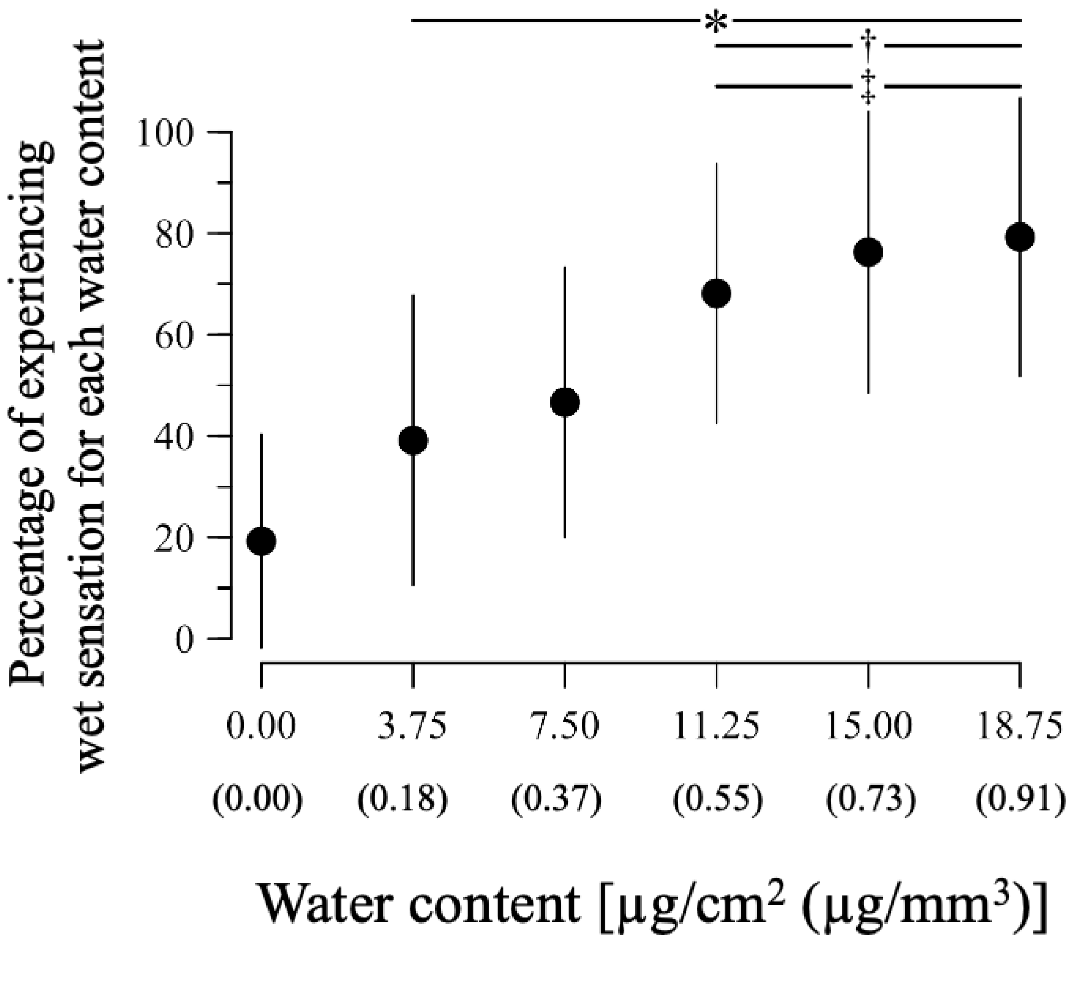

15 s
Stimulation period
5 s
Preparation period
5 s
Report period
25 s
Recovery period

Figure 6



Percentage of experiencing wet sensation for each water content
100
80
60
40
20
0
*
†
‡
0.00
3.75
7.50
11.25
15.00
18.75
(0.00)
(0.18)
(0.37)
(0.55)
(0.73)
(0.91)
Water content [μg/cm² (μg/mm³)]

Figure 7

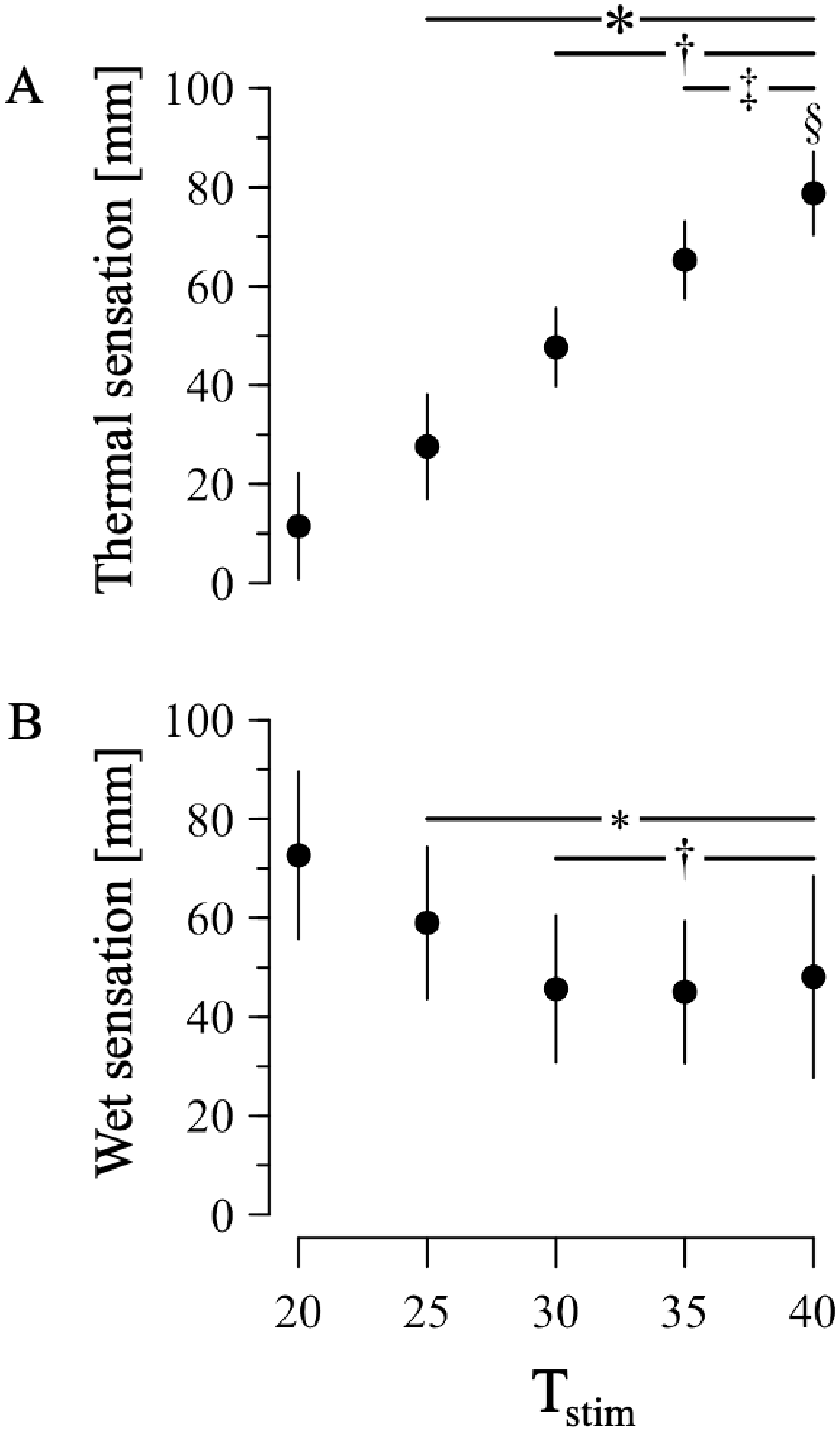

A
B
Thermal sensation [mm]
Wet sensation [mm]
100
80
60
40
20
0
*
†
‡
§
20
25
30
35
40
T_{stim}

Figure 8

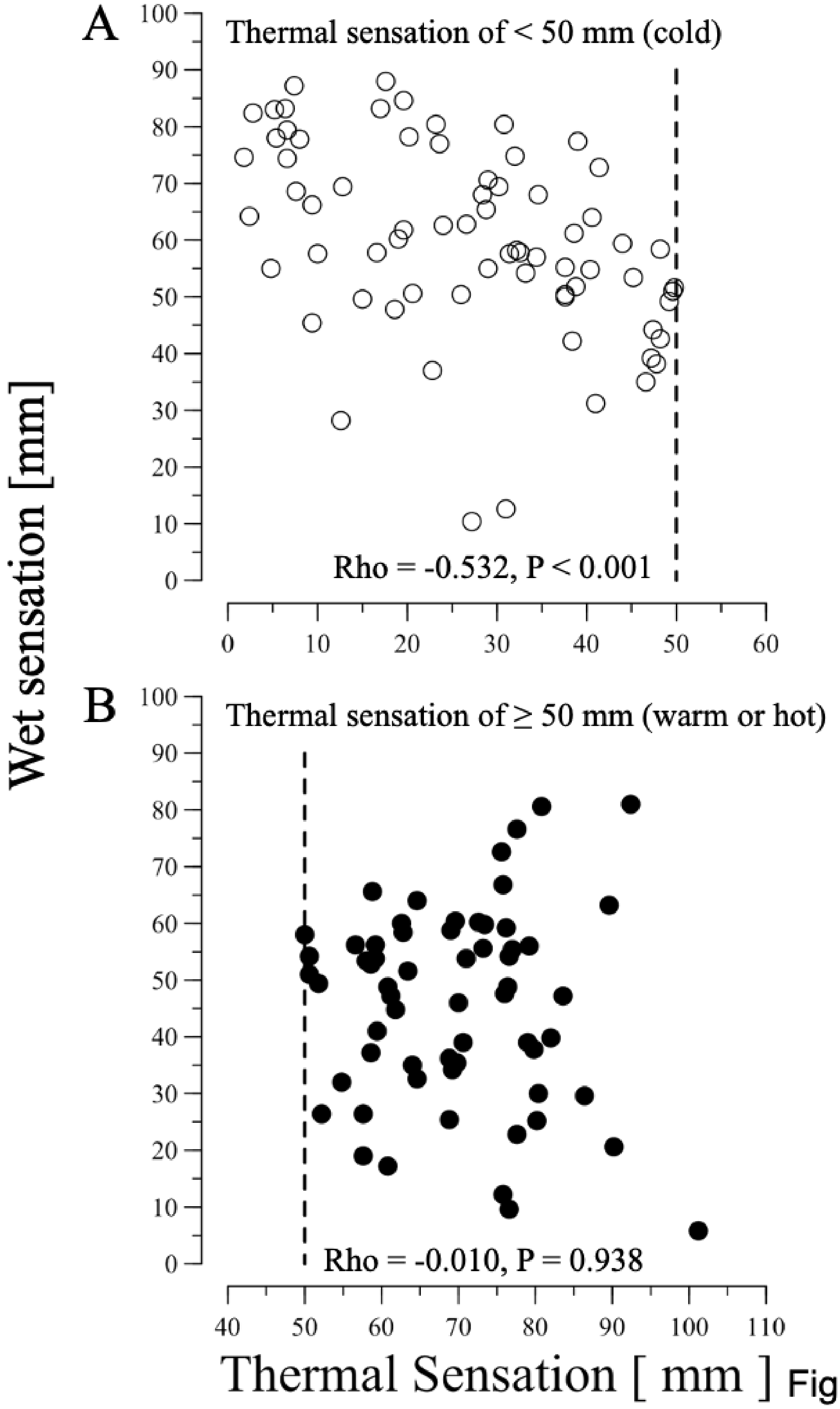

A
Thermal sensation of < 50 mm (cold)
Rho = -0.532, P < 0.001
B
Thermal sensation of ≥ 50 mm (warm or hot)
Rho = -0.010, P = 0.938
Wet sensation [mm]
Thermal Sensation [mm]

Figure 9