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Regional differences in temperature sensation and thermal comfort in humans

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General abstract

Sensations evoked by thermal stimulation (temperature-related sensations) can be divided into two categories, "temperature sensation" and "thermal comfort". While several studies have investigated regional differences in temperature sensation, less is known about the sensitivity differences in thermal comfort for the various body regions. In this study, I examined regional differences in temperature-related sensations with special attention to "thermal comfort".

In chapter 2, I reported the new system for monitoring sensations of many body parts as well as comprehensively showing the distribution of overall skin temperature and temperature-related sensations. The system's utility was demonstrated with physiological experiments. Subjects were exposed to step change of ambient temperature. This system greatly facilitates the perception and analysis of spatial relationships and differences in skin temperature and sensation in various areas of the body. And in the physiological experiments, the face tended to show stronger discomfort during heat exposure than other areas of the body, and the abdomen tended to show stronger discomfort during cold exposure.

In Chapter 3, I examined regional differences in temperature sensation and thermal comfort by applying local temperature stimulation for the face, chest, abdomen, and thigh during whole-body exposure to mild heat or cold. The thermal comfort seen in this study suggests that if given the chance, humans would preferentially cool the head in the heat, and maintain the warmth of the trunk areas in the cold. As for the thigh, although the skin temperature change was always larger than that of other areas in all conditions, thermal comfort was never strongest, indicating that the thigh is insensitive for temperature change. The head contains the brain, preference for a low facial temperature in the heat would help avoid heat-induced damage to the brain. Preference for a warm trunk area would help avoid cold-induced disorder of the internal organs. Because there are no important organs such as brain in the thigh, characteristics in thermal comfort like that of the face and trunk would not be necessary for the thigh.

In Chapter 4, regional differences in temperature sensation and thermal comfort for the neck, abdomen, hand, and sole are examined with the same methods as Chapter 3. Although there was no difference between "local" thermal comfort of the hand and neck,

thermal stimulation of the hand produced less effect on “whole-body” thermal comfort than the stimulation of the neck. And although the hand and sole showed larger skin temperature change than the neck, local and whole-body thermal comfort was never stronger for the hand and sole than the neck. These peripheral parts inevitably show large temperature fluctuation. If the peripheral parts were sensitive for whole-body comfort, we would frequently feel whole-body thermal discomfort, which should be very stressful. Therefore insensitivity of the peripheral part for thermal comfort is advantageous. As for the neck, the characteristic in thermal comfort was in between those of the face and abdomen. Because there is no important organs in the neck, characteristics in thermal comfort like that of the face and trunk would not have been developed for the neck.

Regional differences in thermal comfort investigated in this dissertation cannot be explained solely by the density or properties of the peripheral thermal receptors, and consistent with the biological roles of each body part. Therefore I speculate that a CNS map weighing the input from each body area would be involved in the production of regional differences in thermal comfort.

These knowledge will be valuable not only for physiological understanding but also for the design of a comfortable environment, and efficient clothing in such field as sports. The results would also be valuable for the optimization of nursing and athletic conditioning practices.

Contents

Chapter 1

General Introduction

In daily life or in fields of sports or nursing, we often use local cooling or warming to reduce whole-body warm or cold discomfort. Sensations evoked by thermal stimulation (temperature-related sensations) can be divided into two categories, “temperature sensation” and “thermal comfort” (37). Temperature sensation is utilized by the body to obtain information concerning the thermal condition of external objects or the environment, and is evoked by signals from warm and cold receptors in the skin. The other category of temperature-related sensations, thermal comfort (which in this paper also embraces thermal discomfort) is important for temperature regulation in that it drives an individual to search for the appropriate thermal environment, or to make local alterations or postural changes to maintain normal body temperature.

1. 1 Temperature sensation

Temperature sensation is divided into “warm sensation” and “cold sensation”. Painful hot sensation and painful cold sensation are evoked by temperature above 45ºC and below 17ºC respectively. Further on strong heat stimulation above 45 ºC one can feel a peculiar quality of cold that has been called “paradoxical cold sensation” (1, 30, 31, 37, 86). Both warm and cold sensation have static and dynamic components.

Static temperature sensation (adaptation)

While constant temperatures nearby skin temperature evoke instant warm or cold sensation, the temperature sensation disappear (adaptation). The temperature range that the adaptation occur is called “neutral zone”. Above or below the neutral zone, even long and constant temperatures evoke cold or warm sensation. For example, the neutral zone is 30 - 36 ºC for the thermal stimulation of 15 cm^2 to the forearm (43). The bigger magnitude of skin temperature changes, the longer time required for the adaptation (36).

Dynamic temperature sensation

To investigate the characteristics of dynamic thermal sensation, detection threshold to warming and cooling were often measured applying equal cooling or warming steps at various adapting temperature. The dynamic thermal sensations depend on i) rate of skin temperature change, ii) adapting temperature, iii) stimulus area.

When a small cutaneous area (e.g. 20 cm^2) is adapted to a temperature of 34 ºC, the subject will feel neither warm nor cold. Linear temperature rises from this point of indifference lead to warm sensations, linear cooling to cold sensations. The threshold of warm or cold sensations deviates the more from this point, the slower the temperature is changed. By plotting the rate of change versus the thermal threshold, a hyperbolic function is obtained (Fig. 1-1) (37).

Starting from various adapting temperatures, the threshold for warm sensations at equal rates of warming increases with decreasing adapting temperature (Fig. 1-2) (37). An analogous behavior has been found for cold sensations. The fact that the warm thresholds increase at lower adapting temperature, while the highest cold thresholds are found at high adapting temperatures (35, 43).

Some investigations have revealed a considerable influence of stimulus area on threshold. The threshold for warm sensations at equal rates of warming increases with decreasing the stimulus area (Fig. 1-3) (36, 37, 80).

1. 2 Cutaneous thermoreceptors

The above-noted characteristics of static and dynamic thermal sensations depend on the characteristics of cutaneous thermoreceptors. In neurophysiological terms, the general properties of specific cutaneous thermoreceptors can be described as follows: i) they have a static discharge at constant temperature (*T*), (ii) they show a dynamic response to temperature change (d*T*/d*t*), with either a positive temperature coefficient (warm receptors) or a negative coefficient (cold receptors); (iii) they are not excited by mechanical stimuli; (iv) their activity occurs in the non-painful or innocuous temperature range (37).

The variety of cutaneous thermoreceptors can be divided, by the criterion of their dynamic response, into the well-defined classes of warm and cold receptors (38). Irrespective of the initial temperature, a warm receptor will always respond with an overshoot of its discharge on sudden warming and a transient inhibition on cooling, whereas a cold receptor will respond in the opposite way, namely, with an inhibition on warming and an overshoot on cooling. Besides this dynamic behavior there are also typical differences in the static frequency curves of both types of cutaneous receptors, in that the temperature of the maximum discharge is much lower for cold receptors than it is for warm receptors (37).

Cold receptors

At constant skin temperature in the normal range all cutaneous cold receptors exhibit a static discharge with constant impulse frequency. The static impulse frequency of individual cold receptors rises with temperature, reaches a maximum and falls again at high temperature. For various cold fibers in different species the static maxima are scattered over a temperature range from -5 to 40ºC. The average static maxima of larger cold fiber populations in various skin areas are rather similar, ranging from 25 to 30ºC in monkeys, cats, and rats (Fig. 1-4) (27, 37, 42).

Cold fibers show a dynamic response to cooling steps. When equal cooling steps are applied at various adapting temperatures, the dynamic overshoot is a function of temperature and follows approximately the shape of the static activity curve (37, 44). The higher the rate of cooling at a given adapting temperature, the higher is the dynamic responses (35, 57). Likewise the larger the magnitude of temperature decrease is, the more frequent the dynamic responses become (22).

Warm receptors

At constant temperature, warm receptors exhibit a static discharge that begins in the range above 30ºC, increases its frequency with rising temperature and decreases again at still higher levels. The maximum static frequency of individual warm receptors in various species is scattered over a temperature range from 41 to 47ºC (Fig. 1-4) (35, 37, 39, 42, 47).

Dynamic activities of warm receptors are also influenced by initial temperature, rate of warming, and the magnitude of temperature increase like the cold receptors (46).

These properties of cutaneous thermoreceptors should depend on function of a subset of the transient receptor potential family of ion channels, which are expressed in sensory nerve endings and in skin, respond to distinct thermal thresholds (Thermo TRPs) (24).

1. 3 Distribution of peripheral warm and cold spots over the body surface

While it is difficult to quantitatively evaluate differences in the density of skin thermoreceptors in humans, the density of “warm and cold spots” would be expected to correlate positively with the density of warm and cold receptors (37). The distribution of warm or cold spots was investigated by using pointed thermal stimulators and counting warm or cold sensitive points per a certain area over the various body surfaces. The distribution of peripheral warm and cold spots over the body surface is not uniform (Fig. 1-5, 6) (49, 69, 82, 85). The cold spots are particularly dense for the face and trunk areas, especially for the lips, least for the foot and lower legs, and intermediate for the upper limbs and thigh. As for the warm spots, while the density is less than the cold spots, the face has particularly dense warm spots, on the other hand the sole has the thinnest dense.

1. 4 Regional differences in temperature sensation

Interestingly, the sensitivity of temperature sensation is not uniform, but rather depends upon the body region. The regional difference in the ability of detecting thresholds to warming and cooling should be related to the distribution of the warm and cold spots. Among the body surface the thresholds were lowest for the face, especially the lip, and highest for the calf and foot (79). As for suprathreshold thermal sensitivity, although high enough levels of warm stimulation were estimated to feel nearly the same to all body regions, low to moderate levels of warm stimulation were estimated to feel warmest in the forehead, intermediate in the torso, and least warm in the limbs (80). Further the forehead showed a much greater suprathreshold cold sensitivity, than back, lower leg, chest, thigh, and abdomen in a 39ºC environment (19). However, in neutral ambient temperature, the head was least sensitive to cold as compared with trunk and limbs (77). Thus, regional temperature sensitivity might depend on thermal conditions of environment.

1. 5 Afferent innervation and receptive fields of temperature sensation

Neurons responding to innocuous thermal stimulation of the skin are located in the lamina I of the spinal cord (25, 32). Signals from these neurons then reach the thalamus, mainly in the posterior part of the ventral medial nucleus (V_{mpo}) in primates (17). Recent studies on humans that utilized positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) have shown that thermal signals from skin seen to reach several regions in the cerebral cortex, including the insula, primary and secondary somatosensory (SI and SII), orbitofrontal, and cingulated cortices (7, 18, 23, 76).

1. 6 Body temperature regulations

In both the heat and cold, homeothermic animals utilize behavioral and autonomic effecter responses to regulate their body temperature (40, 62). As behavioral responses, animals seek preferable thermal environment or change posture. We human beings take on or off clothes or just turn on air-conditioner. Behavioral thermoregulation are driven by "thermal comfort/discomfort". Because behavioral responses, when available, are quicker and less energetically costly than autonomic responses, the behavioral responses are activated before autonomic responses. However, if these behaviors are not fully effective or do not fulfill the immediate thermal requirements, autonomic responses are activated. For example, as an autonomic process, human beings dilate the skin blood vessels in the heat, which redistribute warm blood in the body core to the body surface and increase dry heat loss. We also sweat to facilitate evaporative heat loss. In the cold, human beings constrict the skin blood vessels, and decrease heat loss from the skin surface. We also generate heat by increasing muscle tonus (shivering thermogenesis) or by activating metabolism in the brown fat cells (non-shivering thermogenesis), which is seen in neonates and disappears in adults. The autonomic and behavioral regulations in both the heat and cold are produced by signals from thermoreceptors of the body (40, 62). The thermoreceptors are distributed in the skin, the hypothalamus and other brain areas and the body core (83). This multiple-input/output system is controlled primarily by the central nervous system. The hypothalamus in the brain plays a central role in autonomic thermoregulation (28). Especially, the preoptic area (PO) in the hypothalamus is thought to be the most important region (40, 62). Although we know little about the mechanism involved in behavioural thermoregulation, Satinoff et al. reported that lesions of the lateral hypothalamus resulted in loss of behavioural thermoregulation (75).

1. 7 Thermal comfort

As mentioned above, thermal comfort is important for body temperature regulation in that it drives an individual to search for a better environment to maintain optimal body temperature. While temperature sensation is not affected by body core temperature, thermal comfort depend on the thermal state of the body (5, 6, 14, 48, 59). For example, the hand warming produces a comfortable or uncomfortable feeling when the individual is “hypothermic” or “hyperthermic”. A thermal stimulation is felt comfortable when it serves to regain appropriate body temperature, and felt uncomfortable when it worsens internal thermal conditions. Humans have little problem discerning local from whole-body sensations for thermal comfort. For example, during cold exposure if one dips the hands into warm water he/she would feel local comfort of the hand but simultaneously whole-body discomfort would remain.

The hypothermia or hyperthermia is not determined by the absolute body temperature, it depends on the level at which body temperature is regulated (set point). Therefore, when the body temperature is lower than the set point, it is called hypothermia, and when the body temperature is higher than the set point, it is called hyperthermia. In normal condition human body temperature is maintained around 37ºC, therefore the set point is around 37 ºC.

Fever has been extensively reviewed (9, 45, 54-56, 72). During a fever’s first phase, autonomic effectors and thermoregulatory behaviour are all modulated to increase body temperature (87). In a fever the set point shift higher level than the normal state, and body temperature of 37ºC is lower than the set point. Therefore, during a fever’s first phase, even if our body temperature is 37ºC, such a state is hypothermia, and we feel whole-body cold and uncomfortable, and we feel comfortable for warming stimuli. Such thermal comfort during a fever's first phase drives an individual to search for a warmer environment and the behaviour help to raise body temperature. Fever is beneficial for the organism in that it facilitates activation of immune system and suppresses proliferation of bacteria (10, 15, 51, 70).

Experiments on rodents (20), and humans (90, 91) have shown that for low doses of alcohol, autonomic effectors and thermoregulatory behaviour all operate to decrease body temperature, it means that the set point shift to lower level. During mild cold exposure, whole body sensations of cold and thermal discomfort were greatly diminished after drinking alcohol (Fig. 1-7) (91), and during mild heat exposure whole body sensation of hot was increased (Fig. 1-8) (90). These changes of thermal sensation and thermal comfort drives an individual to search for a cooler environment and facilitate to decrease body temperature. The decrease in body temperature after alcohol administration is beneficial. Ethanol increases the fluidity of cell membranes which interferes with many functional aspects of the cell. This disruption can be counteracted to some extent by decreasing the temperature of the cell, thus returning cell membrane fluidity to more normal levels (20).

It could be said that thermal comfortable feeling is obtained when environmental condition is appropriate for keeping optimal body temperature to maintain the organismic functions.

1. 8 Neuronal mechanism of thermal comfort

It is generally assumed that inputs from the same warm or cold skin thermoreceptors are utilized for both temperature sensation and thermal comfort, although there is no direct experimental evidence for this supposition. While the neuronal mechanism of thermal comfort is poorly understood, the amygdala, mid-orbitofrontal and pregenual cingulate cortex, and striatum, and cerebellum have been implicated in the genesis of thermal comfort (41, 71, 84).

1. 9 Previous study of regional difference in thermal comfort

Cotter and Taylor (16) assessed whole-body thermal comfort when local thermal stimulation of various skin sites was applied in mildly heat-stressed humans. While they reported that the face displayed stronger sensitivity than other body regions for producing changes in whole-body thermal comfort, they did not analyze how the stimulated site itself was locally felt. Zhang et al. (92) and Arens et al. (2) measured both local and whole-body thermal comfort by applying local warming and cooling in a warm, neutral or cool environment. Sensitivity differences between the local areas could not be directly compared, however, because the size of local temperature stimulation was different among the areas stimulated. Attia and Engel (4) reported that the thermal alliesthesial response in man is independent of the skin location stimulated using a small thermal stimulator of 55 mm long and 27 mm wide. However, thermal pleasure does depend on the dimension of area stimulated (52). Regional differences in thermal comfort are more likely when using a larger thermal stimulator. Therefore, little is known about how the elicitation of thermal comfort, local as well as whole-body, differs among certain body regions.

1. 10 Purpose of the thesis

Understanding how the elicitation of thermal comfort, local as well as whole-body, differs among certain body regions is the goal of this study. The information will be valuable not only for physiological understanding but also for the design of a comfortable environment, and efficient clothing for such field of sports. The results will also aid in the optimization of medical, nursing, and athletic conditioning practices.

1. 11 Outline of the thesis

To these ends, I conducted three series of experiments. In **Chapter 2** a new system for monitoring sensations of many body parts as well as comprehensively showing the distribution of overall skin temperature, temperature sensation, and thermal comfort is reported. In **Chapter 3** regional differences in temperature sensation and thermal comfort are examined by applying local temperature stimulation for the face, chest, abdomen, and thigh during whole-body exposure to mild heat or cold. In **Chapter 4** regional differences in temperature sensation and thermal comfort for the neck, abdomen, hand, and sole are examined with same methods as Chapter 3. In **Chapter 5** I discus the mechanisms for the production of regional differences in temperature sensation and thermal comfort, and limitation and future direction of this study.

1. 12 Published papers concerned with this dissertation

This dissertation is based on the following manuscripts and a book.

1. Nakamura M, Yoda T, Crawshaw LI, Yasuhara S, Saito Y, Kasuga M, Nagashima K, and Kanosue K. Regional differences in temperature sensation and thermal comfort in humans. J Appl Physiol (in press, 2008).

2. Yoda T, Crawshaw LI, Saito K, Nakamura M, Nagashima K, and Kanosue K. Effects of alcohol on autonomic responses and thermal sensation during cold exposure in humans. Alcohol 42: 207-212, 2008.

3. Nakamura M, Esaki H, Yoda T, Yasuhara S, Kobayashi A, Konishi A, Osawa N, Nagashima K, Crawshaw LI, and Kanosue K. A new system for the analysis of thermal judgments: multipoint measurements of skin temperatures and temperature-related sensations and their joint visualization. J Physiol Sci 56: 459-464, 2006.

4. Yoda T, Crawshaw LI, Nakamura M, Saito K, Konishi A, Nagashima K, Uchida S, and Kanosue K. Effects of alcohol on thermoregulation during mild heat exposure in humans. Alcohol 36: 195-200, 2005.

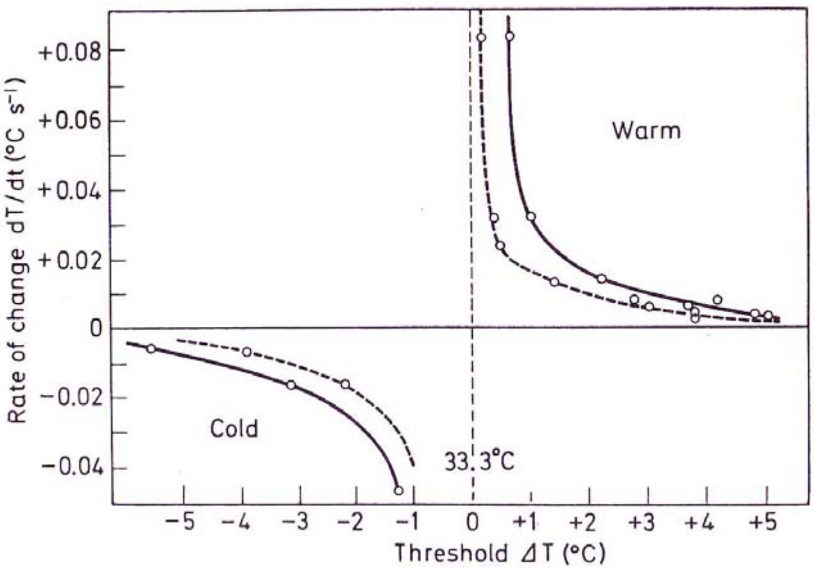

Figure 1-1. Average thresholds (ΔT) of warm and cold sensations on the forearm (20 cm^2) as a function of rate of temperature change. Dashed lines thresholds; solid lines distinct sensations. (From Hensel, 1981)

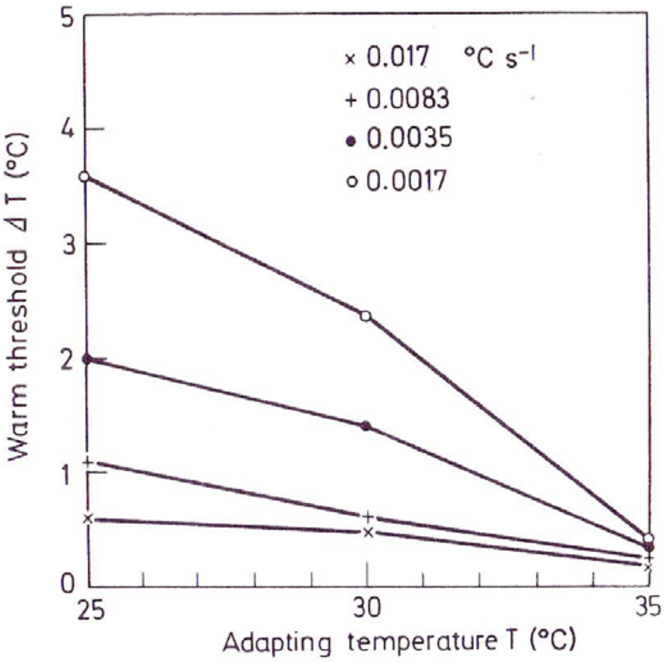

Figure 1-2. Average thresholds (ΔT) of warm on the hand as a function of adapting temperature (T) for linear temperature rises from 0.0017 to 0.017°C s^{-1}. (From Hensel, 1981)

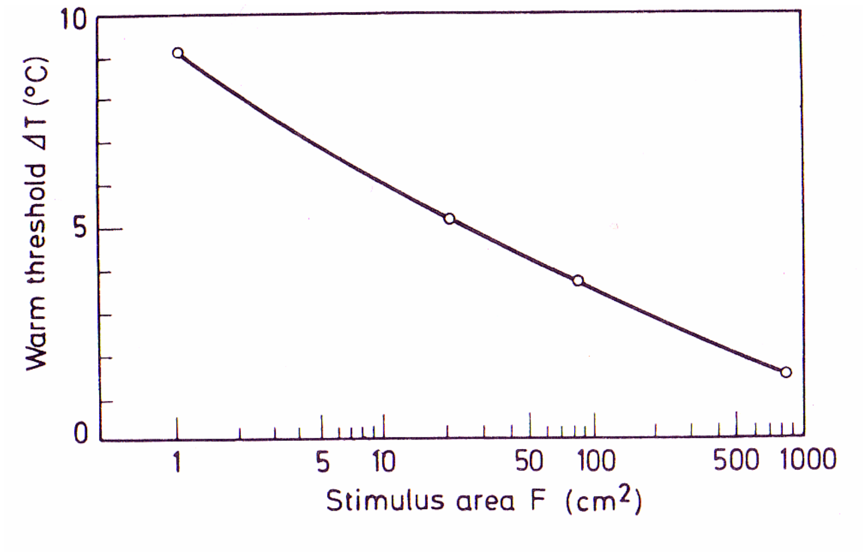

Figure 1-3. Average thresholds (ΔT) of warm sensation on the forearm for linear temperature rises of 0.017°C s^{-1} as a function of stimulus area (F). Initial temperature 30°C. (From Hensel, 1981)

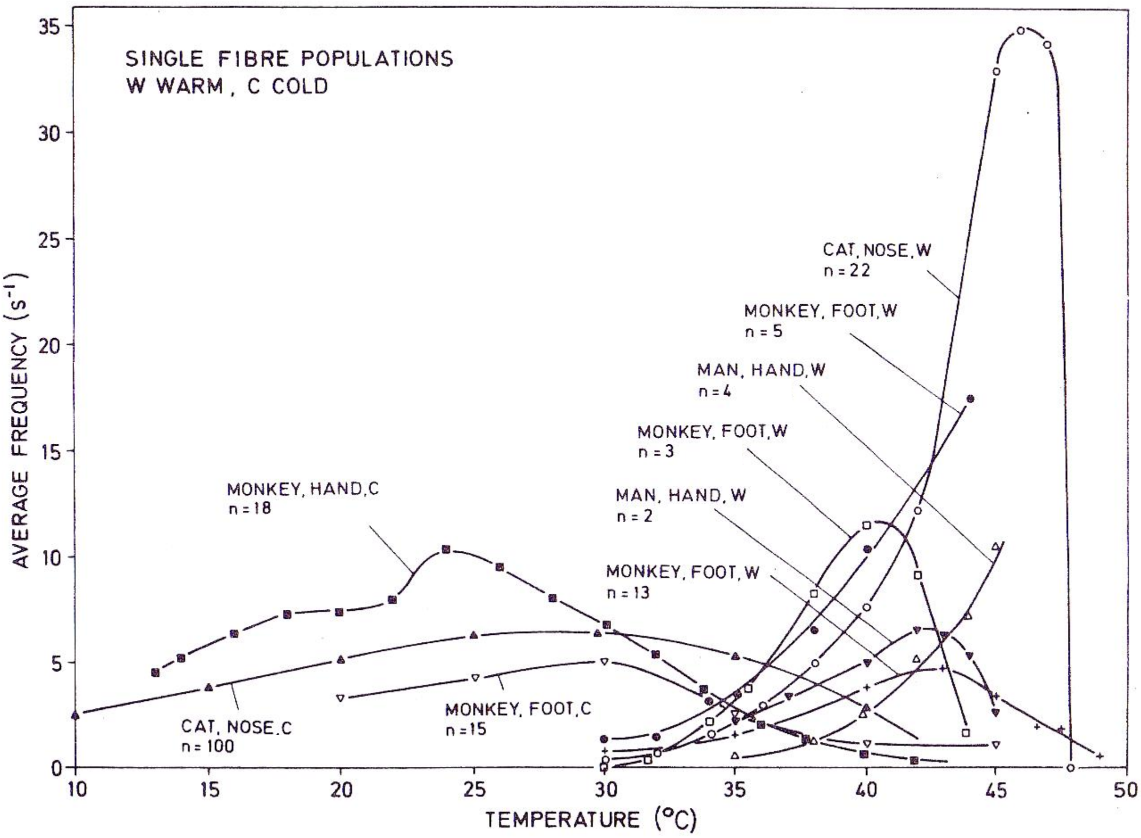

Figure 1-4. Average static discharge frequency of populations of cold and warm fibres as function of skin temperature. (From Hensel, 1981)

Cold spots

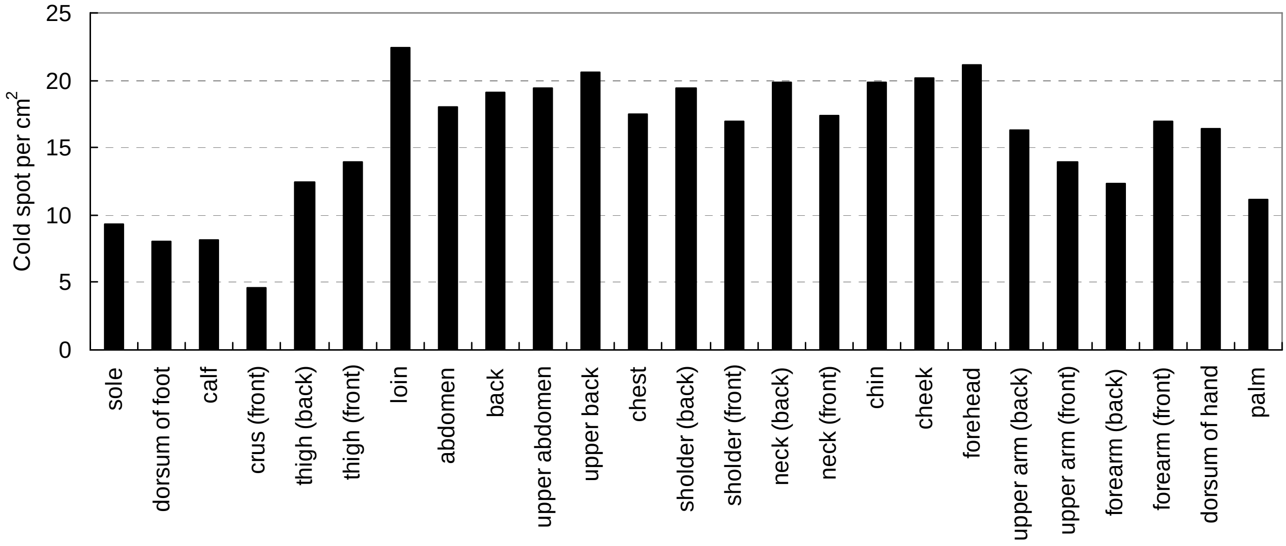

Figure 1-5. The distribution of peripheral cold spots over the body surface.
(From Lee and Tamura, 1995)

Warm spots

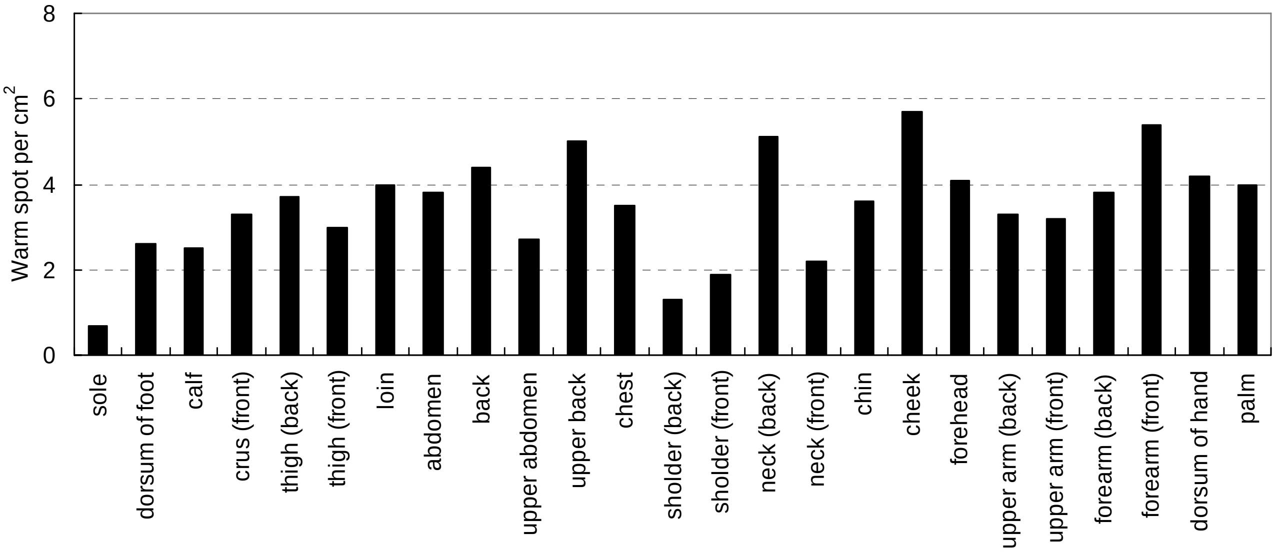

Figure 1-6. The distribution of peripheral warm spots over the body surface.
(From Tamura and Lee, 1995)

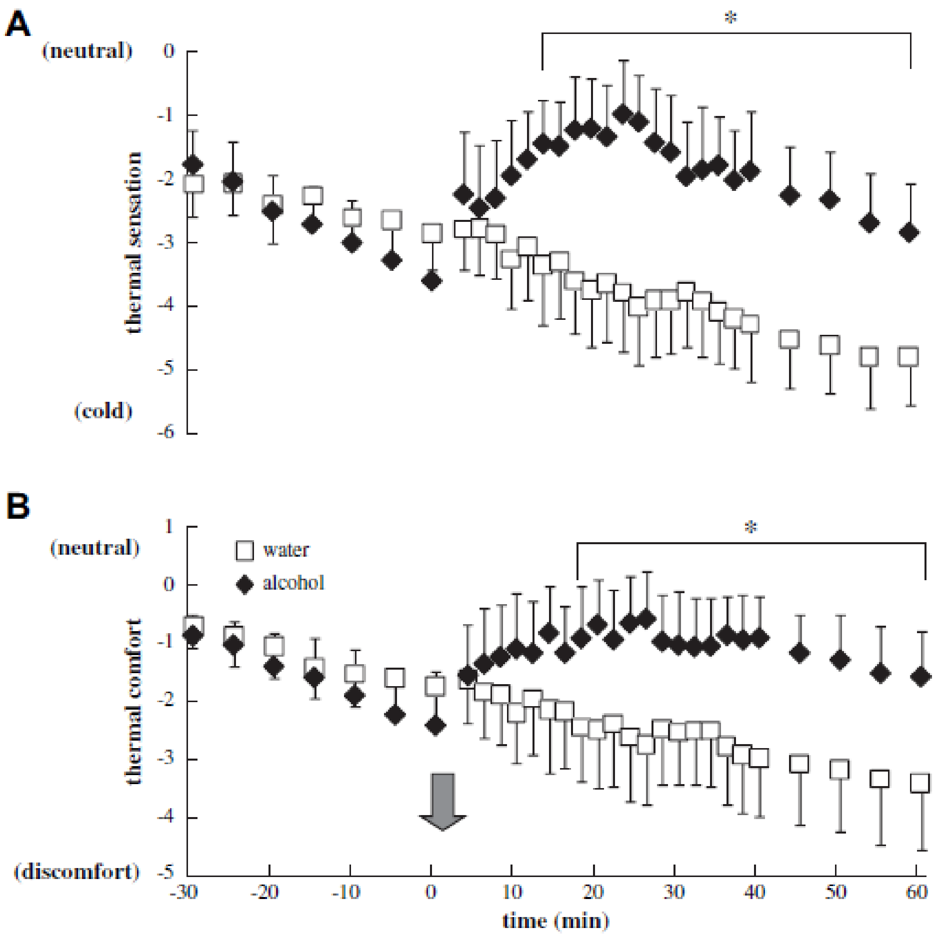

Figure 1-7 Scores of subjective (A) thermal sensation and (B) thermal comfort sensation in the alcohol and control sessions during mild cold exposure. (A) Positive and negative values indicate hot and cold sensations, respectively, and the score 0 indicates neutral (no sensation at all). Maximum score is 5 and minimum score is -5. (B) Positive and negative values indicate comfort and discomfort, respectively, and the score 0 indicates neutral. The arrow shows the time of drinking alcohol or water. Values are means ± S.E.M. (n = 8). *$P < 0.05$ (alcohol vs. control sessions). (From Yoda et al., 2008)

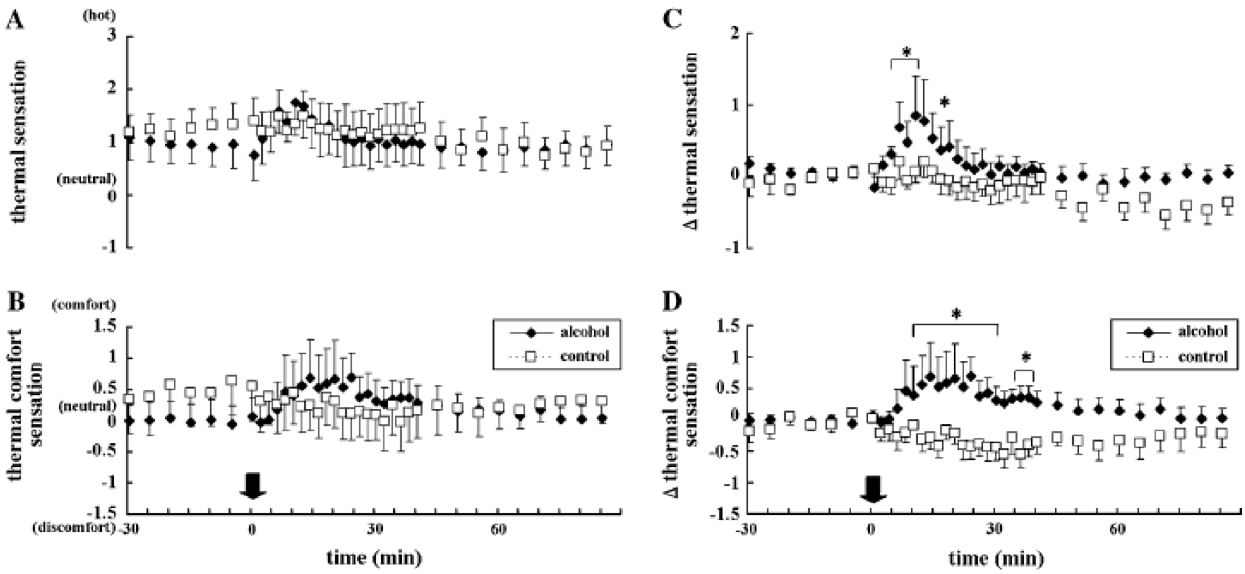

Figure 1-8 Scores of subjective thermal sensation (A) and thermal comfort sensation (B) during the alcohol and control sessions during mild heat exposure. (A) Positive and negative values indicate hot and cold, respectively, and the score 0 indicates neutral. Maximum score is 5 and minimum score is -5. (B) Positive and negative values indicate comfortable and uncomfortable, respectively, and score 0 indicates neutral. (C, D) Values which are changes from the averages in the period prior to drinking (-20 to 0 min). The arrows show the time of drinking alcohol or water. Values are means ± S.E.M. (n = 8). *P < 0.05, alcohol versus control sessions. (From Yoda et al., 2005)

Chapter 2

A new system for the analysis of thermal judgments: multi-point measurement of skin temperatures, temperature related sensations, and their joint visualization.

2. 1 Introduction

To investigate detailed regional sensitivity in temperature-related sensations (temperature sensation and thermal comfort), a global assessment of T_{sk} is necessary. However to estimate the thermal state of the body surface, skin temperature (T_{sk}) is generally measured from a limited number of points (usually less than 10) and averaged to get a mean skin temperature (mean T_{sk}). While infrared thermography is commonly used for this purpose, it has limitations: *e.g.,* it can not detect the T_{sk} of areas that are covered with clothes or that do not directly face the camera. Multi-point measurement of sensations is also required to clarify the regional sensitivity of temperature-related sensations. While verbal reporting is typically used to measure temperature-related sensations, this approach is inconvenient for a large number of skin loci which must be assessed in rapid succession. For the present study we developed a new system to analyse the distribution of whole body skin temperature and temperature-related sensations. Therefore, I directly measured T_{sk} at 50 locations and concurrently obtained measurements of local temperature sensation and thermal comfort at 25 locations. I created a computer-generated display of the data in order to facilitate visualization and interpretation of the results. To evaluate the system I conducted a physiological experiment in which human subjects were exposed to heat and cold. I confirm the utility of the new system in that the overall characteristics of T_{sk} and temperature-related sensations can be easily obtained and displayed in a format that is easy to comprehend.

2. 2 Methods

The system for monitoring sensations of many body parts

Temperature sensations and thermal comfort at 25 areas of the body surface (head, chest, abdomen, neck, back, lumbus, buttocks, as well as right and left of upper arm, forearm, dorsum of hand, palm, anterior thigh, posterior thigh, lower leg, instep, sole), plus those of the whole body are reported with a console of 52 levers (Fig. 2-1). Levers in the upper row are used for the report of thermal comfort and levers in the lower row are used for the report of temperature sensations. There are 26 levers in each row; one lever is used for reporting overall sensation and the others are used for reporting local sensations of the 25 body areas. The levers can be moved up and down on a 5 cm straight line. The center of the line represents "neutral" (neither pleasant nor unpleasant for thermal comfort, and neither cold nor hot for temperature sensation). Moving the lever up represents increasing degrees of comfortable or hot (depending on the lever) and moving the lever down represents increasing degrees of uncomfortable or cold (depending on the lever). Increasing the distance of the levers from the center of the line produces increases in voltage, which are stored in a computer. The voltage is calibrated to correspond to the score of the relative intensity of the sensations that are defined to be from -5 (the lowest point of the scale) to +5 (the uppermost point of the scale).

The data of T_{sk} measured from 50 sites of the body (Fig. 2-2) and local temperature-related sensations displayed on the human body model with custom made software are illustrated in Fig. 2-3. The body model is divided into 25 parts. The data obtained from each body part are displayed with color coding. The model can be rotated so that the distribution of T_{sk} and the sensations are visible from any angle.

Human experiment (Experiment 1 and 2)

The experiments were done with three males (mean ± S.E.M., age 32.3 ± 9.9 years, W 79 ± 7 kg, H 1.76 ± 0.02 cm) and three females (age 23.3 ± 2.4 years, body weight 55.8 ± 6.5 kg, height 1.63 ± 0.07 cm). Each subject gave informed consent for the experimental protocol, which was approved by the Human Research Ethics Committee in School of Sport Sciences, Waseda University.

Subjects fasted from 7:00 AM on the day of the experiment. They arrived at the laboratory at 8:30 AM, dressed in a T-shirt and short pants, and entered the environmental chamber which was maintained at 25°C (Experiment 1) or 30°C (Experiment 2) with relative humidity 50%. Subjects rested in a sitting position while all measuring devices were applied. Next, they were exposed to step changes of ambient temperature (T_a). In Experiment 1, the order was cold (23°C, 80 min), neutral (28°C, 80 min), and hot (33°C, 80 min); in Experiment 2, step changes were of the reverse order but of the same duration. Relative humidity at each step was 50%. T_{sk} at 25 sites on each side of the body (total = 50 sites) was measured with copper-constantan thermocouples (Fig. 2-2). Core temperature (T_{co}) was measured with a telemetry system (CoreTemp2000, HTI Technologies, Inc.). For this measurement a transmitter pill was swallowed 3.5 hour before the initiation of the experiment. T_{sk} and T_{co} were recorded every 30 seconds. Temperature sensations and thermal comfort at 25 areas of the body surface and those of the whole body were reported by the subjects using the aforementioned console. The subjects were instructed that the upper and lower extents of the console lever indicated the greatest sensation. Each sensation was reported by subjects whenever they felt a change; the data were recorded every 30 seconds along with T_{sk} and T_{co}.

2. 3 Results

Fig. 2-4 shows overall thermal states and overall temperature-related sensations averaged for the six subjects of Experiments 1 and 2. Mean T_{sk} was calculated utilizing the formula of Hardy and DuBois (33). Mean T_{sk} increased and decreased with corresponding changes of T_a. T_{co} was maintained about 37°C throughout all experiments. In Experiment 1 scores of overall temperature sensation and thermal comfort were “cold” and “unpleasant” at a T_a of 23°C, shifted to “neutral” at 28°C, and gradually became “hot” and “uncomfortable” at 33°C. In Experiment 2 the “hot” and “uncomfortable” sensation at a T_a of 33°C was greater than that of Experiment 1, and became “neutral” at 28°C, and immediately became “cold” and “uncomfortable” at 23°C.

Fig. 2-5 shows the color coding presentation on the human model of local T_{sk}, scores of local temperature sensation, and local thermal comfort. These values are the averages for the six subjects, for the last 10 minutes at each T_a level. With this display, regional differences in T_{sk} and the sensations, and changes of them in different conditions, can be easily seen. In Experiment 1, at a T_a of 23°C, T_{sk} decreased mainly in the distal appendages, and the local cold sensation and discomfort were strongest on the instep. Interestingly, though the trunk area was at a higher temperature than that of the limbs, the same degree of cold discomfort as the limbs was shown by the abdomen. At a T_a of 33°C in both Experiments 1 and 2, the difference in T_{sk} among body areas was small, although local hot sensation and discomfort were particularly strong in the head area. In Experiment 2, at a T_a of 23°C, while the overall distribution of T_{sk} was similar to that of Experiment 1, the local cold sensation and discomfort extended to a wider area than in Experiment 1.

Fig. 2-6*A* shows the relationships between T_{sk} and local thermal comfort for the 25 body areas at the end of the T_a 23°C steps of Experiments 1 and 2. In Experiment 1, T_{sk} of the instep was the lowest and showed the strongest cold discomfort (blue arrow in Fig. 2-6*A*).

In Experiments 1 and 2, T_{sk} of the abdomen shows the highest temperature, but relatively stronger thermal discomfort due to cold was shown (green arrows in Fig. 2-6*A*). Fig. 2-6*B* shows the relationships between T_{sk} and local thermal comfort at the end of the T_a 33°C steps of Experiments 1 and 2. The difference in the T_{sk} among each of the body areas was small, but local unpleasantness in the heat was particularly strong in the head area (red arrows in Fig. 2-6*B*).

2. 4 Discussion

The recording of verbal reports is often used to assess temperature-related sensations. This technique is difficult to utilize when many body regions are being monitored. By using the console developed in the present study, subjects only moved the levers when they felt a change in the sensations at a particular body region. In the present experiments, T_a was changed in steps, and maintained at each step for a long period. When T_a was stable, subjects moved the levers much less frequently. When the ambient temperature was changed, however, sensations changed markedly, and the subjects had to move many levers in rapid succession. Nevertheless, this procedure is easier and more straightforward than would have been the case with recording verbal responses.

In the present study I measured local skin surface temperatures and temperature sensations and thermal comfort concurrently and in detail. Although it may seem time-consuming to set up so many temperature sensors, if it is done systematically it takes only an hour and the subjects are not unduly constrained. Since it is very difficult to interpret this volume of data if all numerical values are plotted against time, I developed software to visualize the distribution of T_{sk}, temperature sensation, and thermal comfort. Infrared thermography is generally used to obtain such a temperature distribution of the entire body surface. But, since the measured areas must be visible from the camera, many areas cannot be assessed. With the present system, the whole body surface, including areas covered by clothing, could be displayed on a human body model. In addition, the distribution of temperature-related sensations could also be displayed on an identical model. The resulting display makes it easy to perceive spatial relationships and differences in temperature and the temperature-related sensations of the various areas of the body surface.

Although the present experiment was performed largely for establishing the validity of the new system, several interesting aspects of sensitivity in temperature sensation and thermal comfort were obtained and will be noted. At the T_a 33°C step of Experiment 1, overall hot and uncomfortable sensations were weaker than those of Experiment 2 (Fig. 2-4). In Experiment 2, before the experiments started, subjects were exposed to T_a 30°C for about 100 min. But in Experiment 1, before the T_a 33°C step, subjects were exposed to T_a 23°C and 28°C. Thus in Experiment 1, T_{co} tended to be lower than at the T_a 33°C step of Experiment 2. This probably caused weaker hot and uncomfortable sensations in Experiment 1. On the other hand at the T_a 23°C step of Experiments 1 and 2, though previous conditions were different (In Experiment 1, T_a before the start of the experiment was 25°C), differences in the overall sensory estimations were not apparent. Further, there were no differences in the subjects' T_{co} in this case.

At the T_a of 23°C in Experiment 1, the strongest cold and the most uncomfortable sensations were felt in the feet (Fig. 2-5). However, this does not necessarily imply that the feet are the most sensitive for feeling cold. Rather, it might simply be due to a large decrease in the local skin temperature (blue arrow in Fig. 2-6*A*) caused by strong vasoconstriction in the lower extremities. On the other hand, while T_{sk} of the abdomen was the highest, relatively strong discomfort from cold was obtained (green arrows in Fig. 2-6*A*) in this area, suggesting that the abdomen is especially sensitive for the production of cold discomfort. At a T_a of 33°C, in both experiments, T_{sk} was similar over the entire body surface. However, the head area subserved input for particularly hot and uncomfortable sensations (red arrows in Fig. 2-6*B*).

In this chapter I demonstrated a new system that was useful to display the distribution of T_{sk} and local temperature related sensations. Further regional characteristics in the production of thermal comfort, especially those of 7 areas, will be described in the chapter 3 and 4.

Figure 2-1. A console with 52 levers for reporting temperature-related sensations. The levers in the upper row are used for the report of thermal comfort and those in the lower row are used for the report of temperature sensations. Among 26 levers in each row one is used to report overall sensation and the others are used to report local sensations of 25 body areas.

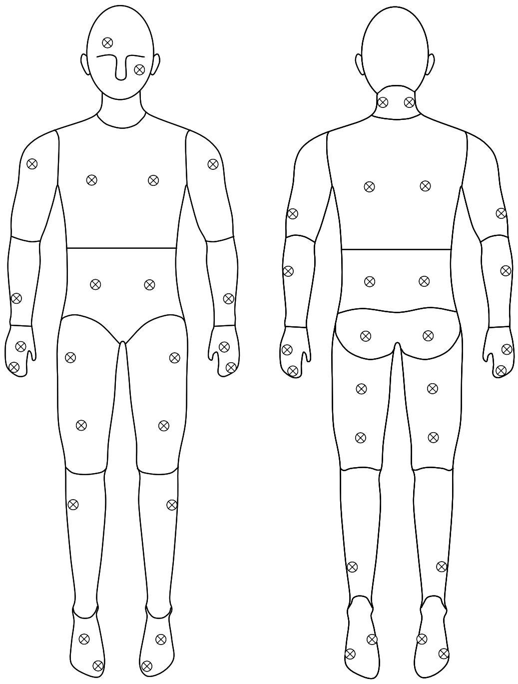

Figure 2-2. The fifty sites for skin temperature measurement.

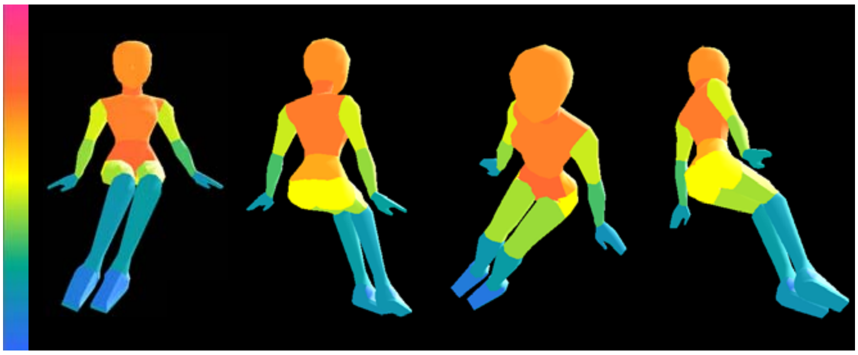

Figure 2-3. Color-coded representation of overall skin temperature. The human body model can be rotated so that it is possible to see the distribution of T_{sk} and the sensations from any angle.

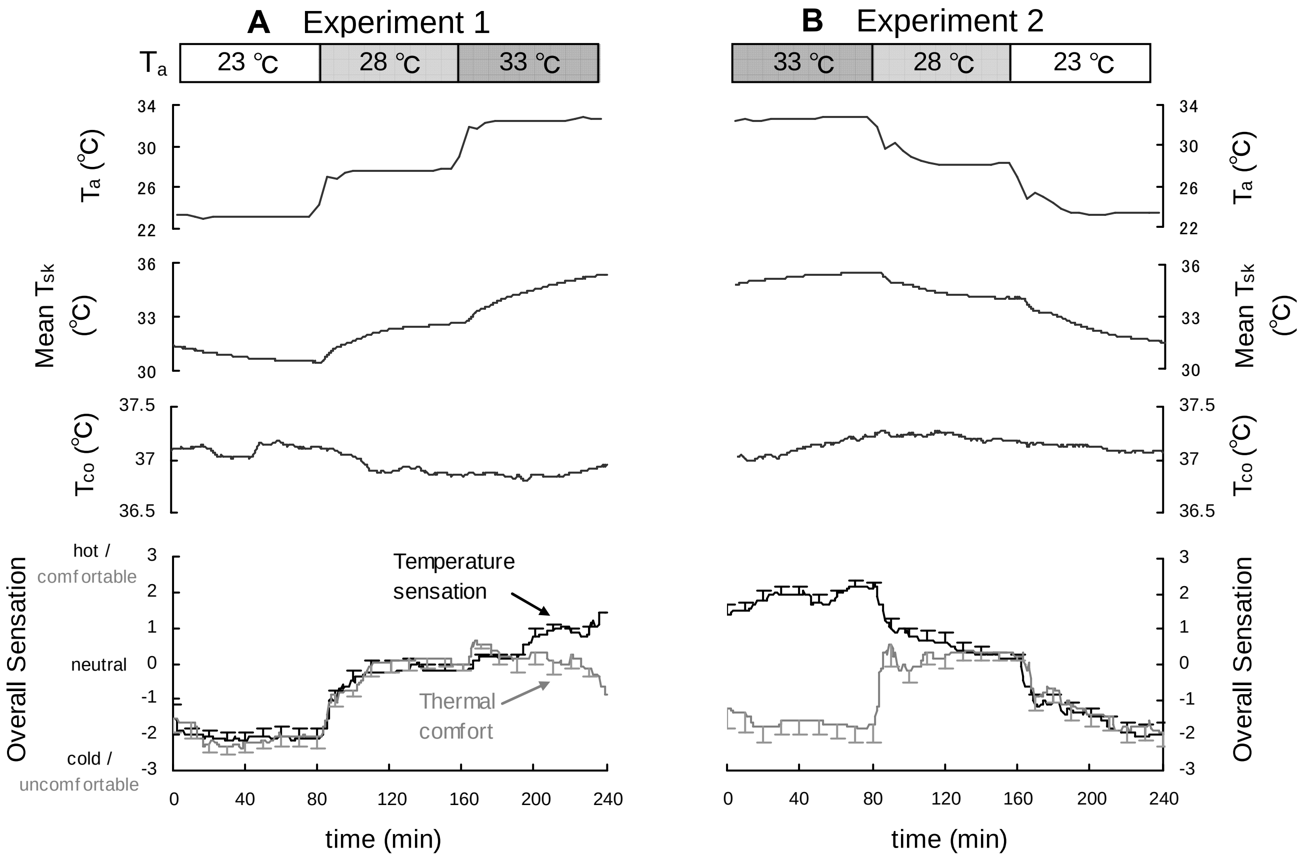

Figure 2-4. Ambient temperature (T_a), overall mean skin temperature (mean T_{sk}), core temperature (T_{co}), overall temperature sensation and thermal comfort in Experiments 1 (A) and 2 (B). Values are means ± SEM (n = 6).

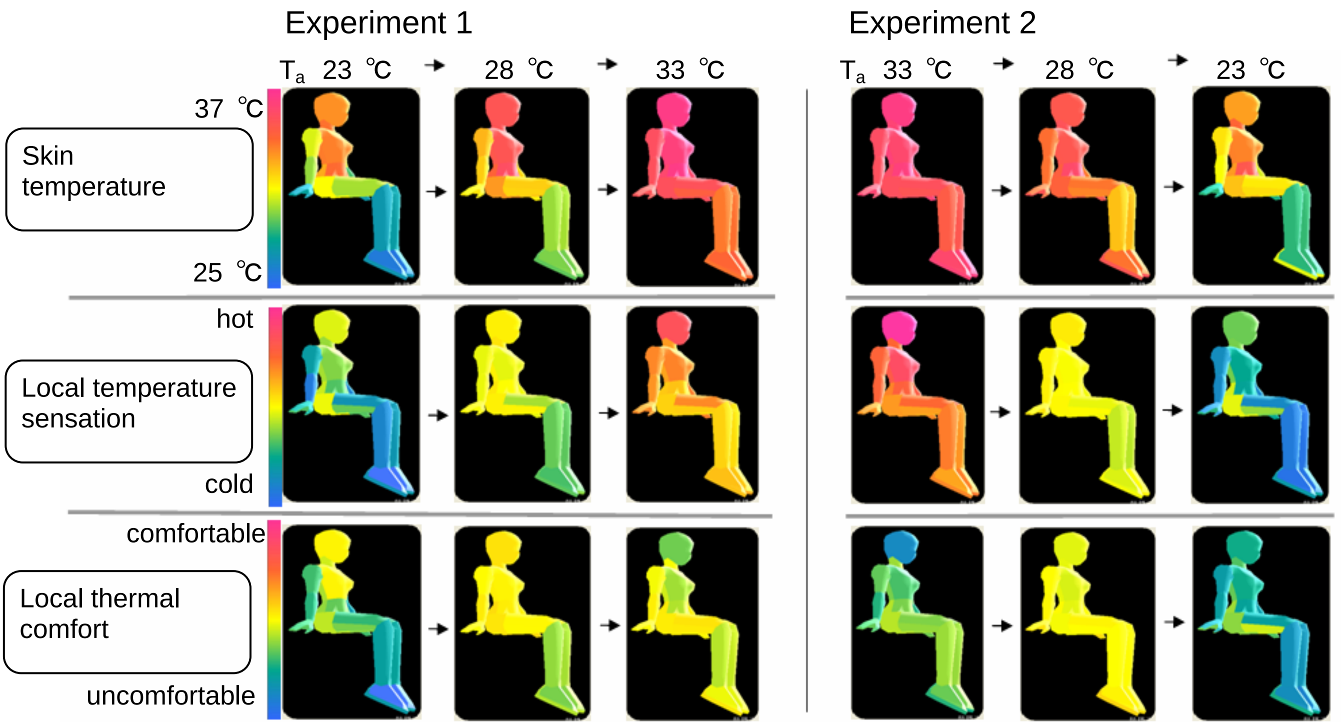

Figure 2-5. Color coded skin temperature (top), scores of local temperature sensation (middle) and the local thermal comfort (bottom) averaged for 10 minutes at the end of each T_a level in the Experiment 1 (left) and 2 (right). Values are the average for six subjects.

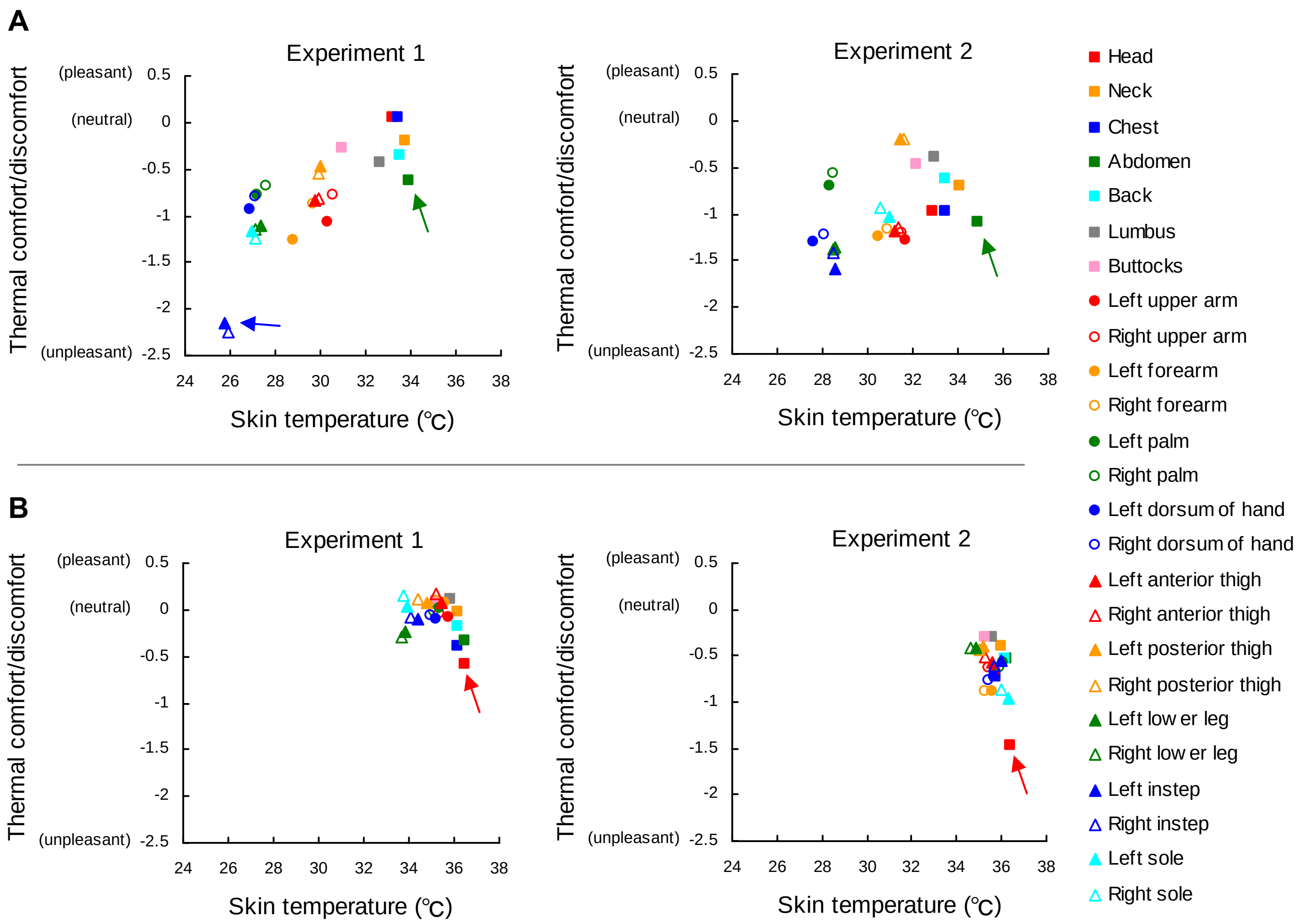

Figure 2-6. The relationships between T_{sk} and local thermal comfort for the 25 body areas averaged for 10 minutes at the end of the exposure to T_a 23°C (A) and T_a 33°C (B) in the Experiment 1 and 2. Values are means (n = 6).

Chapter 3

Regional differences in temperature sensation and thermal comfort among the face, chest, abdomen, and thigh

3. 1 Introduction

In chapter 2 I developed a system to monitor temperature-related sensations of many body locations as well as to comprehensively depict the distribution of overall skin temperature (T_{sk}) and the local sensations (64). In an initial experiment, subjects were exposed to step changes of ambient temperature from 23ºC to 33ºC and asked to assess the temperature sensation and thermal comfort at many surface areas. The face tended to show stronger discomfort during heat exposure than other areas of the body, and the abdomen tended to show stronger discomfort during cold exposure. These tendencies are interesting but not conclusive, since the experiment was done only with whole-body heat or cold exposure. Thus, T_{sk} differed depending on body area, which made an accurate comparison of sensation in different areas difficult.

Understanding how the elicitation of thermal comfort, local as well as whole-body, differs among the face, chest, abdomen, and thigh is the goal of this chapter. I paid special attention to the face and abdomen, since as noted above, these areas showed unusual tendencies in thermal comfort in Experiment 1 and 2. To these ends, I examined regional differences in temperature sensation and thermal comfort by applying local temperature stimulation during whole-body exposure to mild heat or cold.

3. 2 Methods

Experiment 3 (mild heat exposure)

Subjects

Eleven healthy male subjects (mean ± S.E.M., age 23.0 ± 0.7 years, W 66.2 ± 1.7 kg, H 1.73 ± 0.02 m) participated in this study. Each subject gave informed consent for the experimental protocol, which was approved by the Human Research Ethics Committee in the Faculty of Sport Sciences, Waseda University. The experiments were conducted in accordance with the Declaration of Helsinki. Subjects were instructed to avoid alcohol (from the evening of the day before the experiment), caffeinated drinks, hot food and physical training (on the experiment day), and eating (for at least 1 h prior to participation in the experiment).

Experimental procedure

The experiments were done in the period from November to December, 2006. Subjects arrived at the laboratory at 9:30 a.m. or 2:30 p.m., changed to short pants (only), and entered a climatic chamber which was maintained at 32.5 ± 0.5 (S.E.M)ºC with a relative humidity of 50%. Subjects rested in a sitting position while all measuring devices and thermal stimulators were applied. About 1.5 h after arrival, the local warming and cooling protocol was initiated with water perfused stimulators (0.027 m^2) made with vinyl tubes 7 mm in diameter (Fig. 3-1). Thermally conductive sheet (GP1-0.5, Kitagawa Industries Co., Ltd.) of 0.027 m^2 was stuck to the contacting surface of the stimulator so as to facilitate heat conductance. The perfusion water for the basal condition was set at 35ºC, for warming at 42ºC, and for cooling at 25ºC, and supplied to the stimulators from three thermostatic bath/circulators (Ecoline Low-temperature thermostats RE 206, LAUDA DR. R. WOBSER GMBH & CO. KG). Flow to the stimulators was controlled using three-way valves. The areas stimulated were the face, chest, abdomen, and thigh (Fig. 3-2). Each stimulus lasted 90 s. The interval between stimulation of different areas was 4.5 min (Fig. 3-3). The order of stimulation of the four areas was randomized and the order of cooling and warming was balanced among all subjects.

Measurements

Temperature sensation and thermal comfort of the stimulated area, and whole-body thermal comfort were reported by the subject in the period from 120 s before to 90 s after each local stimulation whenever any change in the sensations was felt. The sensations were reported by rotating each of dials located in front of the subject and numbered from -10 ("maximal cold" or "maximal uncomfortable") to 10 ("maximal hot" or "maximal comfortable"), 0 indicated "neutral". The experiment was actually done with Japanese words. In the scale, only the term cold (SAMUI or TSUMETAI in Japanese)" or "unpleasant (FUKAI)" were indicated at the number -10, "hot (ATSUI)" or "pleasant (KAI)" at 10, and "neutral (CHU-RITSU)" at 0. No other word was indicated on the scale. The setting of the dial was measured as a voltage every 5 s and averaged over 10 s. Core temperature (T_{co}) was recorded with a telemetry system (CoreTemp2000, HTI Technologies, Inc.) every 20 s and averaged over 60 s. For this record a transmitter pill was swallowed 1.5 h before the initiation of local stimulation. T_{sk} was recorded with copper-constantan thermocouples every 5 s at forehead, chest, abdomen, back, upper arm, forearm, hand, thigh, lower leg, and foot for the calculation of mean skin temperature (mean T_{sk}), and at two points under each stimulation device. Mean T_{sk} was calculated with the formula of Hardy and DuBois (33) and averaged over 60 s. The T_{sk} of each stimulated area was obtained by averaging two temperatures at the area over 10 s.

Statistical analysis

For the comparison of differences in T_{co}, and mean T_{sk} during each area's stimulation, two-way repeated measures ANOVA was performed for the four stimulated areas (face, chest, abdomen, and thigh) and four times (start of stimulation and 1, 2, and 3 minutes after the start of stimulation. The T_{sk} at the start of stimulation, changes in T_{sk} (ΔT_{sk}), and changes in temperature-related sensations of the four stimulated areas were analyzed using one-way repeated-measures ANOVA, followed by a Tukey post hoc test. For the comparison of differences in temperature-related sensations during each area's stimulation, two-way repeated measures ANOVA was performed for the four stimulated areas and two times (before and end of stimulation). If the result of ANOVA revealed statistically significant main effects for stimulated areas, Tukey post hoc test were performed for four stimulated areas on each time. If the interaction of the two factors was significant, one-way repeated measures ANOVA on 8 conditions (4 stimulated areas × 2 times) followed by a Tukey post hoc test was performed. All values are presented as means ± S.E.M. and significant difference was set at a level of $P < 0.05$.

Experiment 4 (mild cold exposure)

The experiments were done in the period from February to March, 2007. Ten healthy male subjects (age 21.5 ± 0.5 years, W 64.9 ± 1.8 kg, H 1.73 ± 0.02 m) participated in this study. Subjects sitting in the climatic chamber at 21.3 ± 0.1ºC with a relative humidity of 50% were locally cooled and warmed with the same water perfused stimulators as in Experiment 3. In this condition overall skin temperature was lower than that during the mild heat exposure of Experiment 3. Therefore, water temperature for the basal condition was set at 33ºC, 2ºC lower than for Experiment 3.

In a preliminary experiment, local stimulation temperatures as in Experiment 3 (25ºC for cooling, and 42ºC for warming) were tested, but the subjects reported only weak sensations following local cooling of the four areas. For this reason, the water source for local cooling was set at 22ºC, 3ºC lower than in Experiment 3. The water source temperature for local warming was the same as in Experiment 3, 42ºC. The other experimental methods, protocol, and statistical analysis were as in the Experiment 3.

3. 3 Results

Experiment 3 (mild heat exposure)

Local cooling

T_{co} during the 30 min of local cooling trials was 37.3 ± 0.1ºC, and it remained unaltered during the period of local stimulations. Mean T_{sk} was also the same (34.4 ± 0.1) when local cooling was initiated at each of the local areas. Although the local basal T_{sk} of the stimulated areas differed less than 1ºC, T_{sk} for the face was significantly higher than for the chest ($P < 0.05$), abdomen and thigh ($P < 0.01$), and significantly lower for the thigh than for the abdomen ($P < 0.05$), face and chest ($P < 0.01$, Fig. 3-4*A*). The magnitude of local ΔT_{sk} during 90 s of cooling was greater for the thigh than for the abdomen ($P < 0.05$), face and chest ($P < 0.01$, Fig. 3-4*B*).

Before local cooling, subjects reported "slightly hot" for local temperature sensation and "slightly uncomfortable" for local comfort (white bars in Figs. 3-4*C left* and *D left*). Neither sensation differed significantly among the four areas to be stimulated. At the end of 90 s of cooling, subjects reported a definite "cold" sensation (score -4.8 ± 0.3) with no significant difference among the four areas (black bars in Fig. 3-4*C left*). Neither was a significant difference observed among the magnitude of change in local temperature sensation (Δlocal temperature sensation) during 90 s of cooling of the four stimulated areas (Fig. 3-4*C* *right*). The concurrent estimations of local thermal comfort, however, did depend on the area stimulated. While facial cooling produced a strong "comfortable" feeling, abdominal cooling produced no local comfort, and the difference between face and abdomen was significant ($P < 0.01$, black bars in Fig. 3-4*D left*). And chest or thigh cooling produced a sufficient change in comfort score to convert uncomfortable to comfortable. The magnitude of change in local thermal comfort (Δlocal thermal comfort) during 90 s of cooling of the four stimulated areas was greater for the face than for the chest ($P < 0.05$), and abdomen ($P < 0.01$, Fig. 3-4*D right*).

As for whole-body thermal comfort, the subjects reported very similar "unpleasant" responses just before local cooling of each area (white bars in Fig. 3-4*E left*). After local cooling, the changes in whole-body thermal comfort differed depending on the area cooled. During facial cooling "unpleasant" changed to "pleasant". This effect was observed also for thigh cooling, but not for chest or abdominal cooling (Fig. 3-4*E left*). The score of whole-body thermal comfort at the end of cooling was significantly higher for the face than for the abdomen ($P < 0.05$, black bars in Fig. 3-4*E left*). The magnitude of change in whole-body thermal comfort (Δwhole-body thermal comfort) during 90 s of cooling was greater for the face than for the abdomen ($P < 0.01$, Fig. 3-4E *right*).

Local warming

T_{co} during the 30 min of local warming trials was 37.3 ± 0.1ºC and mean T_{sk} during the same 30 min of local warming trials was 34.3 ± 0.1ºC. Neither value differed for any time period during stimulation of the four areas. At the start of warming, local T_{sk} of the stimulated areas was significantly higher for the face than for the chest ($P < 0.05$), abdomen and thigh ($P < 0.01$), and significantly lower for the thigh than for the abdomen ($P < 0.05$), face and chest ($P < 0.01$, Fig. 3-5*A*). The magnitude of local ΔT_{sk} during 90 s of warming was greater for the thigh than for the abdomen ($P < 0.05$), face and chest ($P < 0.01$, Fig. 3-5*B*).

Before local warming, subjects reported "slightly hot" for the local temperature sensation and "slightly uncomfortable" for local comfort (white bars in Figs. 3-5*C left* and *D left*). The two types of sensation did not significantly differ among the four areas. At the end of 90 s of warming, subjects reported a distinct "hot" sensation that was significantly stronger for the face than for the thigh ($P < 0.05$, black bars in Fig. 3-5*C left*). The magnitude of Δlocal temperature sensation during 90 s of warming of the four stimulated areas was greater for the face than for the thigh ($P < 0.05$, Fig. 3-5*C right*). And local thermal discomfort increased. This effect was stronger for the face than for the chest ($P < 0.05$, black bars in Fig. 3-5*D*). While the magnitude of Δlocal thermal comfort was greater for the face, a significant difference was not observed among the four areas stimulated (Fig. 3-5*D right*).

For whole-body thermal comfort subjects reported "uncomfortable" just before local warming of each area without any significant difference among the four areas (white bars in Fig. 3-5*E left*). Local warming increased the "uncomfortable" feeling except for chest warming. While this effect was stronger for facial warming, a significant difference was not observed among the four areas stimulated (black bars in Fig. 3-5*E left,* and Fig. 3-5*E right*).

Experiment 4 (mild cold exposure)

Local cooling

T_{co} during the 30 min of local cooling trials was 37.1 ± 0.1ºC and mean T_{sk} during the same 30 min of local cooling trials was 29.4 ± 0.2ºC. Neither value differed for any time period during stimulation of the four areas. The difference in local T_{sk}s at the start of local cooling among the stimulated areas was more prominent than in Experiment 1, and significant differences were observed for all combinations of the four areas ($P < 0.01$, Fig. 3-6*A*). The T_{sk} was highest for the face (34.9 ± 0.1ºC) and lowest for the thigh (33.1 ± 0.1ºC). The magnitude of local ΔT_{sk} during 90 s of cooling was greater for the thigh than for the other three areas ($P < 0.01$, Fig. 3-6*B*).

Before local cooling, subjects reported sensations close to "neutral" both for local temperature sensation and for thermal comfort (white bars in Figs. 3-6*C* left and *D left*). Neither sensation differed significantly among the four areas. At the end of 90 s of cooling, subjects reported a definite "cold" sensation (score -4.1 ± 0.3) and no significant difference was observed among the four areas (black bars in Fig. 3-6*C left*). The magnitude of Δlocal temperature sensation during 90 s of cooling of the four stimulated areas was greater for the abdomen than for the face ($P < 0.05$, Fig. 3-6*C right*). For local thermal comfort, while facial cooling produced no local uncomfortable, cooling of the other body surfaces produced clear "uncomfortable" feeling (black bars in Fig. 3-6*D left*). Local discomfort at the end of cooling was significantly stronger for the abdomen and thigh than for the face ($P < 0.01$, black bars in Fig. 3-6*D left*). The magnitude of Δlocal thermal comfort during 90 s of cooling of the four stimulated areas was greater for the abdomen, thigh ($P < 0.01$), and chest ($P < 0.05$) than for the face (Fig. 3-6*D right*).

For whole-body thermal comfort subjects reported "uncomfortable" just before local cooling of each area without any significant difference among the four areas (white bars in Fig. 3-6*E left*). The whole-body "uncomfortable" sensation was increased by local cooling, but significant differences between the stimulated areas were not observed (black bars in Fig. 3-6*E left, and* Fig. 3-6*E right*).

Local warming

T_{co} during the 30 min of local warming trials was 37.1 ± 0.1ºC and mean T_{sk} during the same 30 min of local warming trials was 29.3 ± 0.2 ºC. Neither value differed for any time period during stimulation of the four areas. At the start of warming, significant differences in local T_{sk}s among the stimulated areas were observed in all combinations of the four stimulated areas ($P < 0.01$, Fig. 3-7*A*). The magnitude of local ΔT_{sk} during 90 s of local warming was greater for the thigh than for the other three areas ($P < 0.01$, Fig. 3-7*B*).

Before local warming, subjects reported sensations close to "neutral" both for local temperature sensation and local comfort (white bars in Figs. 3-7*C left* and *D left*). Neither type of sensation differed significantly among the four areas. At the end of 90 s of warming, subjects reported a distinct "hot" sensation (score 3.5 ± 0.2) and no significant difference was observed among the four areas (black bars in Fig. 3-7*C left*). Nor was a significant difference observed among the magnitude of Δlocal temperature sensation during 90 s of warming of the four stimulated areas (Fig. 3-7*C right*). The concurrent estimations of local thermal comfort, however, did depend on the area stimulated. While warming of the abdomen and chest produced a definite "comfortable" feeling, facial warming had only a little effect that was weaker than chest ($P < 0.05$) and abdomen ($P < 0.01$, black bars in Fig. 3-7*D left*). The magnitude of Δlocal thermal comfort during 90 s of warming of the four stimulated areas was greater for the abdomen than for the face ($P < 0.01$, Fig. 3-7*D right*).

For whole-body thermal comfort subjects reported "uncomfortable" just before local warming of each area without any significant difference among the four areas (white bars in Fig. 3-7*E left*). Whole-body discomfort was decreased by local warming. While this effect was stronger for the chest and abdominal warming, a significant difference was not observed among the four areas stimulated (black bars in Fig. 3-7*E left*, and Fig. 3-7*E right*).

3. 4 Discussion

In the present study, 4 body surfaces of equivalent area (0.027 m^2) were heated or cooled and the ensuing temperature-related sensations were analyzed with special attention to thermal comfort in healthy male subjects. Definite regional differences in local thermal comfort were observed. During mild heat exposure, when the subjects' whole-body sensation was "uncomfortable", local cooling was most comfortable and local warming was most uncomfortable when applied to the face (Figs. 3-4*D* and 3-5*D*). On the other hand, during mild cold exposure, in which whole-body thermal comfort was "uncomfortable", neither warming nor cooling of the face had a major effect (Figs. 3-6*D* and 3-7*D*). The chest and abdomen had characteristics opposite to those of the face. Local cooling of these areas did not produce explicit comfort even during whole-body heat exposure (Fig. 3-4*D*). But local warming of the chest and abdomen did produce strong comfort during whole-body cold exposure (Fig. 3-7*D*). This effect was more prominent for the abdomen than for the chest. As for the thigh, although the ΔT_{sk} was always larger than that of other areas in all four conditions, thermal comfort was never strongest (Fig. 3-4, 5, 6, 7*B, D, E*).

The effect of adapting temperature and stimulus magnitude

Although the areas locally stimulated were adapted to 35ºC or 33ºC before stimulation, local T_{sk}s at the start of stimulation were not necessarily the same. In the mild heat exposure experiment, the T_{sk}s were in the range of 35-36ºC but were highest in the face and decreased, in order, from chest, to abdomen, to thigh (Figs. 3-4*A* and 3-5*A*). While the magnitudes of thermal stimulation (ΔT_{sk}) were larger in the reverse order both for heating and cooling, there was no significant difference among the face, chest, and abdomen (Figs. 3-4*B* and 3-5*B*). The difference in the ΔT_{sk}s among the various areas is likely caused by differences in skin blood flow due to vasomotor status and tissue vascularity. For the ambient temperature utilized in the heat exposure (Experiment 3), the skin vessels of all areas would be expected to be vasodilated. In the mild cold exposure experiment, differences in local T_{sk}s and ΔT_{sk}s were more prominent (Figs. 3-6*A, B* and 3-7*A, B*), probably due to cold-induced skin vasoconstriction that was stronger for the chest and thigh than for the face and abdomen.

When skin is warmed at a constant rate of temperature change, starting from various levels of temperature adaptation, the response magnitude of skin warm fibers are larger at higher adapting temperatures (26, 46). Further, warm sensations are more sensitive at higher adapting temperatures, and cold sensations are more sensitive at lower adapting temperatures (37). In the present study, in spite of differences in T_{sk}s and ΔT_{sk}s, we could find little difference in temperature sensation among the four areas (Figs. 3-4*C,* 3-5*C,* 3-6*C* and 3-7*C*). Additionally, the regional differences in thermal comfort never correlated with differences in T_{sk}s or ΔT_{sk}s; *e.g.*, thermal comfort was never stronger for the thigh, although the ΔT_{sk} of the thigh was always larger than that of other areas. Regional differences in thermal comfort observed in the present study, therefore, cannot be explained simply by invoking the slight differences in local temperature produced by the thermal stimulation.

Mechanism for the regional difference in thermal comfort

It is generally assumed that inputs from the same warm or cold skin thermoreceptors are utilized for both temperature sensation and thermal comfort, although there is no direct experimental evidence for this supposition. While it is difficult to quantitatively evaluate differences in the density of skin thermoreceptors in humans, the density of hot and cold spots would be expected to correlate positively with the density of warm and cold receptors (37). The distribution of peripheral warm and cold spots over the body surface is not uniform (49, 69, 82, 85), and the face is one of the areas where both warm and cold spots are particularly dense. While this high density might be invoked to explain the strong thermal comfort produced by facial stimulation in the heat exposure experiment, the same facial stimulation produced only a slight change in thermal comfort during cold exposure. Likewise, the chest and abdomen have particularly dense cold spots (82). While thermal stimulation, especially warming, of these areas produced a distinct change in thermal comfort during cold exposure, the same stimulation during heat exposure had a minor effect. Thus, the location-dependent effect of thermal stimulation on thermal comfort cannot be explained simply by the density of cold or warm spots. Additionally, it should be noted that regional differences in temperature sensation were not seen with stimulation that did produce regional differences in thermal comfort. The above observations make it unlikely that regional differences in thermal comfort can be entirely explained by the properties and distribution of peripheral thermoreceptors. A more plausible explanation is that central nervous processing is responsible for the production of the regional differences in thermal comfort. Feelings of warmth and cold correlate with neural activity in insular cortex (18, 67), and the amygdala, mid-orbitofrontal and pregenual cingulate cortex, and ventral striatum have been implicated in the genesis of thermal comfort (41, 71). I speculate that a CNS map weighing the input from each body area would be involved in the production of regional differences in thermal comfort.

It is well known that thermal comfort is affected by the thermal state of the body (5, 6, 14, 48, 52, 53, 59). The same hand warming produces a comfortable or uncomfortable feeling depending on whether the individual is hypothermic or hyperthermic. Thus, a thermal stimulation is felt comfortable when it serves to regain normal body temperature, and felt uncomfortable when it worsens internal thermal conditions. Somehow, the CNS processes sensory input so that it is perceived as comfortable or uncomfortable depending on the thermal status of the body. Interestingly the direction of this alteration in hedonic valence is not uniform for all body areas. As I showed, feelings of comfort in the face are very sensitive to local temperature stimuli in the heat, but less sensitive in the cold. The abdomen demonstrates the opposite tendency. It will be of interest to determine how this alliesthesia (11) occurs and how regional differences between sensation and comfort are created.

Meaning of the regional difference in thermal comfort

Thermal comfort and discomfort are specific aspects of the pleasure-pain system of animals. In an overall sense, comfort and discomfort (including pain) function to interrupt other ongoing behaviors in order to focus the organism on a particular, significant threat to its well being. What is the function of the regional difference in thermal comfort? It is well known that even in homeothermic animals the magnitude of temperature fluctuation inside the body in different thermal environments is dependent on the particular body part (3). The temperature of the body core fluctuates only slightly, while that of the periphery, such as arms and legs, shows large changes. The basic function of temperature regulation must be to maintain the temperature of the body core because the vital organs are located there. Regional differences in thermal comfort can be considered in this light.

The head contains the brain, which possesses a high, continuous rate of heat production. The human brain is particularly susceptible to heat damage and can only tolerate temperatures up to about 40.5ºC, while organs of the torso core temperatures can tolerate temperatures that exceed 42ºC (89). It is critical for organism viability that heat be rapidly removed from the head area, and a special systems to cool the brain are suggested to exist in humans (12, 61) and well documented in many animals (89). In human, venous blood from the scalp and the face is posited to flow, via the emissary veins, into the brain during hyperthermia at a rate sufficient to produce selective brain cooling (12, 61). A hot face would further heat an already overheated brain. Preference for a low facial temperature in the heat would help avoid heat-induced damage to the brain.

Preference for a warm abdomen likewise must reflect important aspects of the organism's need to conserve and produce heat. For most mammals, the abdomen and inner thighs are thinly furred areas that can be utilized to dissipate heat during exercise or in a hot environment. In the cold, mammals curl up, which greatly decreases the surface area and shields the thinly furred areas (58). While humans are not furred, they do benefit from a fetal-like position in the cold which minimizes the surface area for heat loss. The adoption of this posture warms the abdomen, and the pleasant feelings that ensue must contribute to the initiation and maintenance of this postural adjustment. Further, a warm abdomen facilitates digestion, which in the act of altering chemical energy into forms that the body can utilize to produce heat (and all its other functions), also releases substantial amounts of heat in the process (89).

Thermal comfort of the thigh was never particularly strong for the thigh, although the ΔT_{sk} of the thigh was always larger than that of other areas in all four conditions, indicating that the thigh is insensitive for temperature change. Because there are no important organs such as brain in the thigh, characteristics in thermal comfort like that of the face and trunk would not be necessary for the thigh.

Thermal comfort and autonomic thermoregulation

Previous works have repeatedly found that, per unit area of skin, facial temperature exerts the largest peripheral influence on autonomic thermoregulation (8, 16, 19, 60). The effect is not dependent upon the ambient temperature. Heating the face in a warm environment produces a considerably greater increase in sweat rate than heating other skin areas (16, 60), while cooling the face in a warm environment produces a considerably greater decrease (16, 19). Belding et al. (8) also found that at low ambient temperatures, warming the face induced peripheral vasodilatation, while warming the same area of the chest or a much larger area of the leg had no effect. Such a strong, consistent facial sensitivity might be explained by a high density of thermoreceptors (cold and warm spots) in the face.

However, for thermal comfort, the predominance of facial thermosensivity is dependent upon the ambient temperature. The whole-body comfort sensation is likely the primary input for behavioural thermoregulation and if an individual is in a situation where feelings of comfort can be acted upon, it is possible to maintain without utilizing the energy and fluid resources necessary for autonomic regulation. The different regional sensitivities of thermal comfort and autonomic thermoregulation could indicate that autonomic and behavioural temperature regulation are controlled separately in the central nervous system. The ability to regulate body temperature by behavioural (but not autonomic) means remains in animals whose medial preoptic area/anterior hypothalamus has been lesioned (13, 50, 74). Indeed, it has recently been reported that the afferent neuronal pathways for discriminative sensation/localization of a thermal stimulus and for homeostatic control of body temperature are separate (63).

The comfort sensations seen in this study indicate that if given the chance, humans would preferentially cool the head in the heat, and maintain the warmth of the abdomen in the cold. And thermal comfort was never stronger for the thigh, although the ΔT_{sk} of the thigh was always larger than that of other areas in all four conditions. These regional differences in the thermal comfort are consistent with the biological roles of each body part. The qualitative differences seen in thermal comfort for the various areas cannot be explained solely by the density or properties of the peripheral thermal receptors.

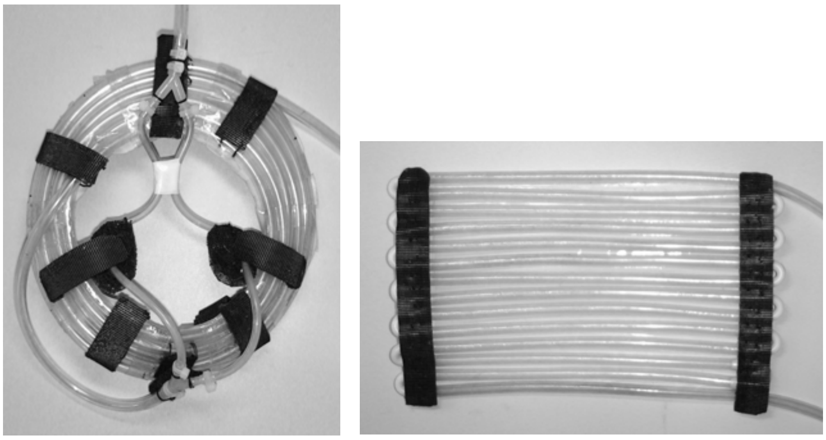

Figure 3-1. Thermal stimulators made with vinyl tubes. Left is for the face and right is for the other areas.

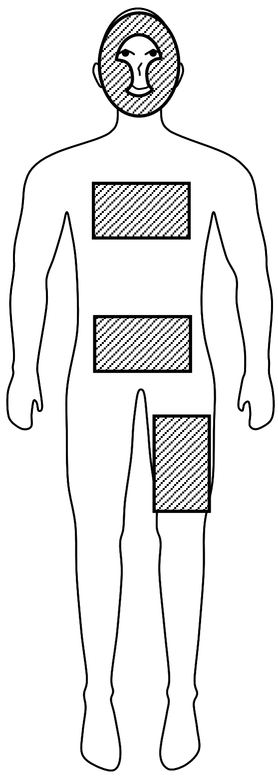

Figure 3-2. Locations of the areas which were thermally stimulated.

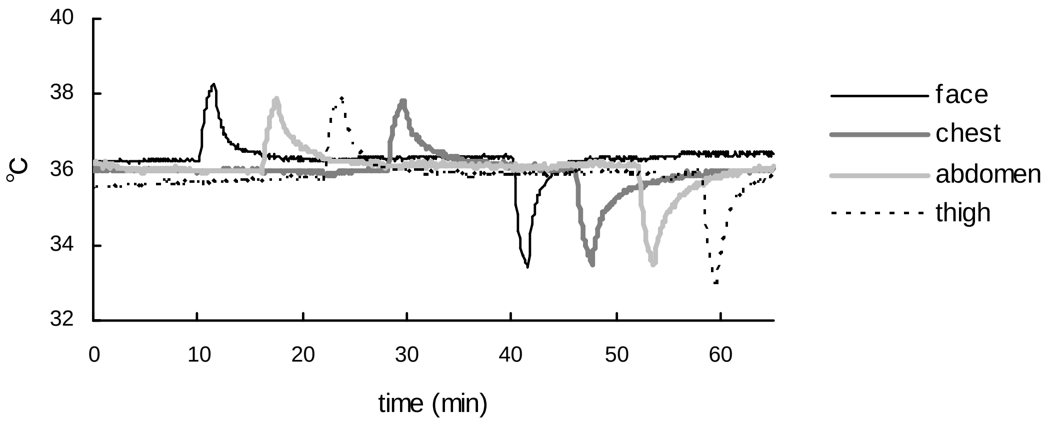

Figure 3-3. Typical example of skin temperature change during local warming and cooling of four stimulated areas in one subject.

Experiment 3

Mild heat exposure + Local cooling

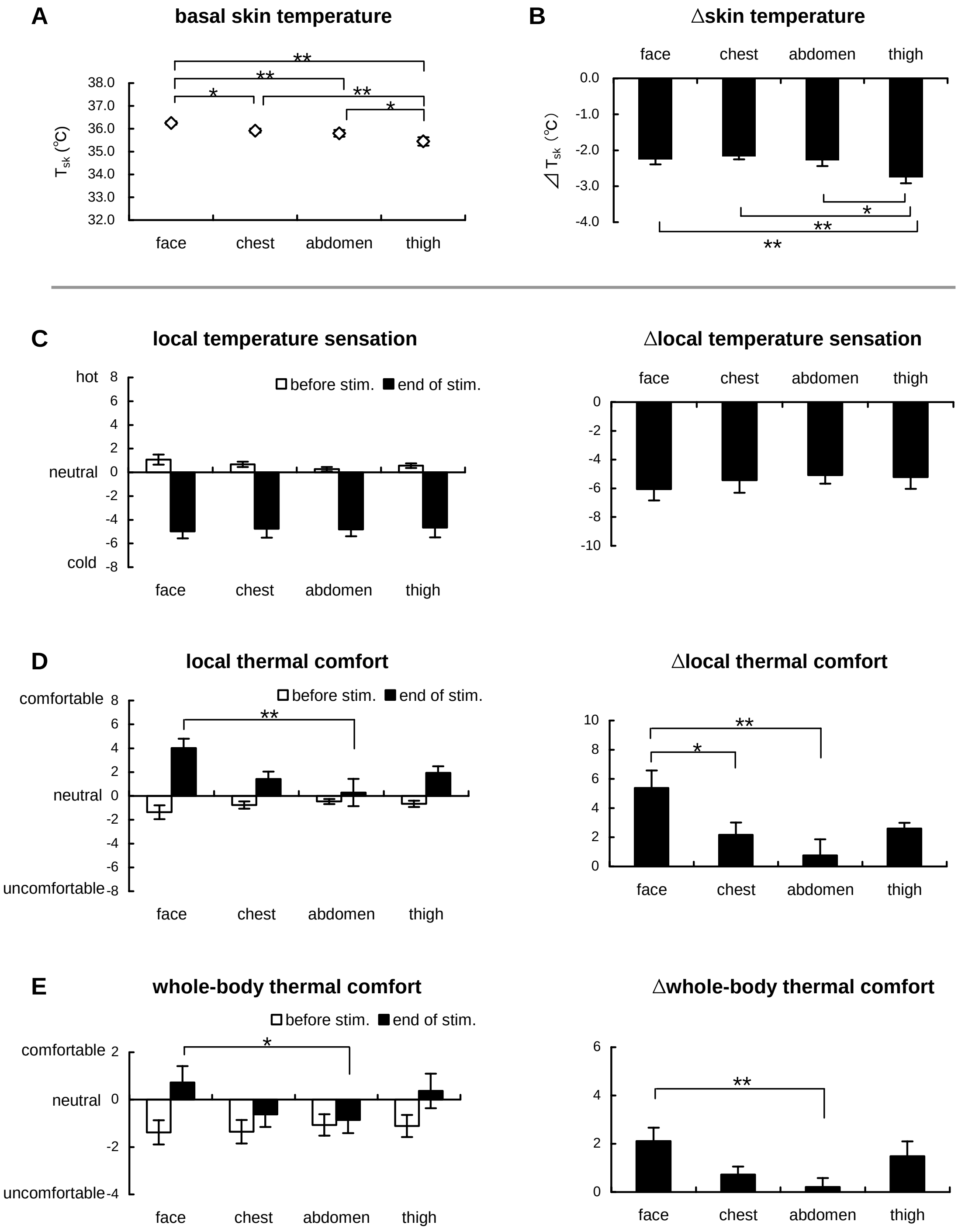

Figure 3-4. Local skin temperature and temperature-related sensations during local cooling of four areas in mild heat exposure experiment. A: local skin temperature at the start of cooling. B: magnitude of local skin temperature changes during 90 s of cooling. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of cooling of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of cooling of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of cooling of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 11). *$P < 0.05$, **$P < 0.01$, significant differences among the four stimulated sites.

Experiment 3

Mild heat exposure + Local warming

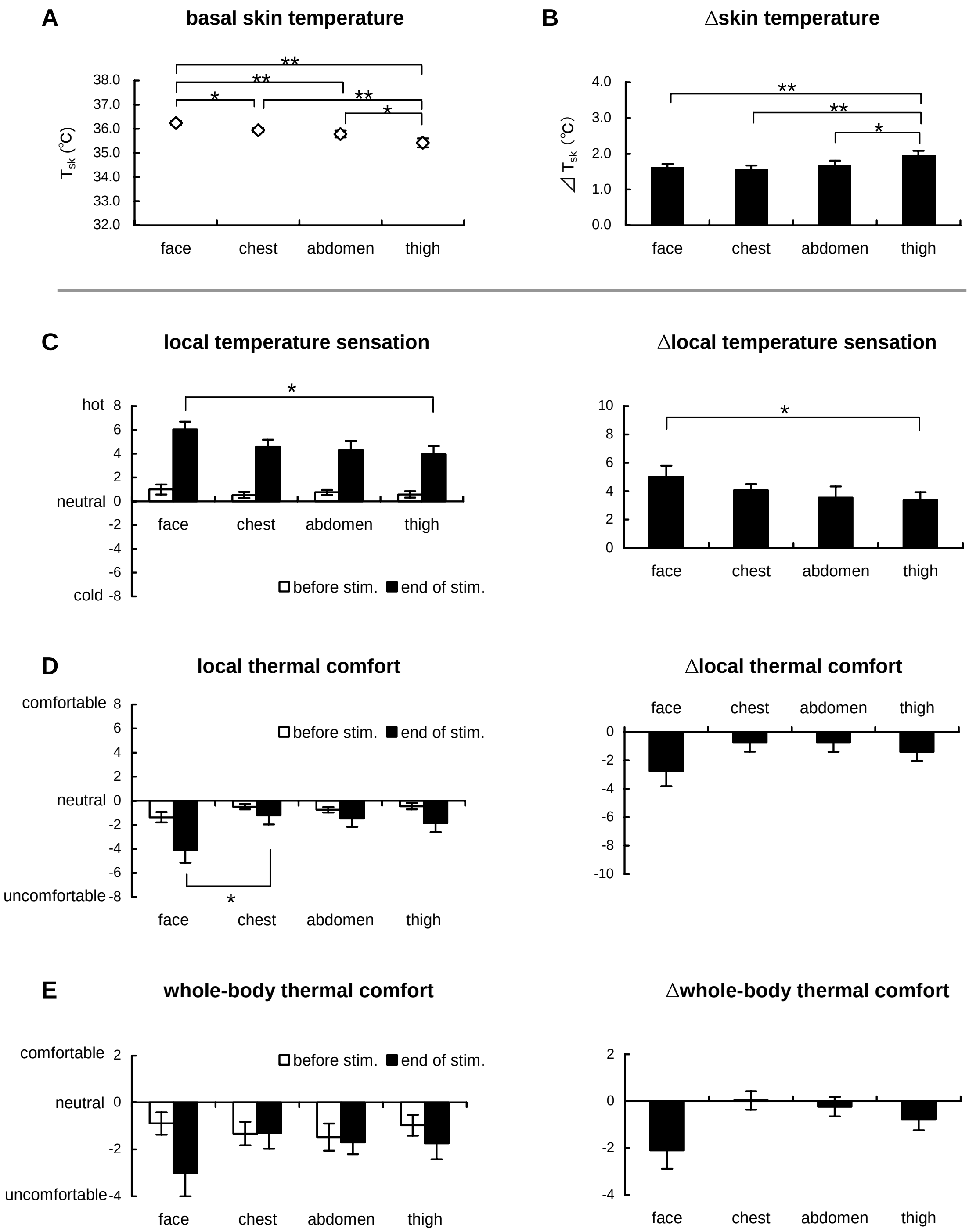

Figure 3-5. Local skin temperature and temperature-related sensations during local warming of four areas in mild heat exposure experiment. A: local skin temperature at the start of warming. B: magnitude of local skin temperature changes during 90 s of warming. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of warming of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of warming of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of warming of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 11). *P < 0.05, **P < 0.01, significant differences among the four stimulated sites.

Experiment 4

Mild cold exposure + Local cooling

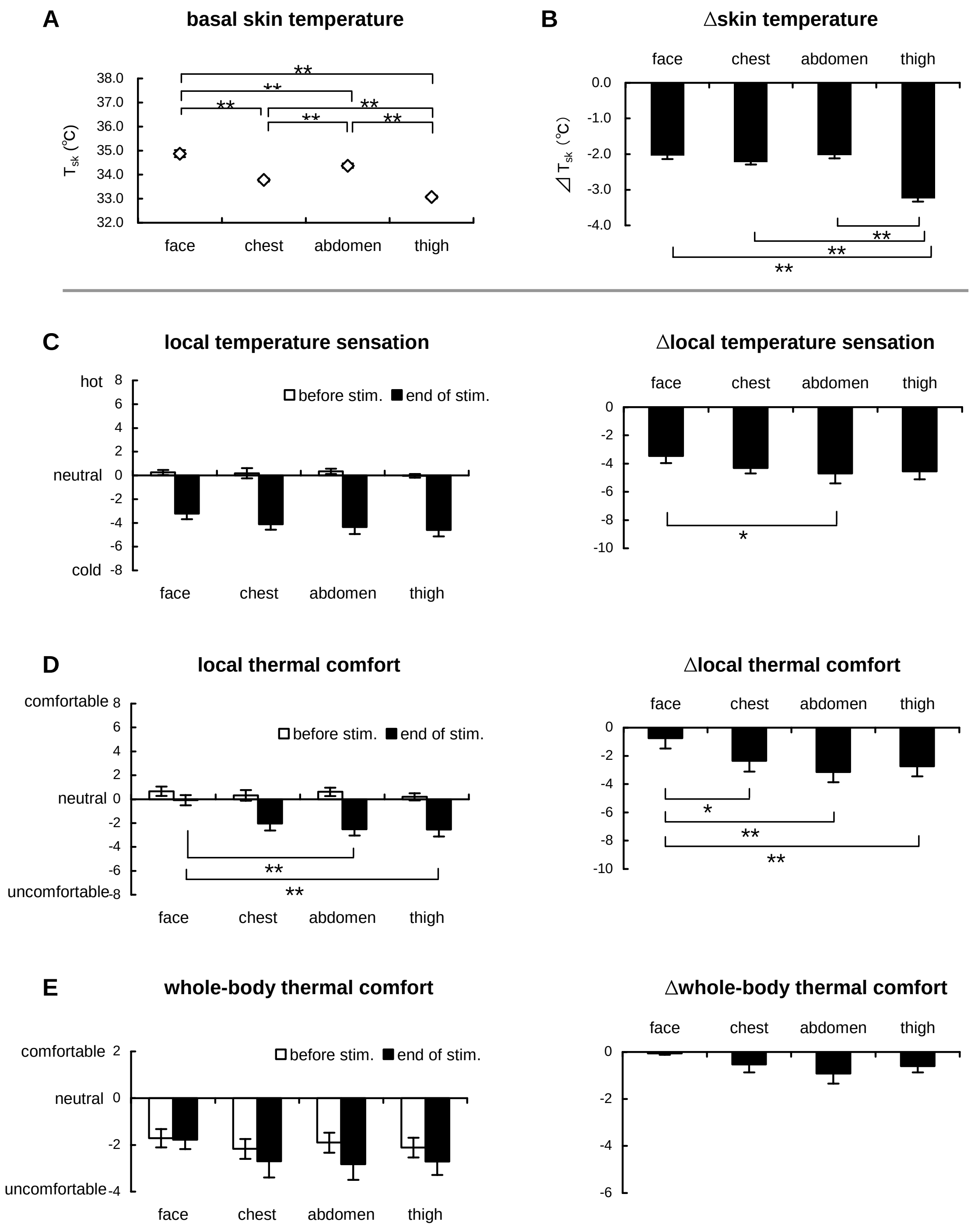

Figure 3-6. Local skin temperature and temperature-related sensations during local cooling of four areas in mild cold exposure experiment. A: local skin temperature at the start of cooling. B: magnitude of local skin temperature changes during 90 s of cooling. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of cooling of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of cooling of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of cooling of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 10). *P < 0.05, **P < 0.01, significant differences among the four stimulated sites.

Experiment 4

Mild cold exposure + Local warming

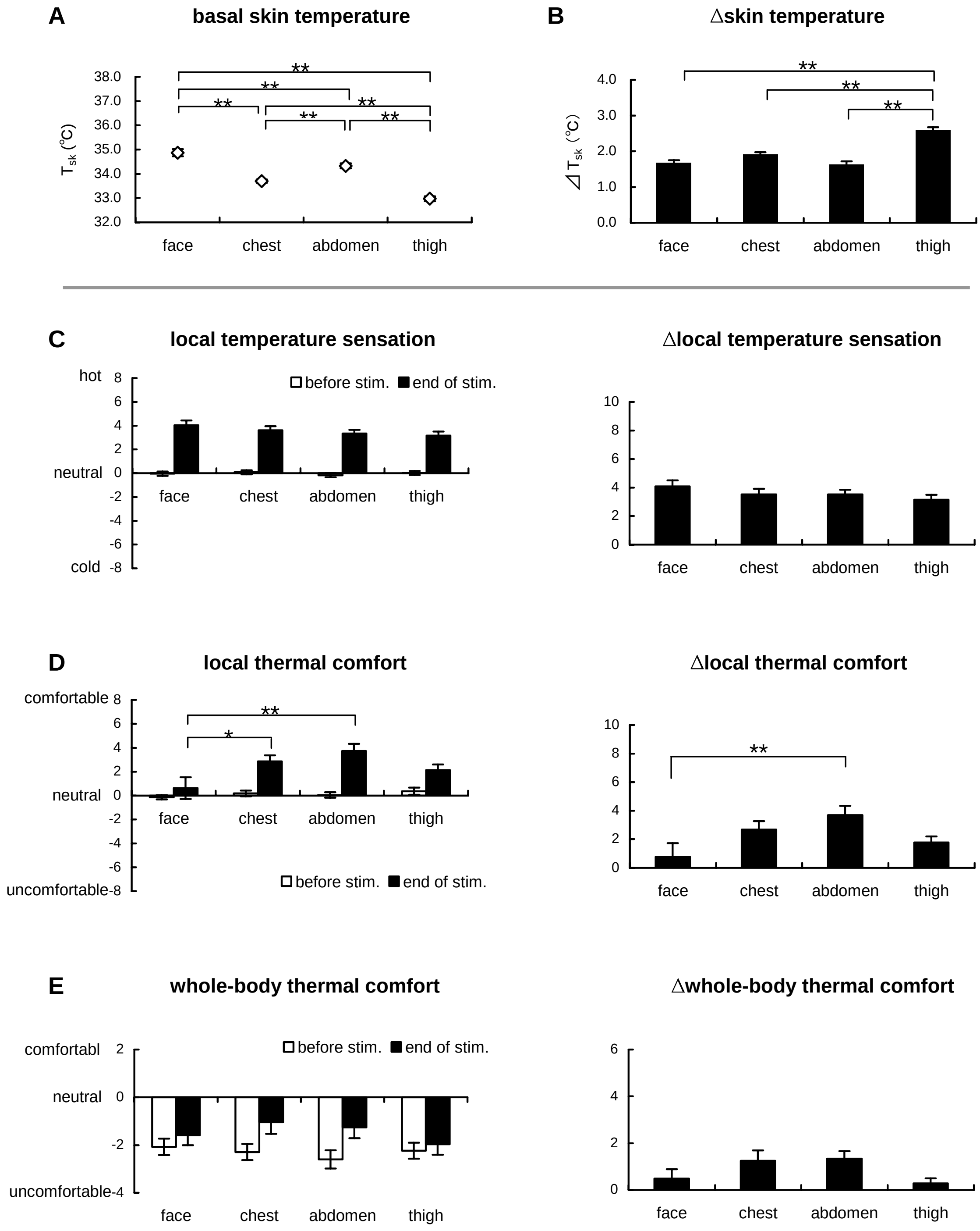

Figure 3-7. Local skin temperature and temperature-related sensations during local warming of four areas in mild cold exposure experiment. A: local skin temperature at the start of warming. B: magnitude of local skin temperature changes during 90 s of warming. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of warming of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of warming of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of warming of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 10). *P < 0.05, **P < 0.01, significant differences among the four stimulated sites.

Chapter 4

Regional differences in temperature sensation and thermal comfort among the neck, abdomen, hand, and thigh

4. 1 Introduction

In the chapter 3 I only tested thermal comfort of four areas near the trunk (65). It would be valuable to examine the thermal and comfort sensitivities of other body areas and consider how the properties of each area's thermal and comfort sensations are related to the physiological functions subserved by that particular area. In this chapter I focus on three areas of the body, hand, feet, and neck. Hand and feet are chosen because they are located in the periphery and shows large fluctuation of skin temperature. As for the neck it is very interesting whether its characteristic of thermal comfort is similar to that observed for the face, or the trunk? Understanding thermal comfort, local as well as whole-body, of the neck, hand and soles is the goal of this study. To these ends I conducted local cooling or warming tests with the same method as the chapter 3. To compare the results with that of the chapter 3, I selected the abdomen as the control area in this chapter.

4. 2 Methods

Experiment 5 (mild heat exposure)

The experiments were done in the period from September to November, 2007. Eleven healthy male subjects (mean ± S.E.M., age 22.0 ± 0.5 years, W 64.2 ± 2.1 kg, H 1.70 ± 0.02 m) participated in this study. Subjects sitting in the climatic chamber at 33.7 ± 0.1ºC with a relative humidity of 50% were locally cooled and warmed. The areas stimulated were the neck (rear neck and adjoining upper back), abdomen, left hand (palmar and dorsal side except the thumb), and both soles (Fig. 4-1). Dimension of the stimulated areas was 0.027

m^2 for all the areas. Size of the stimulator for the neck and abdomen were 135 mm long and 200 mm wide, and we used two stimulators of 200 mm long and 67.5 mm wide (half size of the stimulator for the neck and abdomen) for the hand and soles (for the palmar and dorsal side of hand, or both soles). The other experimental methods, protocol, and statistical analysis were as in the Experiment 3. Fig. 4-2 shows the typical example of skin temperature change during local warming and cooling of the four stimulated areas in one subject.

Experiment 6 (mild cold exposure)

The experiments were done in the period from February to August, 2008. Ten healthy male subjects (age 23.0 ± 0.7 years, W 67.4 ± 3.0 kg, H 1.71 ± 0.02 m) participated in this study. Subjects sitting in the climatic chamber at 21.3 ± 0.1ºC with a relative humidity of 50% were locally cooled and warmed with the same water perfused stimulators as in the Experiment 5. The other experimental methods were as in the Experiment 4.

4. 3 Results

Experiment 5 (mild heat exposure)

Local cooling

T_{co} during the 30 min of local warming trials was 37.3 ± 0.1ºC and mean T_{sk} during the same 30 min of local warming trials was 34.5 ± 0.1ºC. Neither value differed for any time period during stimulation of the four areas. Although the local basal T_{sk} of the stimulated areas differed less than 0.6ºC, T_{sk} for the hand was significantly higher than for the abdomen and sole ($P < 0.01$), and significantly lower for the sole than for the neck ($P < 0.05$, Fig. 4-3*A*). The magnitude of local ΔT_{sk} during 90 s of cooling was greater for the hand and sole than for the neck ($P < 0.01$, Fig. 4-3*B*).

Before local cooling, subjects reported "slightly hot sensation" for local temperature sensation and "slightly uncomfortable" for local comfort (white bars in Figs. 4-3*C left* and *D left*). Neither sensation differed significantly among the four areas to be stimulated. At the end of 90 s of cooling, subjects reported a definite "cold" sensation with no significant difference among the four areas (black bars in Fig. 4-3*C left*). Neither was a significant difference observed among the magnitude of change in local temperature sensation (Δlocal temperature sensation) during 90 s of cooling of the four stimulated areas (Fig. 4-3*C right*). The concurrent estimations of local thermal comfort, however, did depend on the area stimulated. While abdominal cooling produced only a slight local comfort, cooling of the other body surfaces produced clear "comfortable" feeling, and the local comfort sensations was stronger for the hand, sole ($P < 0.01$), and neck ($P < 0.05$) than for the abdomen (black bars in Fig. 4-3*D left*). The magnitude of change in local thermal comfort (Δlocal thermal comfort) during 90 s of cooling of the four stimulated areas was weaker for the abdomen than for the other three areas ($P < 0.01$, Fig. 4-3*D right*).

As for whole-body thermal comfort, the subjects reported very similar "uncomfortable" responses just before local cooling of each area (white bars in Fig. 4-3*E left*). After local cooling, the changes in whole body thermal comfort differed depending on the area cooled. During cooling of the neck "uncomfortable" changed to "comfort" (Fig. 4-3*E left*). While two-way repeated measures ANOVA demonstrated a significant interaction between the stimulated area and time ($P < 0.05$), one-way repeated measures ANOVA on the 8 conditions (4 stimulated areas × 2 times) followed by a Tukey post hoc test demonstrated no significant difference among whole-body thermal comfort of the four areas before cooling (white bars in Fig. 4-3*E left*), and among those at the end of cooling (black bars in Fig. 4-3*E left*). The magnitude of change in whole-body thermal comfort (Δwhole-body thermal comfort) during

90 s of cooling was greater for the neck than for the hand ($P < 0.01$) and abdomen ($P < 0.05$, Fig. 4-3E *right*).

Local warming

T_{co} during the 30 min of local warming trials was 37.3 ± 0.1ºC and mean T_{sk} during the same 30 min of local warming trials was 34.5 ± 0.1ºC. Neither value differed for any time period during stimulation of the four areas. At the start of warming, local T_{sk} of the stimulated areas was significantly higher for the hand than for the abdomen, sole ($P < 0.01$), and neck ($P < 0.05$), and significantly lower for the abdomen than for the neck ($P < 0.05$, Fig. 4-4*A*). The magnitude of local ΔT_{sk} during 90 s of warming was greater for the sole ($P < 0.01$) and hand ($P < 0.05$) than for the neck.

Before local warming, subjects reported "slightly hot" for the local temperature sensation and "slightly uncomfortable" for local comfort (white bars in Figs. 4-4*C left* and *D left*). The two types of sensation did not significantly differ among the four areas. At the end of 90 s of warming, subjects reported a distinct "hot" sensation and no significant difference was observed among the four areas (black bars in Fig. 4-4*C left*). Neither was a significant difference observed among the magnitude of change in local temperature sensation (Fig. 4-4*C right*). And local thermal discomfort was increased by local warming, but significant differences among the stimulated areas were not observed (black bars in Fig. 4-4*D left, and* Fig. 4-4*D right*).

For whole-body thermal comfort subjects reported "uncomfortable" just before local warming of each area without any significant difference among the four areas (white bars in Fig. 4-4*E left*). While local warming increased the "uncomfortable" feeling, a significant difference was not observed among the four areas stimulated (black bars in Fig. 4-4*E left,* and Fig. 4-4*E right*).

Experiment 6 (mild cold exposure)

Local cooling

T_{co} during the 30 min of local cooling trials was 37.1 ± 0.1ºC and mean T_{sk} during the same 30 min of local cooling trials was 29.5 ± 0.1ºC. Neither value differed for any time period during stimulation of the four areas. The difference in local T_{sk}s at the start of local cooling among the stimulated areas was more prominent than in Experiment 5, and significant differences were observed for all combinations of the four areas except that between the neck and abdomen ($P < 0.01$, Fig. 4-5*A*). The T_{sk} was highest for the neck (35.1 ± 0.1ºC) and lowest for the sole (31.5 ± 0.3ºC). The magnitude of local ΔT_{sk} during 90 s of cooling was greater in the order of sole, hand, abdomen, and neck (Fig. 4-5*B*).

Before local cooling, subjects reported "slightly hot" for local temperature sensation and "slightly comfortable" for local comfort (white bars in Figs. 4-5*C* left and *D left*). Neither sensation differed significantly among the four areas. At the end of 90 s of cooling, subjects reported a definite "cold" sensation. While two-way repeated measures ANOVA of local temperature sensation demonstrated a significant interaction between the stimulated area and time ($P < 0.05$), one-way repeated measures ANOVA on the 8 conditions (4 stimulated areas × 2 times) followed by a Tukey post hoc test demonstrated no significant difference among the temperature sensations of the four areas at the end of cooling (black bars in Fig. 4-5*C left*). The magnitude of Δlocal temperature sensation during 90 s of cooling of the four stimulated areas was greater for the abdomen ($P < 0.01$) and hand ($P < 0.05$) than for the neck (Fig. 4-5*C right*). For local thermal comfort, while cooling of the neck produced no local uncomfortable, cooling of the other body surfaces produced "uncomfortable" feeling (black bars in Fig. 4-5*D left*). Local discomfort at the end of cooling was significantly stronger for the abdomen than for the neck ($P < 0.01$, black bars in Fig. 4-5*D left*). The magnitude of

Δlocal thermal comfort during 90 s of cooling of the four stimulated areas was greater for the abdomen than for the neck ($P < 0.01$, Fig. 4-5*D right*).

For whole-body thermal comfort subjects reported “uncomfortable” just before local cooling of each area without any significant difference among the four areas (white bars in Fig. 4-5*E left*). The whole-body “uncomfortable” sensation was increased by local cooling, but significant differences between the stimulated areas were not observed (black bars in Fig. 4-5*E left, and* Fig. 4-5*E right*).

Local warming

T_{co} during the 30 min of local warming trials was 37.1 ± 0.1ºC and mean T_{sk} during the same 30 min of local warming trials was 29.5 ± 0.2ºC. Neither value differed for any time period during stimulation of the four areas. At the start of warming, significant differences in local T_{sk}s among the stimulated areas were observed in all combinations of the four stimulated areas except that between the neck and abdomen ($P < 0.01$, Fig. 4-6*A*). The magnitude of local ΔT_{sk} during 90 s of warming was greater in the order of sole, hand, abdomen, and neck (Fig. 4-6*B*).

Before local warming, subjects reported “slightly hot” for local temperature sensation and “slightly comfortable” for local comfort (white bars in Figs. 4-6*C left* and *D left*). Neither type of sensation differed significantly among the four areas. At the end of 90 s of warming, subjects reported a distinct “hot” sensation that was significantly stronger for the hand than for the neck and sole ($P < 0.01$, black bars in Fig. 4-6*C left*). The magnitude of Δlocal temperature sensation during 90 s of warming of the four stimulated areas was stronger for the hand than the neck ($P < 0.05$) and sole ($P < 0.01$), and was stronger for the abdomen than for the sole ($P < 0.05$, Fig. 4-6*C right*). For local thermal comfort, local warming produced a definite "comfortable" feeling, and no significant difference was observed among the four areas (black bars in Fig. 4-6*D left, and* Fig. 4-6*D right*).

For whole-body thermal comfort subjects reported "uncomfortable" just before local warming of each area without any significant difference among the four areas (white bars in Fig. 4-6*E left*). After local warming, the changes in whole body thermal comfort differed depending on the area warmed, although the regional difference in "local" thermal comfort was not observed. During warming of the neck "uncomfortable" changed to "comfort", on the other hand during warming of the hand the change in whole-body discomfort was little, and the difference between the neck and hand was significant (Fig. 4-6*E left*). While the magnitude of change in whole-body thermal comfort during 90 s of warming was weaker for the hand, significant difference among the four areas was not observed (Fig. 4-6E *right*).

4. 4 Discussion

In the present study, 4 body surfaces (neck, abdomen, hand, and sole) of equivalent area (0.027 m^2) were heated or cooled and the ensuing temperature-related sensations were analyzed with special attention to thermal comfort in healthy male subjects. Definite regional differences in thermal comfort were observed. During mild heat exposure, when the subjects' whole-body sensation was "uncomfortable", local abdominal cooling was less comfortable than the other three areas (Fig. 4-3*D*). On the other hand, during mild cold exposure, in which whole-body thermal comfort was "uncomfortable", cooling of the abdomen had a strong effect (Fig. 4-5*D*). These results of abdominal stimulation are the same as observed in the results of the previous chapter (65). On the other hand, while no regional difference in "local" thermal comfort was observed between the hand and neck, the magnitude of decrease in "whole-body" thermal discomfort was smaller for the hand than for the neck (Figs. 4-3*D, E* and 4-6*D, E*). The regional difference in "whole-body" thermal comfort without difference in “local” thermal comfort between body parts was not observed in the previous chapter. And although the hand and sole showed larger skin temperature change than the neck, local and whole-body thermal comfort was never stronger for the hand and sole than the neck (Fig. 4-3, 4, 5, 6*B, D, E*).

The effect of adapting temperature and stimulus magnitude

Although the areas locally stimulated were adapted to 35ºC or 33ºC before stimulation, local T_{sk}s at the start of stimulation were not necessarily the same. In the mild heat exposure experiment, the T_{sk}s were in the range of 35.7-36.3ºC but were highest in the hand and decreased, in order, from neck, to abdomen, to sole (Figs. 4-3*A* and 4-4*A*). The magnitudes of thermal stimulation (ΔT_{sk}s) were the greatest in the sole and decreased, in order, from hand, to abdomen, to neck both for heating and cooling (Figs. 4-3*B* and 4-4*B*). The difference in the ΔT_{sk}s among the various areas is likely caused by differences in skin blood flow due to vasomotor status and tissue vascularity. At the ambient temperature utilized in the heat exposure (Experiment 5), the skin vessels of all areas would be expected to be vasodilated. In the mild cold exposure experiment, differences in local T_{sk}s and ΔT_{sk}s were more prominent (Figs. 4-5*A, B* and 4-6*A, B*), probably due to cold-induced skin vasoconstriction that was stronger in the periphery (hand and sole) than for the central part of the body (neck and abdomen) (66).

In the present study, while differences in T_{sk}s and ΔT_{sk}s were observed, the regional differences in thermal comfort never correlated with differences in T_{sk}s or ΔT_{sk}s; *e.g.*, the magnitude of local and whole-body thermal comfort changes during the thermal stimulations were never stronger for the hand and sole than the neck, although the ΔT_{sk}s of the hand and sole was always larger than that of the neck. Regional differences in thermal comfort observed in the present study, therefore, cannot be explained simply by invoking the slight differences in local temperature produced by the thermal stimulation.

Characteristic for the production thermal comfort of the neck

Is the characteristic in thermal comfort of the neck similar to that of the face or abdomen? Local cooling of the neck produce strong comfort sensation during mild heat exposure, and during mild cold exposure, produce no uncomfortable sensation (Figs. 4-3*D, E* and 4-5*D, E*). This characteristic of the neck for local cooling is similar to that of the face obtained in the chapter 3 (Figs. 3-4*D, E* and 3-6*D, E*), and is different from that of the abdomen (Figs. 4-3*D, E* and 4-5*D, E*). On the other hand, local warming of the neck produced the same degree of comfort as local warming of the abdomen both during mild heat and cold exposure (Figs. 4-4*D, E* and 4-6*D, E*), and this characteristic of the neck for local warming is different from the face. Thus, for local cooling the neck is similar to the face, and for local warming the neck is similar to the abdomen.

Mechanism for the regional difference in thermal comfort

Dominant nerve

Distinct difference in thermal comfort between the face and abdomen was observed in the chapter 3 (65). The face is innervated by trigeminal nerves, on the other hand, the abdomen is innervated spinal nerve. This difference of the dominant nerve might be the origin of the regional differences in thermal comfort. In the present study the regional differences were observed among the neck, abdomen, hand, and sole, all these areas investigated in this study are innervated by the spinal nerve. Therefore the regional difference in thermal comfort cannot be explained simply by which the trigeminal or spinal nerve innervation.

Distribution of peripheral warm and cold spots over the body surface

The neck is one of the areas where both warm and cold spots are particularly dense (Fig. 1-5, 6) (49, 82, 85). This high density might explain the distinct change of the local and whole-body thermal comfort by stimulation of the neck in the heat and cold exposure experiment. On the other hand, the abdomen have particularly dense cold spots too (49, 82). While thermal stimulation, especially cooling, of the abdomen produced a distinct change in thermal comfort during cold exposure, the same stimulation during heat exposure had a minor effect for the local and whole-body thermal comfort. Although the sole is one of the areas where both warm and cold spots are the most thinly dense (49, 82, 85), the warming of the soles produced equally strong local thermal comfort as warming of the other three areas (Fig. 4-4*D* and 4-6*D*), and even stronger local thermal comfort produced by cooling of the soles than by the abdominal cooling in the heat exposure experiment (Fig. 4-3*D*). Thus, the location-dependent effect of thermal stimulation on thermal comfort cannot be explained simply by the density of cold or warm spots.

Regional difference in effect for "local" and "whole-body" thermal comfort

While no regional difference in "local" thermal comfort was observed between the hand and neck, the magnitude of "whole-body" thermal comfort changes during the thermal stimulations were smaller for the hand than for the neck (Figs. 4-3*D, E* and 4-6*D, E*). In the previous study, it is reported that the limb extremities ranked as the least thermosensitive segment for whole-body thermal comfort (2, 16). The densities of warm and cold spots are lower for the hand than for the neck (49, 82, 85). Although the lower distribution of warm and cold spots might be related to the low sensitivity for "whole-body" thermal comfort, as mentioned above the regional difference in thermal comfort could not be explained simply by the distribution of hot and cold spot.

The threshold of warm or cold sensation for change of skin temperature are lower when the two hands or forearms were simultaneously stimulated than when either hand or forearm was stimulated alone (34, 73). In the present study, only left hand was stimulated, and other three areas were stimulated symmetrically. The less change of “whole-body” thermal comfort during the stimulation of hand might be caused by the unilateral stimulation. While thermal stimulation of bilateral hand might produce bigger change of whole-body thermal comfort than the stimulation of unilateral hand, further experiments are required to answer this question.

It was implicated that the amygdala plays a role in the genesis of “whole-body” thermal discomfort due to cold (41). On the other hand, other studies suggested that activation of the frontal gyrus, the striatum, and the cerebellum related to “local” thermal pleasant feelings (71, 84), and activations in the lateral parts of the orbitofrontal cortex were correlated with the “local” unpleasantness of the thermal stimuli (71). For the genesis of “local” thermal comfort and “whole-body” thermal comfort, the different areas in the brain might be involved. Therefore the phenomenon that the regional differences in the effect for “whole-body” thermal comfort vary from the regional differences in “local” thermal comfort could be programmed in the brain.

Meaning of the regional difference in thermal comfort

The extremities

We obtain information concerning the thermal condition of external objects mainly by touching it with the hand. As for the soles, especially in ancient times humans had not put on shoes, and the soles touched the cold or hot ground. Further the extremities have arteriovenous anastomoses (AVAs). During hyperthermia AVAs dilate and promote dumping of heat as the blood passes through the cutaneous venous system, and constricted to prevent heat dissipation in hypothermic condition (29). Therefore the hands and soles inevitably show large temperature fluctuation. If the peripheral parts were sensitive for whole-body comfort like the neck, for example we would frequently feel whole-body thermal discomfort, which should be very stressful. Therefore insensitivity of the peripheral part for whole-body thermal comfort is advantageous. However as noted above the hand is used to judge the thermal condition of external objects. It is convincible that the hand has equal sensitivity for "local" thermal comfort to the other parts, although hand is insensitive for "whole-body" thermal comfort.

The neck

The characteristic in thermal comfort of the face and trunk observed in the chapter 3 are consistent with the biological roles of each body part. Preference for a cool face would help avoid heat-induced damage to the brain, and preference for a warm trunk areas would help to facilitate the function of the internal organs (65). The characteristic in thermal comfort of the neck was just in between those of the face and abdomen. Because there is no brain nor internal organs in the neck, characteristics in thermal comfort like that of the face and trunk would not have been developed firmly for the neck.

In summary, although there was no difference between "local" thermal comfort of the hand and neck, thermal stimulation of the hand produced less effect on "whole-body" thermal comfort than the stimulation of the neck. And although the hand and sole showed larger skin temperature change than the neck, local and whole-body thermal comfort was never stronger for the hand and sole than the neck. Characteristic in thermal comfort of the neck was similar to that of the face for local cooling, and similar to that of the abdomen for local warming.

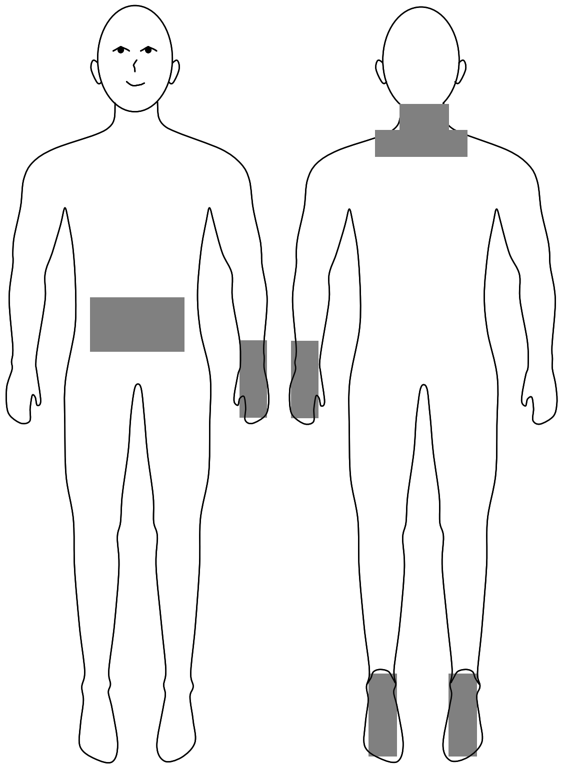

Figure 4-1. Locations of the areas which were thermally stimulated.

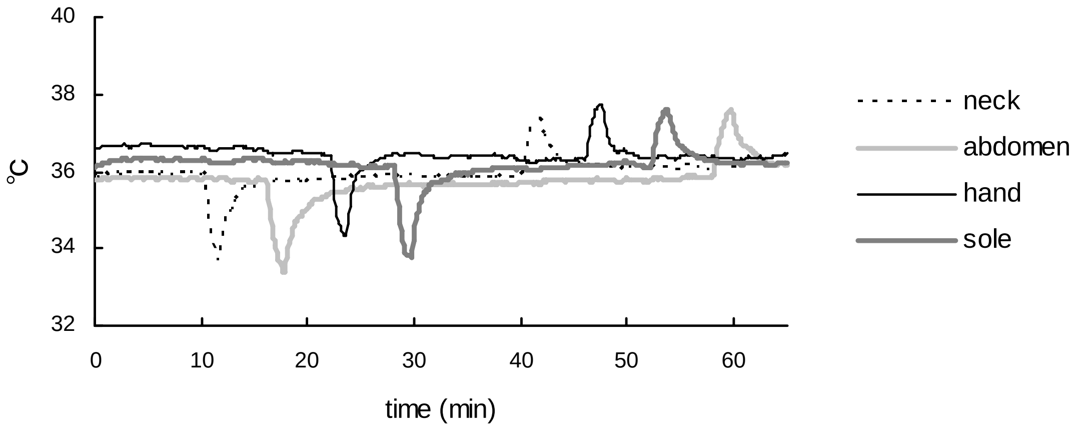

Figure 4-2. Typical example of skin temperature change during local warming and cooling of four stimulated areas in one subject.

Experiment 5

Mild heat exposure + Local cooling

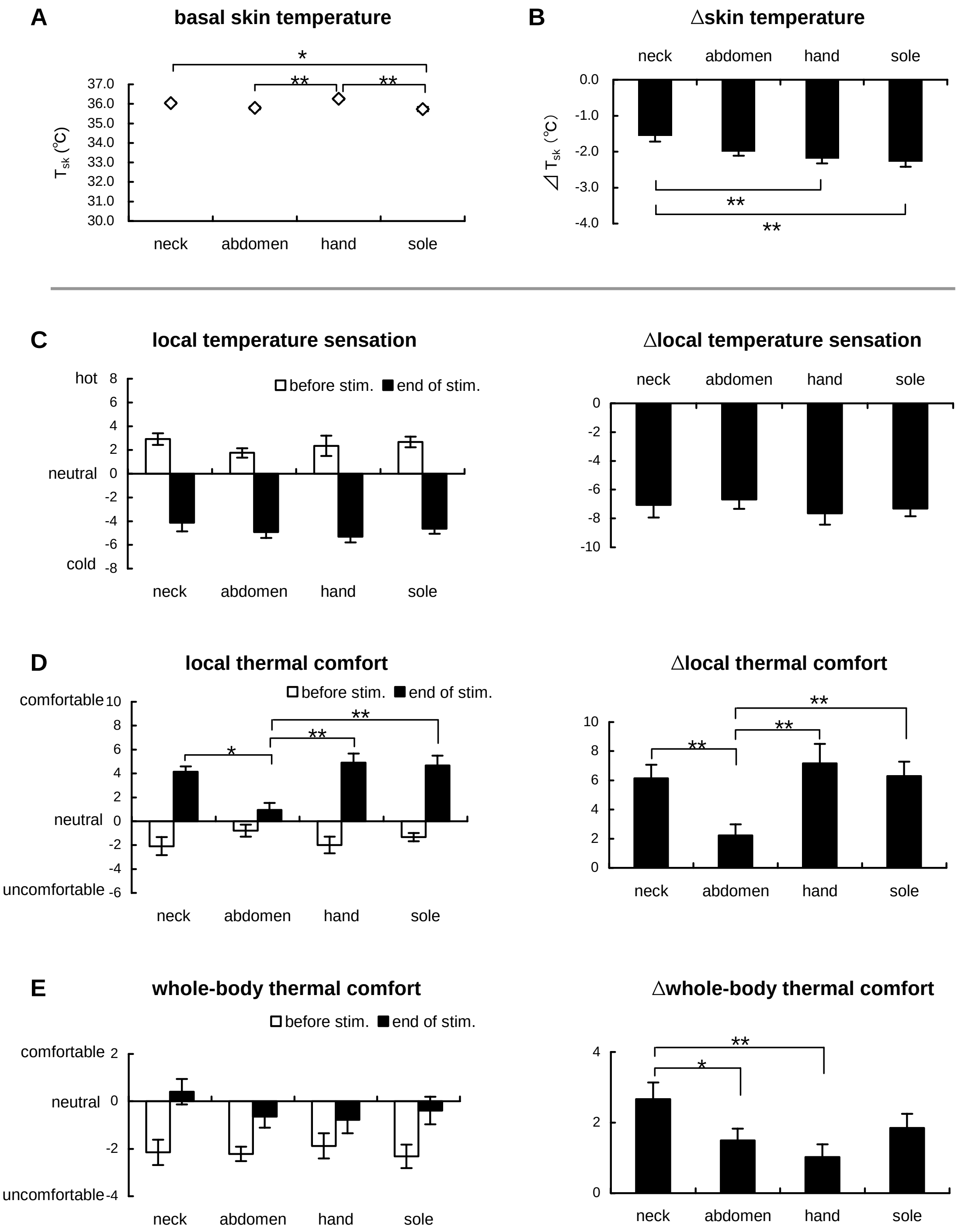

Figure 4-3. Local skin temperature and temperature-related sensations during local cooling of four areas in mild heat exposure experiment. A: local skin temperature at the start of cooling. B: magnitude of local skin temperature changes during 90 s of cooling. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of cooling of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of cooling of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of cooling of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 11). *P < 0.05, **P < 0.01, significant differences among the four stimulated sites.

Experiment 5

Mild heat exposure + Local warming

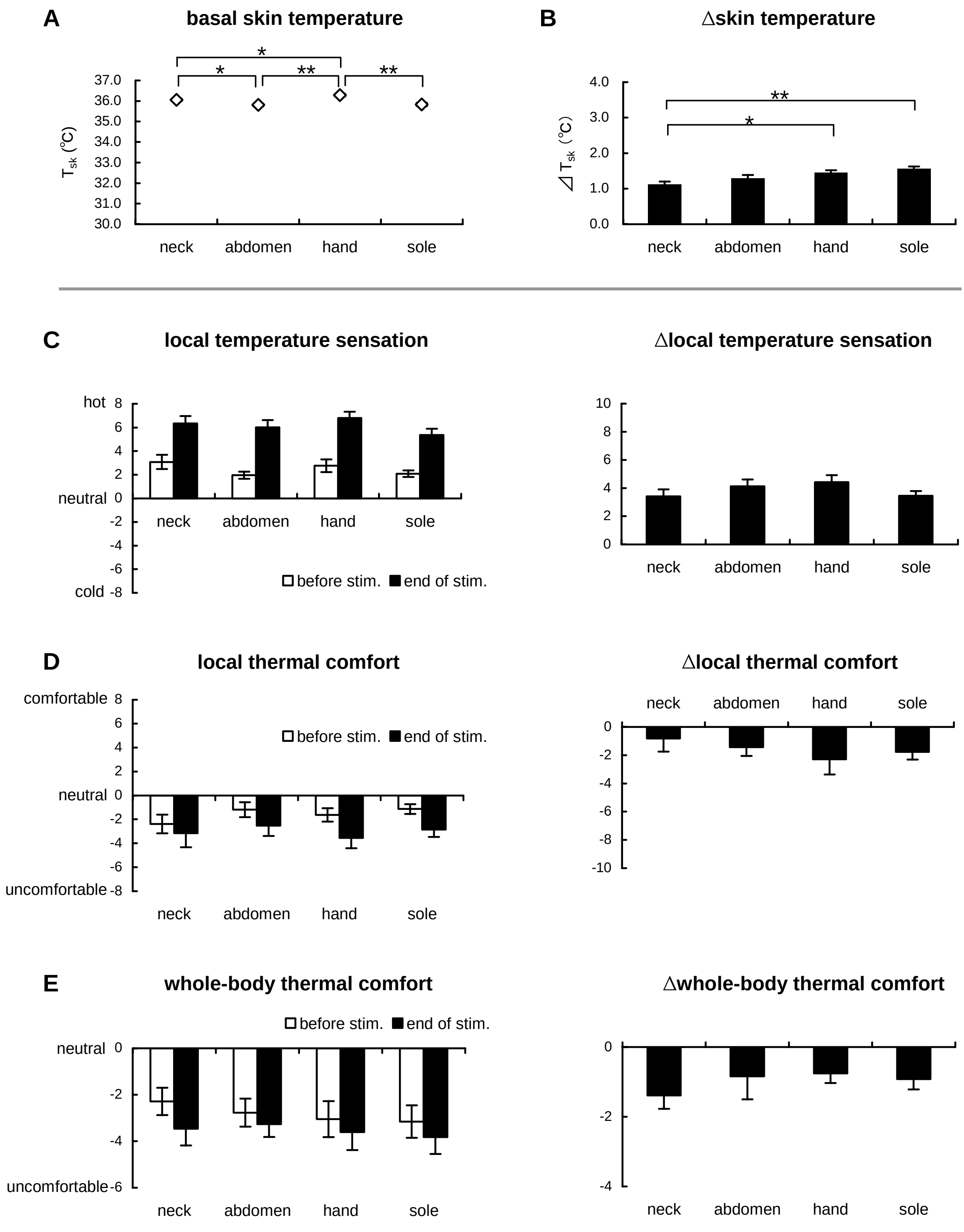

Figure 4-4. Local skin temperature and temperature-related sensations during local warming of four areas in mild heat exposure experiment. A: local skin temperature at the start of warming. B: magnitude of local skin temperature changes during 90 s of warming. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of warming of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of warming of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of warming of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 11). *P < 0.05, **P < 0.01, significant differences among the four stimulated sites.

Experiment 6

Mild cold exposure + Local cooling

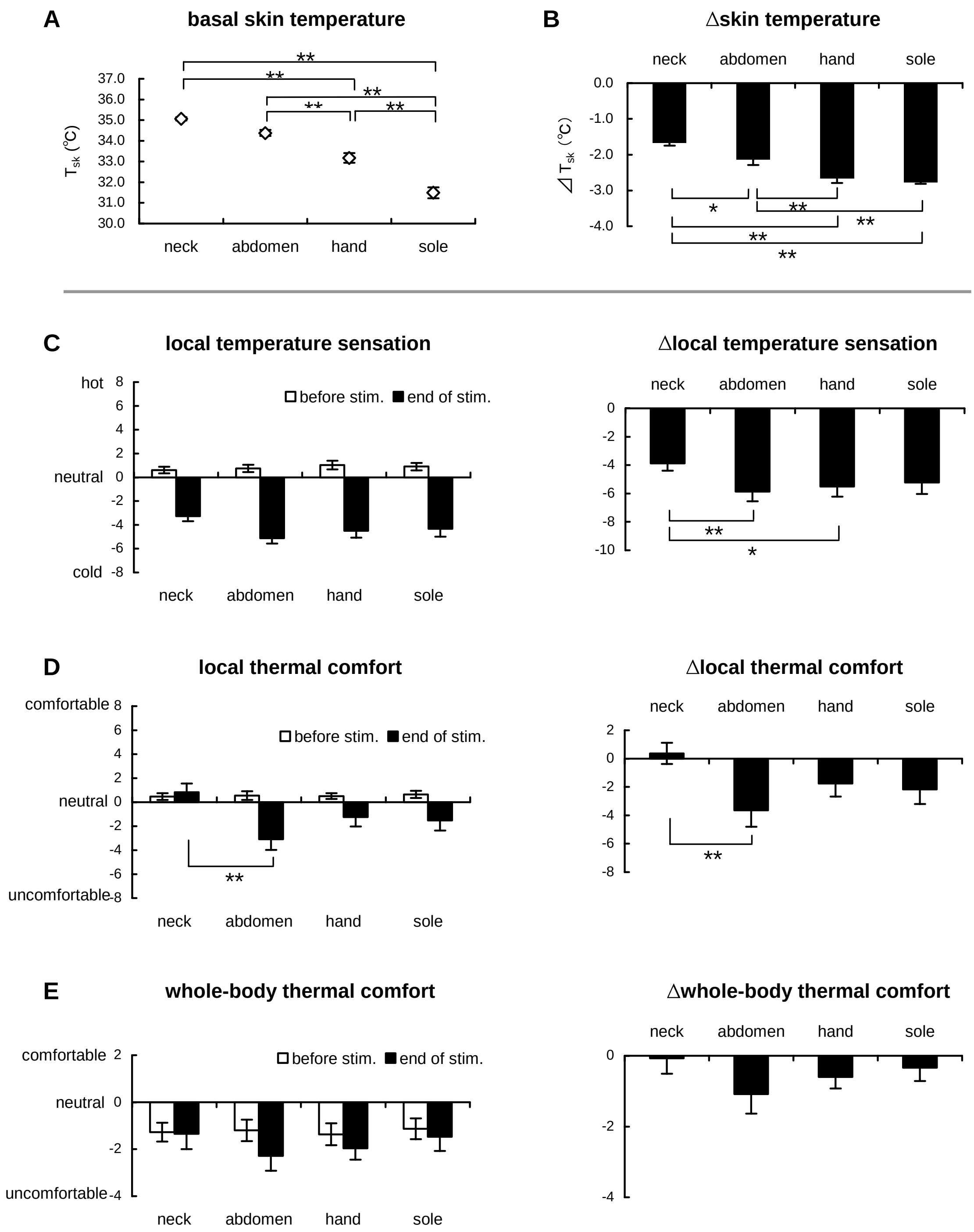

Figure 4-5. Local skin temperature and temperature-related sensations during local cooling of four areas in mild cold exposure experiment. A: local skin temperature at the start of cooling. B: magnitude of local skin temperature changes during 90 s of cooling. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of cooling of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of cooling of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of cooling of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 10). *P < 0.05, **P < 0.01, significant differences among the four stimulated sites.

Experiment 6

Mild cold exposure + Local warming

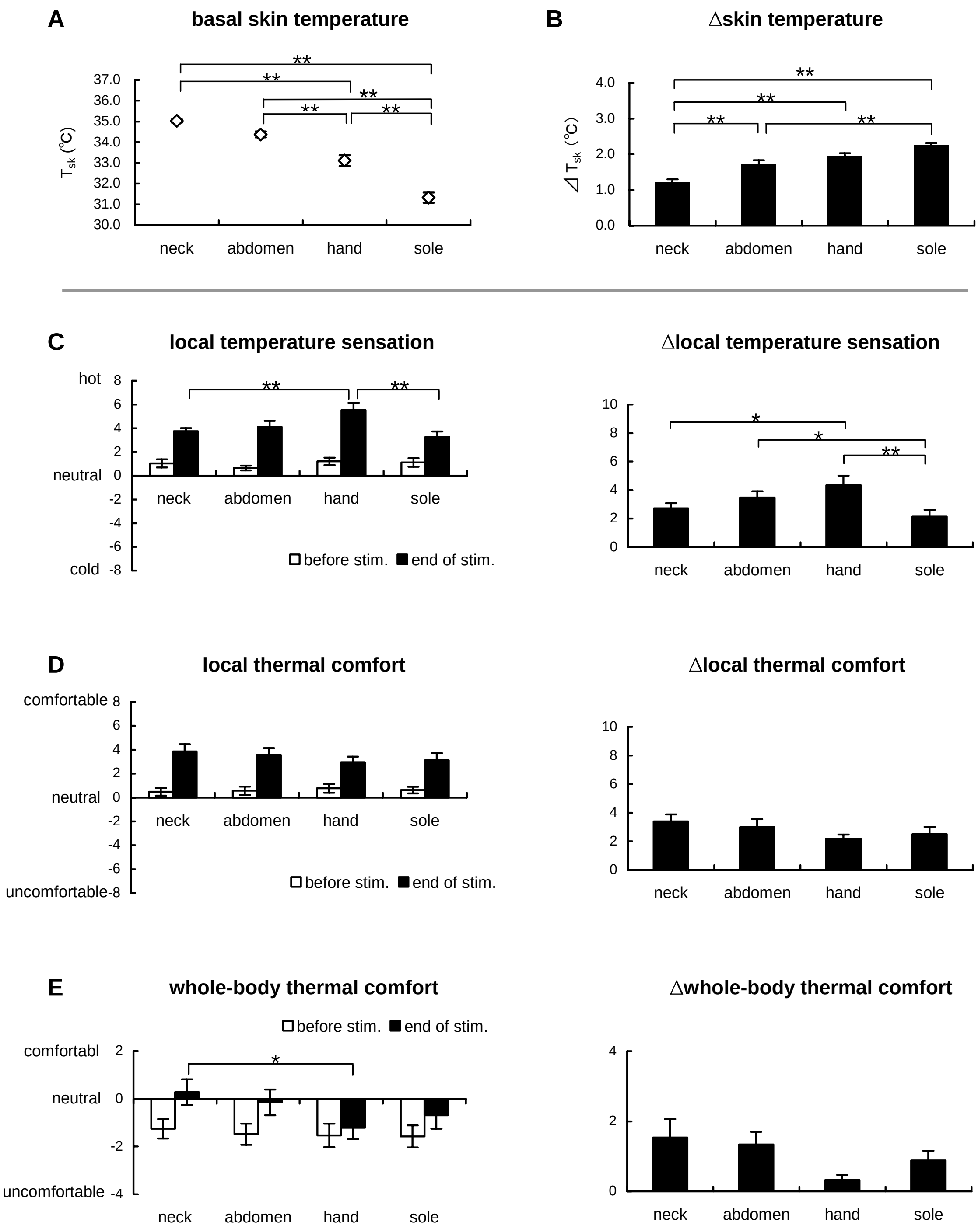

Figure 4-6. Local skin temperature and temperature-related sensations during local warming of four areas in mild cold exposure experiment. A: local skin temperature at the start of warming. B: magnitude of local skin temperature changes during 90 s of warming. C left: local temperature sensation of areas stimulated. C right: magnitude of local temperature sensation changes during 90 s of warming of areas stimulated. D left: local thermal comfort of areas stimulated. D right: magnitude of local thermal comfort changes during 90 s of warming of areas stimulated. E left: whole-body thermal comfort during the stimulation of each area. E right: magnitude of whole-body thermal comfort changes during 90 s of warming of areas stimulated. In left graph of C-E white bars show the sensations before stimulation and black bars show the sensations at the end of stimulation. Values are means ± S.E.M. (n = 10). *$P < 0.05$, **$P < 0.01$, significant differences among the four stimulated sites.

Chapter 5

General discussion

In the present study, I examined regional differences in temperature-related sensations with special attention to "thermal comfort". In chapter 2, I reported a new system for monitoring sensations of many body parts as well as comprehensively showing the distribution of overall skin temperature and temperature-related sensations. In chapter 3, regional differences in temperature sensation and thermal comfort among the face, chest, abdomen, and thigh was investigated. The thermal comfort seen in this chapter suggests that if given the chance, humans would preferentially cool the head in the heat, and maintain the warmth of the trunk areas in the cold. And thermal comfort was never stronger for the thigh, although the ΔT_{sk} was always larger than that of other areas in all four conditions. In chapter 4, regional differences in temperature sensation and thermal comfort among the neck, abdomen, hand, and sole was investigated. Although there was no difference between "local" thermal comfort of the hand and neck, thermal stimulation of the hand produced less effect on "whole-body" thermal comfort than the stimulation of the neck. In addition, although the hand and sole showed larger skin temperature change than the neck, local and whole-body thermal comfort was never stronger for the hand and sole than the neck. And characteristic in thermal comfort of the neck was similar to that of the face for local cooling, and similar to that of the abdomen for local warming. By combining the data obtained in the chapter 3 and 4, Fig. 5-1, 2, 3, 4 show magnitudes of local and whole-body thermal comfort changes during 90 s of thermal stimulation that are normalized with those of the abdomen. During mild heat exposure facial cooling and warming had great effect for thermal comfort (Fig. 5-1, 3). On the other hand, during mild cold exposure the face was not sensitive and the abdominal cooling and warming had strong effect for producing thermal comfort among the seven parts (Fig. 5-2, 4). Meanwhile, the hand and sole did not have major effect during mild heat nor cold exposure. Fig. 5-5 summarizes the regional characteristics in thermal comfort observed in the present study. These regional differences cannot be explained solely by the density or properties of the peripheral thermal receptors, and consistent with the biological roles of each body part.

Speculation about representation of the regional difference in temperature sensation and thermal comfort in the brain

Regional differences in thermal comfort investigated in this dissertation cannot be explained solely by the density or properties of the peripheral thermal receptors, and consistent with the biological roles of each body part. Therefore I speculate that a CNS map weighing the input from each body area would be involved in the production of regional differences in thermal comfort.

Over the primary somatosensory cortex, the regional differences in tactile sensitivity is clearly represented as Homunculus (68). Likewise the temperature sensitivity of all over the body surface might be represented in some region of the brain. Thermal signals from skin seem to reach several different regions in the cerebral cortex, including the insula, primary and secondary somatosensory (SI and SII), orbitofrontal, and cingulated cortices (7, 18, 23, 76). The regional difference in temperature sensation might be represented as a somatotopic map in these regions. Further studies are necessary to answer this question.

The regional sensitivity in thermal comfort is changed with whole-body thermal condition. Therefore, the representation like the homunculus for mechanical sensation might be too simple for the thermal comfort. For the production of the local thermal comfort, the temperature information of local body surface, overall skin, and body core should be integrated. It will be of interest to determine the mechanisms how the regional differences in thermal comfort are generated, because they do not depend on the regional difference in "temperature sensation" and are consistent with the biological roles of each body part.

Regional sensitivity in pain or tactile sensation

Thermal sensation and pain are common in that information from the skin once change synapses in the dorsal horn and is conveyed through the contralateral spino-thalamic tract to the higher brain (21, 37). However, the density of pain spots is very high, about 10 times as large as that of cold spots all over the body surface (49, 81). Strughold investigated distribution of the pain spots on forty two areas all over the body surface (81). While the hand finger, sole, nose, and ear have thin density, the all other parts have high density of pain spots. Therefore it could be said that we have high sensitivity overall the body surface with little regional differences. This overall high sensitivity with little regional differences in pain is not similar to the regional difference in temperature sensation and thermal comfort. Because the sensation of pain is the invasive signal, we have to avoid the pain stimulation. Otherwise our body get damaged. Therefore the high density of pain spots is important for us to survive.

The regional difference in tactile sensation is also not the same as the regional difference in temperature sensation and thermal comfort. For example, while the abdomen has superior sensitivity in temperature sensation and thermal comfort to the other body regions in cold or neutral environment (Fig. 3-6, 4-5, 5-2,4) (65, 77), it have far low sensitivity in tactile sensation than the hand and face (78, 88). The hands, especially the fingers, have definitely high sensitivity to the tactile sensation among all over the body surface although the sensitivity of temperature sensation is not especially high. We obtain information concerning roughness, stiffness, form, and size of external objects, and make or manipulate various things mainly by the hands. Superior sensitivity to the tactile sensation of hands should be helpful to carry out such a task with hands. On the other hand, the abdomen does not have such roles. Therefore the high sensitivity in tactile sensation should not be needed for the abdomen.

Thus each sensory modality has the different regional sensitivity that reflects important aspects of the each body area's functional roles.

Limitation and future direction

In chapter 3 and 4, I investigated only temperature sensation and thermal comfort in responses to the 90 s thermal stimulation. Neither T_{co} nor mean T_{sk} changed during the stimulation, and change of autonomic thermoregulatory responses, such as cutaneous vasomotion, non-shivering thermogenesis, shivering, sweat secretion, would be small, if any. It would be interesting to see how the regional differences in thermal comfort were altered, and how the autonomic responses change by longer periods of thermal stimulation. As we tested only in mild heat and mild cold ambient temperatures, and only in male subjects, it would be interesting to know how these regional differences in thermal comfort might be changed in more severe thermal condition, during exercise, and/or in female subjects. Further, in the present study I did not test the back, loin, and arm. It would be valuable to examine the thermal and comfort sensitivities of such body areas.

The mechanisms that generate the regional differences in thermal comfort could not be examined in this study. Investigating regional activation of the brain during the same thermal stimulation as this study should become a clue to clarify the mechanisms. These knowledge will be valuable not only for physiological understanding. The results will also aid in efficient conditioning of thermal environment for making comfortable condition, prevention of heat stroke, improvement sport performance, normalization hypothermia or hyperthermia. Efficient conditioning practices of thermal comfortable environment should be helpful to keep our health, promote energy saving, by extension, prevent the environmental destruction of our planet.

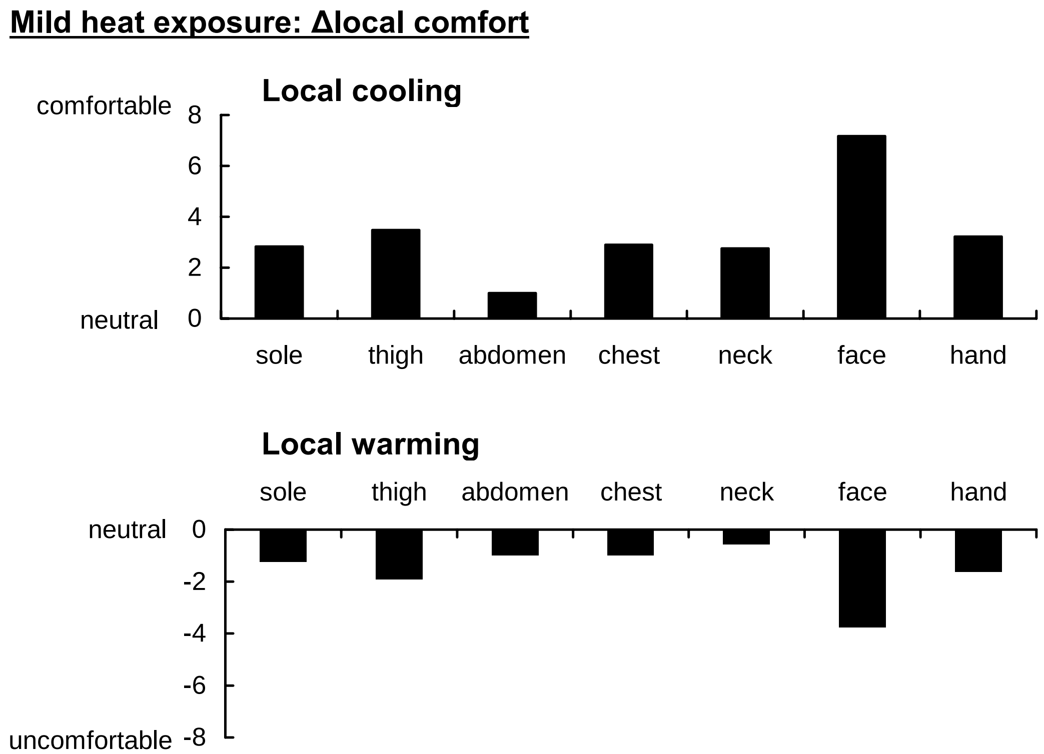

Figure 5-1. Magnitude of local thermal comfort changes during 90 s of thermal stimulation of areas stimulated during mild heat exposure normalized to that of the abdomen in the chapter 3 and 4.

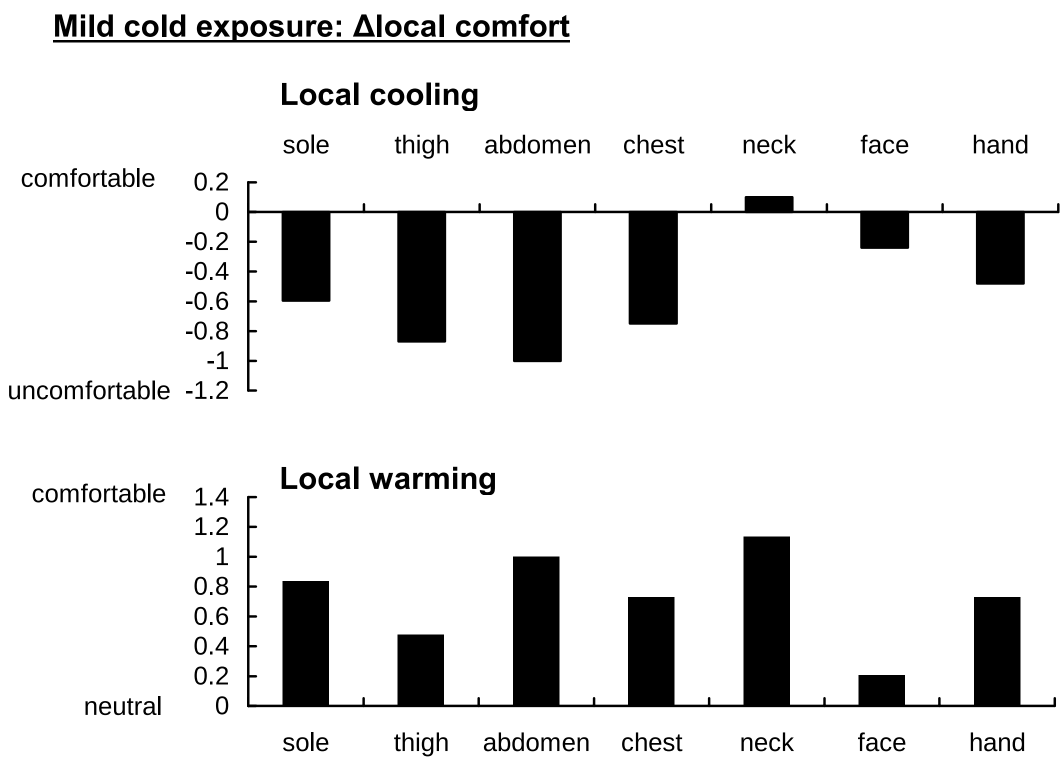

Figure 5-2. Magnitude of local thermal comfort changes during 90 s of thermal stimulation of areas stimulated during mild cold exposure normalized to that of the abdomen in the chapter 3 and 4.

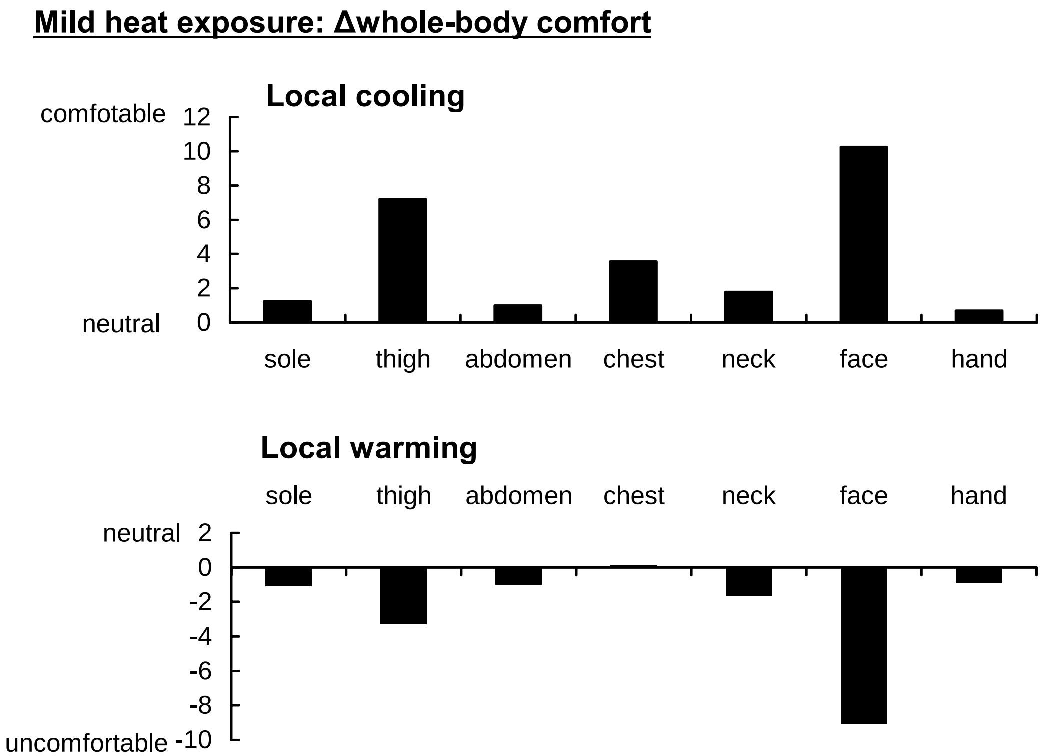

Figure 5-3. Magnitude of whole-body thermal comfort changes during 90 s of thermal stimulation of areas stimulated during mild heat exposure normalized to that of the abdomen in the chapter 3 and 4.

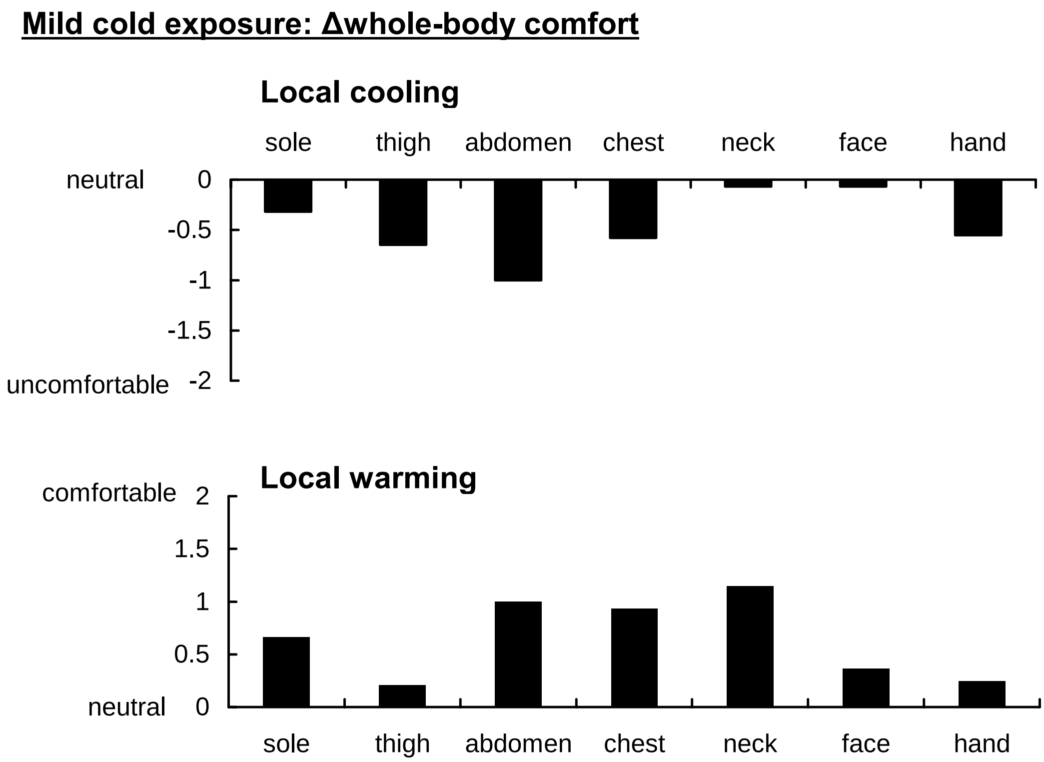

Figure 5-4. Magnitude of whole-body thermal comfort changes during 90 s of thermal stimulation of areas stimulated during mild cold exposure normalized to that of the abdomen in the chapter 3 and 4.

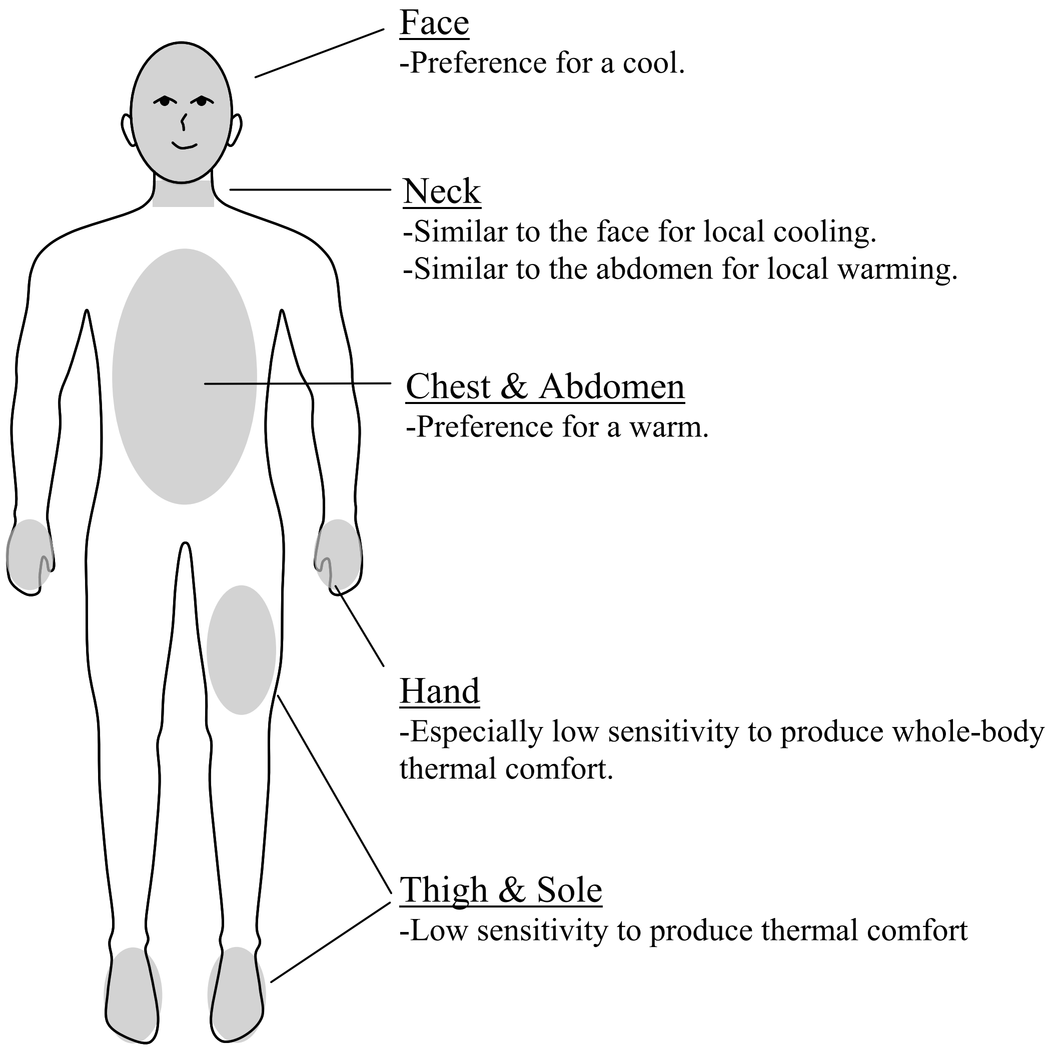

Figure 5-5. Regional characteristics in thermal comfort.

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