

Thermoregulatory responses of young and elderly adults under temperature ramps

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ABSTRACT

As the world population ages, there is a growing focus on the health and well-being of elderly individuals. In line with this, research findings are now highlighting the potential threats that extreme climates pose to the health of the elderly. Therefore, this study aims to investigate age differences in thermoregulatory abilities under various temperature ramps. This study collected physiological and psychological responses from 20 elderly and 20 younger subjects in experiments involving four different temperature ramp types. The statistical approach was used to analyze the differences between ages and types of temperature ramps, and the results were analyzed in the view of thermoregulatory mechanisms. The results showed significant differences in thermoregulatory abilities between young and elderly subjects. By analyzing the overshooting and stabilization time, elderly individuals were found to have insensitive thermoreceptors and were more likely to have risks in maintaining homeostasis. Additionally, the study found that different types of temperature ramp affected thermoregulatory abilities differently for both age groups. This study can contribute by suggesting guidelines for elderly individuals regarding temperature ramps that can be formed outdoors and indoors.

1. Introduction

1.1. Research background

'Lonely death' of elderly individuals is a phenomenon that has emerged as a poignant issue in various countries due to the aging population. About 700 elderly individuals in South Korea died alone in 2022, while Japan saw a doubling of lonely deaths from 1,451 in 2003 to 2,869 in 2013 [1,2]. The global population is rapidly aging due to longer life spans of elderly individuals with advancements in healthcare and improved living conditions. Data from World Population Prospects in 2019 says that one in six people in the world will be over age 65, and the number of people over 80 will be tripled from 143 million in 2019 to 426 million in 2050 [3]. This demographic shift brings numerous challenges, including the health and wellness of elderly individuals. The focus has also changed from merely living longer to enhancing the quality of life. Promoting healthy aging is a prominent area of focus, as demonstrated by its inclusion in the WHO's Ageing and Health program [4]. In response to these demands, an extensive body of research and policies to enhance the health and wellness of elderly individuals have been investigated.

Recently, the possible correlation between the thermal environment and the mortality of elderly individuals has been discovered. Due to global warming, extreme climates and weather are formed worldwide, and temperature ramps made by heat and cold waves affect elderly individuals' health. Iniguez et al.(2010) discovered a 4.83% rise in the mortality rate for individuals aged 70 or above for each 1 °C increment in temperature [5]. Vaneckova et al.(2010) discovered a temperature increase of 10 °C corresponded to a mortality rate of the elderly increase of up to 21.8% [6]. National Institute on Aging and governments of various nations also warn about the effects of heatwave and coldwave on elderly individuals such as heatstroke and hypothermia [7,8]. In this regard, appropriate thermal environments should be provided to elderly individuals to prevent unexpected death caused by extreme temperature ramps. Therefore, this study aims to investigate the age differences in thermoregulatory responses.

1.2. Thermoregulation

1.2.1. Thermoregulatory mechanism

Thermoregulation is a physiological mechanism by which an organism maintains its body temperature within a certain range via a

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negative feedback loop [9]. The hypothalamus in the cerebrum controls this mechanism, which is a representative example of homeostasis, the ability of the body to maintain its condition at a certain level in response to a changing external environment. As shown in Fig. 1(A), the thermoregulatory mechanism consists of three basic components: thermoreceptors, control center, and effectors. First, thermosensitive neurons and thermoreceptors detect rapid fluctuations in body temperature according to the surrounding thermal environment and transmit information about the thermal state to the hypothalamus in the brain [10, 11]. Next, the control center (i.e., the hypothalamus in the brain) compares the current body temperature that acquired from thermoreceptors with the set point value. If the body temperature deviates from the set point range, the control center transmits signals through efferent neurons to specific effectors, such as skin tissue and skeletal muscles. Lastly, effectors respond to the signals to set out heat loss or heat conservation mechanisms such as sweating and dilating or constricting blood vessels to get body temperature back [12,13].

1.2.2. Thermoregulatory responses to the temperature ramp

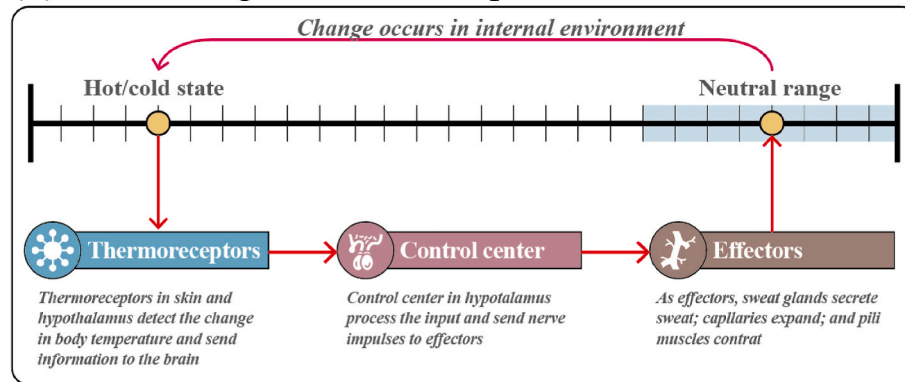
Temperature ramps are extreme or gradual temperature changes that occupants experience over time. These temperature ramps occur when occupants move from outdoors to indoors or between indoor spaces, or when they use a heating and cooling system while staying indoors. Several studies stated that sudden changes in indoor temperature can cause thermal discomfort and stress on the thermoregulatory system [14]. In particular, such a temperature ramp occurs frequently in summer and winter, when there is a large difference between indoor and outdoor temperatures. Therefore, exploring a method to reduce thermal discomfort based on the analysis of occupants' thermoregulatory responses is necessary.

Fig. 1(B) shows the thermoregulatory response according to the time exposed to the temperature ramp. This characteristic lies in the difference between the initial and subsequent reactions to the temperature ramp. The most typical characteristic is overshooting, which occurs at the beginning of the exposure. This phenomenon is described as an initial overreaction to a thermal stimulus, which may cause it to be perceived as warmer or colder than its actual temperature [15,16]. When a temperature change occurs, more thermoreceptors increase their firing rates to send additional high-frequency impulses to the brain. This can amplify psychological and physiological responses because the brain receives stronger signals than normal [17]. However, as the time exposed to the temperature ramp increases, the firing rate of thermoreceptors stabilizes, and the physiological response returns to its pre-exposure level or maintains a level within a certain range [18]. Multiple chamber experiments have investigated this phenomenon of thermoregulation [14,19,20].

1.2.3. Thermoregulation of elderly individuals

Various experimental studies have been conducted in accordance with the Predicted Mean Vote (PMV) and ASHRAE Standard 55 to improve thermal comfort for occupants. However, as research results revealed age differences in physiological and psychological responses [21–23], efforts have been put into studies to improve limitations of the existing standards that did not consider the age differences. According to previous studies, elderly individuals prefer a room temperature similar to that of young individuals, but they lack the ability to recognize and adjust the room temperature [24]. That is, elderly individuals are more likely to be exposed to an inappropriate thermal environment. As people age, they undergo various physical changes, such as decreased cardiac blood output, losing control over perspiration ability, decreased muscle

(A) Process of negative feedback loop



(B) Thermoregulatory responses to temperature ramp

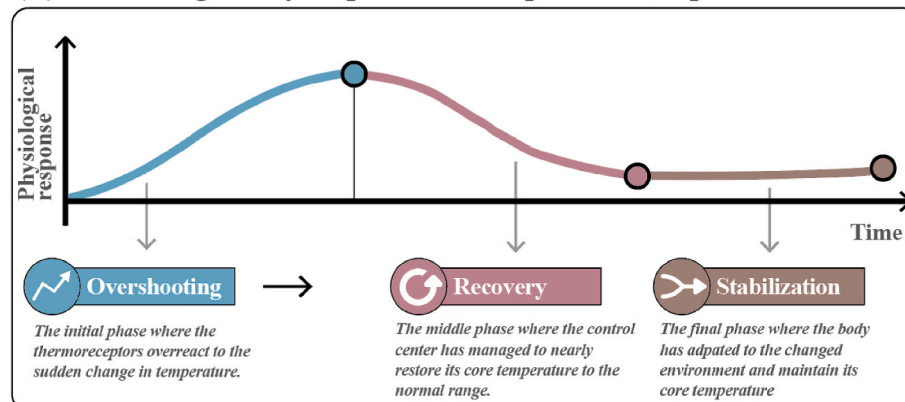


Fig. 1. (A) Process of negative feedback loop; and (B) thermoregulatory responses to temperature ramp.

mass/basal metabolic rate/thermal sensitivity, and increased body fat percentage [25–27]. Consequently, elderly individuals are at various risks due to the temperature ramp. First, aging affects cardiac function, which plays an important role in thermoregulatory [28]. It also reduces cardiac output and increases systemic vascular resistance, decreasing cutaneous blood flow, which is vital to thermoregulation [29]. Second, aging directly affects thermoregulatory mechanisms, such as vasoconstriction, vasorelaxation, or muscle tremors. In addition, elderly individuals have less contraction of blood vessels and less ability to perceive cooling in a cold environment and are subject to a decrease in sweat secretion, skin blood flow and cardiac output in a hot environment [30,31]. Third, the elderly generally has weaker homeostasis. For example, blood glucose levels (BG) generally maintain homeostasis due to insulin and glucagon secreted from the adrenal glands. However, as aging reduces the body's ability to produce or use insulin and glucagon effectively, elderly individuals are at a relatively higher risk of developing type 2 diabetes [32].

1.3. Research aim

With the growing importance of health and wellness among elderly individuals in an aging society and the increasing health risk due to

climate change, the need to investigate the effect of temperature ramp on the physiological response has been highlighted. Accordingly, studies have recently been undertaken to observe the thermoregulatory responses of the elderly population toward the thermal environment. Firstly, to overcome the limitation of general thermal comfort prediction models like PMV, age difference in thermal comfort or perceptions was investigated [33–36]. Natsume et al.(1992) found that there is age differences in thermal comfort and thermal sensitivity between young and old individuals [33]. On the contrary, Veronica et al.(2019) found that thermal comfort is not significantly correlated to frailty levels of the subjects [35]. However, these findings were mostly investigated in static environment without any temperature ramps. Also, earlier studies regarding age difference and thermal environment mostly focused on psychological responses under fixed thermal environments. To explore age differences in thermoregulatory abilities further, studies that observe physiological responses under temperature ramps were required. Wang et al.(2019) investigated elderly individuals' thermal perceptions and physiological responses to moderate temperature ramps ranging from 3 to 6 °C [37]. Wu et al.(2023) found age differences in local skin temperature (SKT) and blood pressure (BP) under continuous temperature ramps [38]. Previous studies found out age difference in physiological responses, but most of them did not analyze those

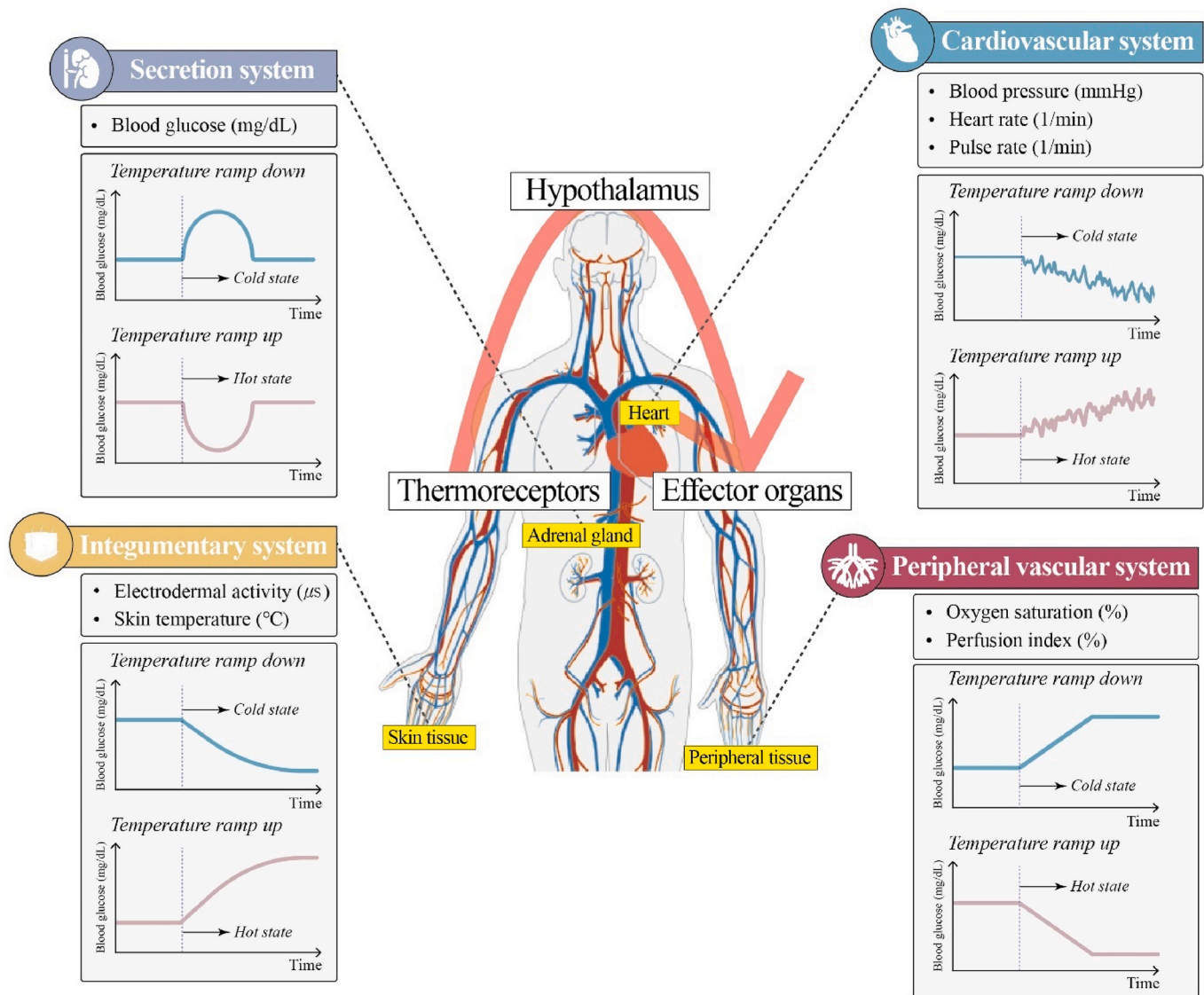


Fig. 2. Classification of physiological responses based on the category of effectors.

responses in the aspect of thermoregulatory mechanism. Additionally, the types of temperature ramps were not diverse enough to observe the thermoregulatory responses of the subjects.

Therefore, this study aims to observe the physiological responses of elderly and younger individuals under discrete and continuous temperature ramps and conduct a comparative analysis to statistically investigate differences between them. First, experiments were conducted with four different types of temperature ramps, collecting physiological responses from 20 elderly and 20 younger subjects. To this end, a statistical approach was then used to analyze the differences between the two age groups and the types and directions of temperature ramps.

2. Materials and methods

2.1. Data measurement

2.1.1. Physiological responses

Nine types of physiological responses related to thermoregulation were recorded in the experiment. Fig. 2 illustrates the classification of these physiological responses into three categories based on the effectors in the negative feedback loop: (i) the secretion system; (ii) the circulatory system consisting of cardiovascular system and peripheral vascular system; and (iv) the integumentary system.

In the secretion system, BG (mg/dL) that provides energy required for metabolic reactions was collected. BG is regulated by various hormones such as glucagon, adrenaline, and insulin. According to a general physiological theory, BG rises when the body is exposed to cold temperatures, while it tends to decrease when exposed to hot temperatures. Kingma et al. (2012) found that the change of BG is further maximized in a cold temperature zone [39]. However, since the result is obtained from the physiological thermoneutral zone (i.e., 26–32 °C), it is difficult to sufficiently explain the result of changing pattern of BG in an extreme thermal environment. Kim et al. (2022) investigated BG changes in response to extreme temperatures and both hot and cold states resulted in decrease in BG [40]. Though the changing pattern of BG according to the thermal temperature is not consistent, the value changes to produce or store energy necessary for metabolic reactions, and it tends to return to the value due to homeostasis. In this experiment, the non-invasive continuous glucose monitoring system (CGMS) was utilized to measure BG. Specifically, the CGMS device used in this study was the FreeStyle Libre 2 (Abbott, USA).

In the circulatory system, six types of physiological responses, such as systolic BP (SBP, mmHg), diastolic BP (DBP, mmHg), heart rate (HR, 1/min), pulse rate (PR, 1/min), oxygen saturation (OS, %), and perfusion index (PI, %), were measured. First, the cardiovascular system is generally regulated by cardiac output and plays an important role in thermoregulation. According to the general physiological theory, BP can be affected by alterations in the blood flow within the skin, which is controlled through vasodilation and vasoconstriction of blood vessels in the skin [41,42]. SBP and DBP were collected using an automated BP monitor (HEM-7600T, Omron, Japan). HR and PR could reflect the human body's metabolism and cardiac output. Wu et al. (2022) [43] and Jia et al. (2022) [44] demonstrated heart rate was affected significantly under temperature changes. HR was collected using the E4 wristband (E4, Empatica Inc, USA), which utilizes a photoplethysmography sensor to measure the blood flow volume and calculates HR automatically. PR was collected using a MightySat fingertip oximeter (MightySat, Masimo, Japan). Similarly, the peripheral vascular system is also subject to the influence of cardiac output and is affected by temperature ramps. OS refers to the amount of oxygen bound to hemoglobin in the blood. PI refers to peripheral perfusion and quantifies the proportion of the arterial blood flow relative to the non-pulsatile blood flow [45]. According to the general physiological theory, exposure to cold temperatures lowers OS and PI because blood flow to the peripheral tissues decreases due to vasoconstriction.

In the integumentary system, EDA (μS) and SKT ($^{\circ}\text{C}$) were measured using EDA electrodes and the infrared thermopile of the E4 wristband. EDA refers skin's electrical conductance, which changes in response to the activity of sweat glands. SKT refers to the thermal energy absorbed or released by the skin tissue. According to the general physiological theory, EDA and SKT tend to decrease in a cold environment because sweat glands are less active, and heat released from the skin transfers to the surroundings. On the other hand, they tend to increase in a hot environment because sweat production from sweat glands becomes active, and the skin tissue absorbs heat from the surrounding environment. Past studies found that SKT tends to be non-linear to the change in air temperatures [43,44,46,47]. It was also found that EDA tends to be proportional to air temperature [48,49].

2.1.2. Psychological responses

Two subjective questionnaires were used to collect thermal sensation vote (TSV) and thermal comfort vote (TCV) to confirm whether the temperature ramp intended in the experiment was appropriately made [40,50,51]. TSV refers to the subjective feeling of coldness or warmth experienced by a subject when exposed to a given thermal environment. It is typically assessed using a descriptive scale, such as the ASHRAE seven-point Likert scale (i.e., -3, -2, -1, 0, +1, +2, and +3 corresponding to cold, cool, slightly cool, moderate, slightly warm, warm, and hot). TCV measures the subjective assessment of thermal comfort in a given thermal environment. It is also often assessed on a descriptive scale such as a seven-point Likert scale (i.e., -3, -2, -1, 0, +1, +2, and +3 corresponding to very uncomfortable, uncomfortable, slightly uncomfortable, unclear, slightly comfortable, comfortable, and very comfortable).

2.2. Experiment design

2.2.1. Subject

In this study, the subjects recruited were divided into two groups, young individuals and elderly individuals, to analyze the age differences in physiological responses under temperature ramps. The age range of the 20s was set for young individuals, while the age group of 60 or older, the standard for aging specified by WHO, was set for elderly individuals [52]. However, since the experimental condition of this study included an extreme temperature ramp, elderly subjects were limited to those 69 or less in consideration of possible negative effects that this experiment might cause. 20 young and 20 elderly individuals were recruited for the study. The institutional review board (IRB) granted permission for this experiment, and experiments were carried out according to the approved procedures (IRB no. 7001988-202304-HR-1863-02).

All 40 subjects were healthy adults who met the age standard as of the experiment date and did not suffer from chronic diseases (e.g., diabetes, hypertension, anemia, stroke, and arrhythmia, etc.). The research team checked subjects' fasting BG and BP one or two days before the experiment. Individuals who had BG and BP within the normal range were eligible to participate as subjects in the experiment. After confirming that the criteria for the experiment, the CGMS was attached to them 1–2 days before the experiment. Table 1 shows the demographic statements of the subjects. As a result, 20 young and 20 elderly subjects that were 24.2 ± 2.6 and 63 ± 2.4 years old respectively participated in the experiment. Young subjects consisted of 10 females

Table 1
Demographic statements of the subjects.

Criteria	Young subjects (n = 20)	Elderly subjects (n = 20)
	Mean $\pm$ SD	Mean $\pm$ SD
Age (year)	24.2 ± 2.6	63 ± 2.4
BMI ^a (kg/m ²)	21.9 ± 2.9	22.7 ± 1.4
Fasting BG ^b (mg/dL)	89.4 ± 5.6	90.8 ± 6.9

Note: BMI stands for the body mass index; and BG for blood glucose level.

and 10 males, while elderly subjects consisted of 15 females and 5 males. The body mass index indicated that none of the subjects was underweight or obese.

2.2.2. Temperature ramp

In this experiment, the subjects' physiological responses were observed according to the temperature ramps, which were formed using Room A and Room B (refer to Fig. 3). Room A is an artificial climate chamber ($W \times D \times H$: $2.8 \times 3.9 \times 2.4 \text{ m}^3$) where air temperature can be controlled ranging from 10 to 80 °C. Room B has an air conditioning system that can keep neutral thermal environment (i.e., 22–24 °C).

Four types of environmental conditions were set for the experiment by combining two types of temperature ramp (i.e., discrete and continuous ramps) and two directions of temperature ramp (i.e., up and down). As a result of referring to experiments in similar previous studies, most elderly subjects suffered difficulties performing experiments in a cold environment, so the ramp to the cold state was reduced by about 3 °C [37]. To sum up, the environmental conditions of this experiment can be described as follows (refer to Fig. 3):

- **Discrete ramp-up (DRU)**: subjects moving from neutral state (22–24 °C) in Room B to hot state (32–34 °C) in Room A
- **Discrete ramp-down (DRD)**: subjects moving from neutral state (22–24 °C) in Room B to cold state (15–17 °C) in Room A.
- **Continuous ramp-up (CRU)**: subjects staying in Room A changing from neutral (22–24 °C) to hot state (32–34 °C).
- **Continuous ramp-down (CRD)**: subjects staying in Room A changing from neutral (22–24 °C) cold state (15–17 °C).

2.2.3. Experiment procedure

Before the experiment, the research team provided a comprehensive explanation of the equipment and the experimental procedures. To eliminate external factors that may affect BG, the subjects were instructed to keep fasting for 8 h before the experiments, and their clothing value was set to 0.7 Clo. The research team obtained the

subjects' consent to participate in the experiment by having them sign the form. On the both days the experiments were conducted, subjects rested for 30 min so that they could acclimate to the built environment [43]. In addition, they were provided with a 30-min break after one experiment to eliminate external factors that may occur due to temperature changes in the previous experiment.

Every subject participated in four experiments involving environmental conditions (i.e., DRU, DRD, CRU, and CRD) described in 2.2.2. The experiments lasted for an hour each, and to avoid excessively long periods of fasting, subjects took part in only two experiments per day. To limit the fasting time or the degree of influence of environmental conditions in the previous experiment, environmental conditions were created in a random order, and one or two subjects participated in one experiment. Fig. 4 depicts the procedure of data collection. At the start of the experiment, the research team ran an E4 wristband and MightySat on the subjects to continuously monitor HR, PR, OS, PI, EDA, and SKT. Subjects were directed to tap CGMS with their smartphones to measure BG every 2 min, and the data were automatically saved on their smartphones. Every 5 min, the research team measured subjects' BP and instructed subjects to respond to questionnaires on TSV and TCV.

2.3. Data analysis

To statistically compare and analyze the thermoregulatory responses according to the age and temperature ramp, the following steps were conducted: (i) data preprocessing; (ii) thermoregulatory feature extraction; and (iii) statistical analysis (refer to Fig. 5). Data preprocessing and thermoregulatory feature extraction were performed using Python (3.9.7 version), and statistical analysis was conducted via a statistical package for the social sciences.

2.3.1. Data preprocessing

Table 2 shows the recording interval of nine physiological response data and the percentage of missing data. Missing data was primarily attributed to issues with the measuring equipment, such as fingertip

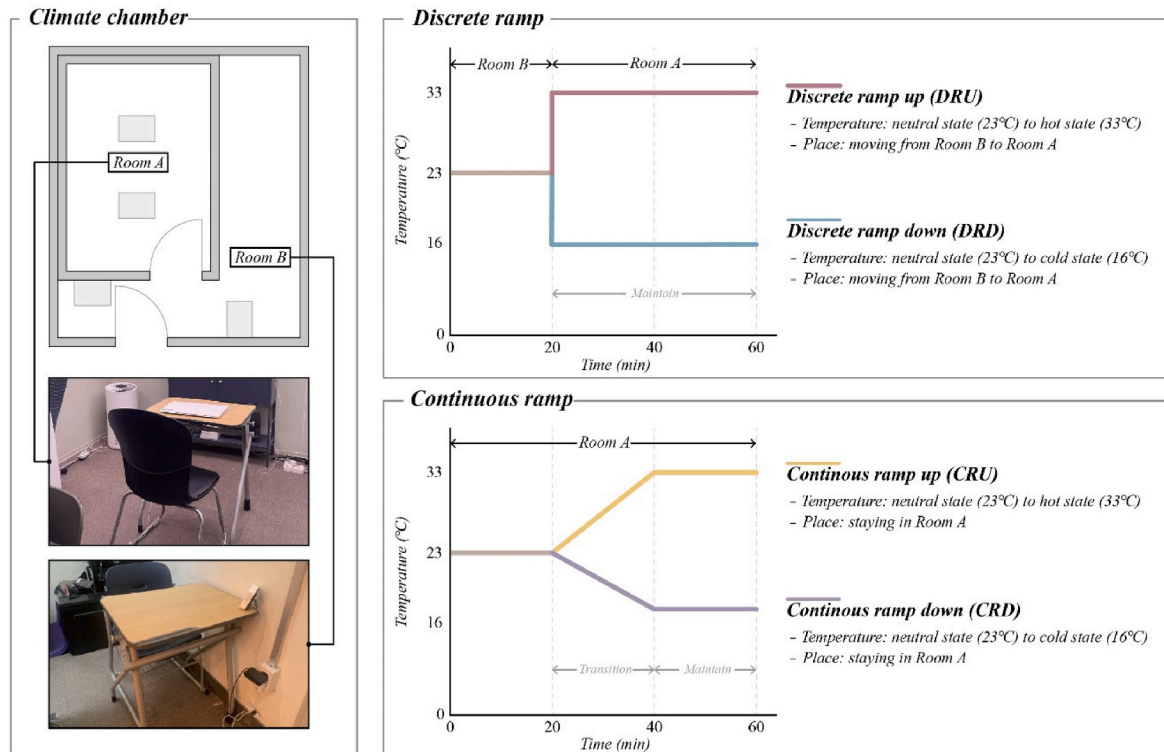


Fig. 3. Climate chamber and temperature ramp of experiment.

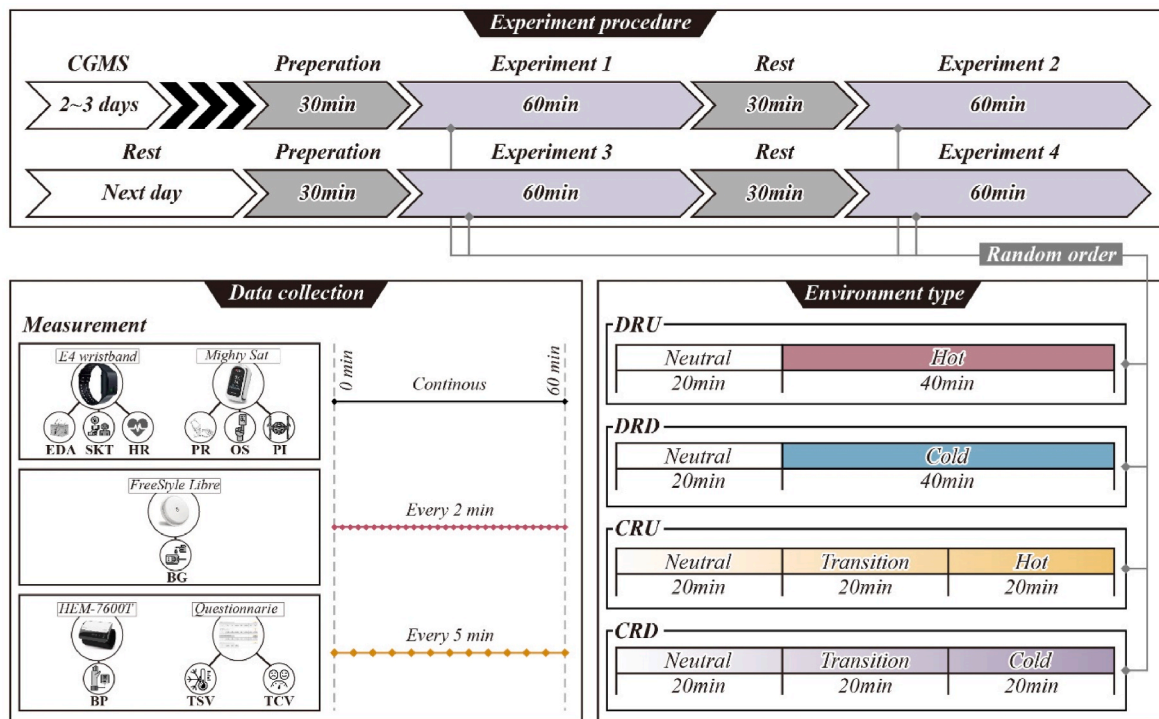


Fig. 4. Experiment procedure.

oximeters accidentally detaching from subjects, BP monitors becoming loosened, and CGMS temporally stopping due to double tagging in a second. Meanwhile, since BG, SBP, and DBP have a higher recording interval than other physiological responses, the impact of missing data seems to be greater in the subsequent process. Therefore, data cleaning was performed to impute missing values via a linear interpolation method.

Data processing was performed to confirm the continuous trend of the physiological response. First, cubic spline interpolation was done to confirm the continuous trend of BG, SBP, and DBP measured every 2 and 5 min. Cubic spline makes continuous and smooth curves with a series of unique cubic polynomials fitting between the discrete data points [53]. Also, the interpolated data could be extracted as datasets with a sampling rate of 1 Hz. Next, other physiological responses (i.e., HR, PR, OS, PI, EDA, and SKT) were preprocessed. As this study aims to measure the continuous physiological response varying on the temperature ramp, tonic components were extracted from the raw EDA data. Then, the moving average was conducted to smooth out fluctuations and highlight underlying trends in a time series dataset [54]. After the preprocessing, screening of each physiological response data was conducted. SBP and DBP were excluded from the next step, feature extraction, as the data trend of individuals was not consistent.

2.3.2. Thermoregulatory feature extraction

Most of the physiological responses showed changing patterns as described in Section 2.1.1 for each system. Accordingly, the thermoregulatory features of each physiological response were selected considering the specific changing pattern of the effector system (refer to Fig. 5).

First, the thermoregulatory features of the secretion system include (i) overshooting and (ii) recovery time. After a distinct overshooting, the secretion system showed a temporal dynamic that recovers to the initial state before the temperature ramp. Overshooting refers to a slope to the highest or lowest peak of BG from the value of 20-min when the temperature ramp occurs. The higher the absolute value of overshooting, the greater the instantaneous intensity. Recovery time is the time required

from 20 min point when overshooting occurs to the point of value recovering to within the range of the initial state after overshooting. The range of initial state is the range from the minimum to the maximum for 0–20 min before the temperature ramp occurs, and it can be determined as recovery when the value stays within this range for at least 5 min.

Second, the thermoregulatory features of the cardiovascular system include (i) overshooting and (ii) variability. In the cardiovascular system, overshooting occurs in a way that the value increases or decreases according to the temperature ramp. However, the cardiovascular system showed a mixture of a data trend that recovers to the range of the neutral state as in the secretion system and a data trend that stabilizes at the highest or lowest peak. Thus, recovery or stabilization time could not be set based on consistent standards. As one of the indicators for time-domain analysis of the cardiovascular system, the standard deviation of normal-to-normal intervals (SDNN), which means variability in the time intervals between consecutive beats, was selected as a thermoregulatory feature. Specifically, increasing SDNN increases variability, suggesting that flexible and adaptive self-regulation is possible [55]. Hence, this study extracted SDNN of HR and PR within 20–60 min to determine the variability of the temperature ramp.

Third, the thermoregulatory features of the peripheral vascular system include (i) overshooting and (ii) stabilization time. OS and PI show an overshooting phenomenon as the temperature ramp occurs, and stabilization takes place without recovering to the initial state at the peak of overshooting. Stabilization time is the time required from the 20 min to the point in time when the value starts to converge to the highest and lowest peak after overshooting.

Fourth, the thermoregulatory features of the integumentary system include (i) overshooting and (ii) residual trend. Unlike the preceding three systems, the integumentary system did not show any noticeable recovery or complete stabilization during the experiment period. The integumentary system showed a logarithmic trend, which indicates a continuous increase or decrease in the data change rate. Overall, the slope becomes less steep, making plateaus, in the 40–60 min trend than in the 20–40 min trend, and it is expected that if the experiment lasts more than 60 min, recovery or stabilization will be made. However,

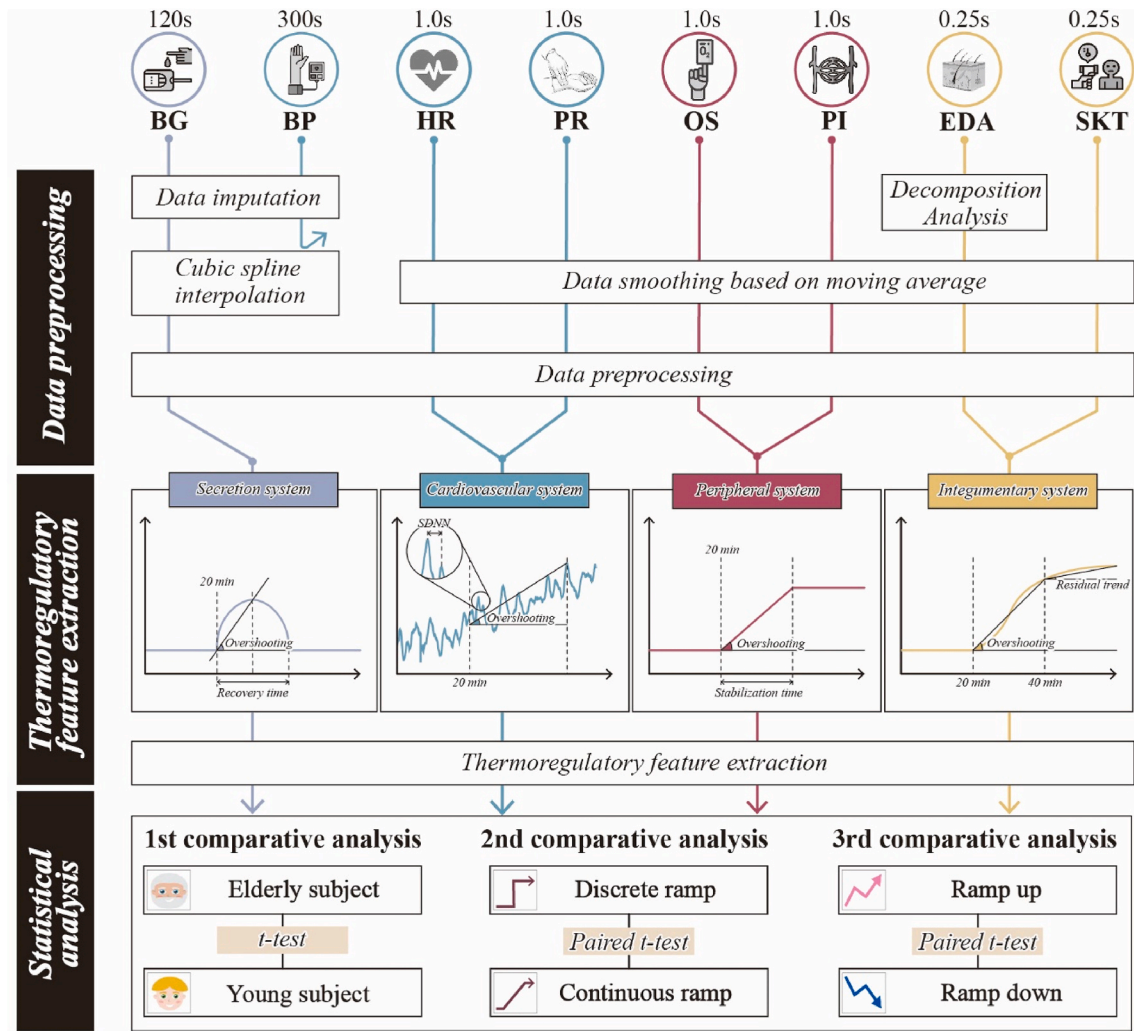


Fig. 5. Process of data analysis.

Table 2
Recording interval and percentage of missing data.

Physiological response	Recording interval (s)	Missing data (%)			
		DRU	DRD	CRU	CRD
Blood glucose	120	2.10	3.23	2.90	2.18
Systolic blood pressure	300	1.67	0.63	0.63	0.21
Diastolic blood pressure	300	1.67	0.63	0.63	0.21
Heart rate	1	2.50	2.50	0	0
Pulse rate	1	4.68	6.75	1.77	13.54
Oxygen saturation	1	4.67	6.73	1.77	13.54
Perfusion index	1	4.67	6.74	1.77	13.54
Electrodermal activity	0.25	2.50	2.50	0	0
Skin temperature	0.25	2.50	2.50	0	0

Note: DRU stands for discrete ramp-up; DRD for discrete ramp-down; CRU for continuous ramp-up; and CRD for continuous ramp-down.

since recovery or stabilization was not clearly observed within the observation time, residual trend was selected as the thermoregulatory feature. The residual trend indicates the fluctuations of the data in the 40–60 min period. So, smaller residual trend indicates plateauing, specifically possibility of faster stabilization. Overshooting means a slope in the 20–40 min period, while residual trend means a slope in the 40–60 min period.

2.3.3. Statistical analysis

Statistical analysis was carried out from three perspectives: (i) age difference; (ii) ramp type; and (iii) ramp direction. Independent samples *t*-test in each temperature ramp (i.e., DRU, DRD, CRU, and CRD) was performed to statistically analyze the age differences concerning thermoregulatory features. Independent sample *t*-test is a statistical test used to compare the means of two independent groups. When the *p*-value is less than 0.05, it indicates a significant difference between the means of the two groups. After comparing age differences, a paired *t*-test was performed to discover differences in thermoregulatory features according to the temperature ramp. Specifically, the thermoregulatory features according to the temperature ramp type (i.e., discrete and continuous ramp) were compared and analyzed, and the difference according to the temperature ramp direction (i.e., ramp up and down) was analyzed. When the *p*-value of the paired *t*-test is less than 0.05, it indicates a significant difference between the means of the two conditions.

3. Results

3.1. Data summary

3.1.1. Controlled temperature ramps

Fig. 6 depicts the temporal dynamics of controlled temperature ramps. Initially, during the 0–20 min period, the temperature in DRU, DRD, CRU, and CRD converged at approximately 22–24 °C. However,

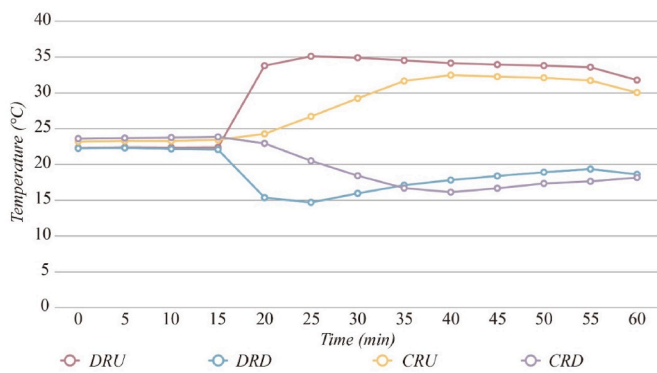


Fig. 6. Temporal dynamics of controlled temperature.

after the discrete temperature ramp at 20 min, DRU and DRD maintained average temperatures in the range of 32–34 °C and 15–17 °C, respectively. Additionally, in CRU and CRD, the peak value was recorded at approximately 45 min, after which the temperatures remained at 32–34 °C and 14–17 °C. These results indicate that the temperature ramps in the artificial climate chamber were effectively generated in accordance with the pre-defined temperature ramps scenario.

Fig. 7 depicts the temporal dynamics of TSV and TCV during temperature ramps. Initially, during the 0–20 min, subjects perceived the exposed thermal environment as neutral and comfortable. However, starting from the 20-min when the temperature ramp occurred, they experienced sensations of coldness or hotness and felt uncomfortable in response to the thermal environment. Notably, in DRU and DRD with extreme temperature ramps, subjects exhibited heightened sensitivity in evaluating the thermal environment, resulting in an earlier emergence of the peak values of TSV and TCV. Additionally, younger subjects have higher peak value in comparison to elderly subjects. After reaching the peak value, the TSV and TCV tended to stabilize and remained relatively consistent until the end of the 60-min experiment. Interestingly, during

DRD and CRD, there were instances where the TSV and TCV displayed a tendency to recover instead.

3.1.2. Physiological responses

Fig. 8 demonstrates the average temporal dynamics of physiological responses under various temperature ramps. First, it can be confirmed that the BG of elderly subjects is consistently higher than that of younger subjects in all temperature ramps. Although the absolute value varies depending on the age group, it shows almost similar patterns in overshooting and recovery according to the temperature ramp. The BG decreased and increased instantaneously in hot and cold environments. In addition, it tended to return to 0–20 min after overshooting of higher intensity in the discrete temperature ramp. On the other hand, moderate overshooting in the continuous temperature ramp, seemed to last a little longer than in the discrete temperature ramp, but showed a tendency to return as well.

The changing patterns of the cardiovascular system and peripheral vascular system, are as follows. In the case of SBP and DBP, the values of elderly subjects were higher than those of younger subjects most of the time during the experiment. In general, BP decreased in the temperature ramp-up condition, while BP tended to increase in the temperature ramp-down. However, the changing patterns of BP were inconsistent, and thus, SBP and DBP were excluded in thermoregulatory feature extraction and statistical analysis. Nevertheless, HR and PR of the cardiovascular system showed consistent temporal dynamics according to the temperature ramp. HR and PR increased in the temperature ramp-up condition, whereas they decreased in the temperature ramp-down condition. In addition, this tendency was more distinct in the discrete ramp, but there was a relatively smaller difference in the continuous ramp.

In the peripheral vascular system, OS and PI showed opposite changing patterns depending on the temperature direction. In the temperature ramp-up condition, OS decreased and PI increased, whereas in the temperature ramp-down condition, OS increased and PI decreased. In all ramp types and directions, they tended to stabilize after achieving the highest or lowest peak due to the overshooting. In OS and PI, the degree of overshooting was more prominent in the discrete ramp than in

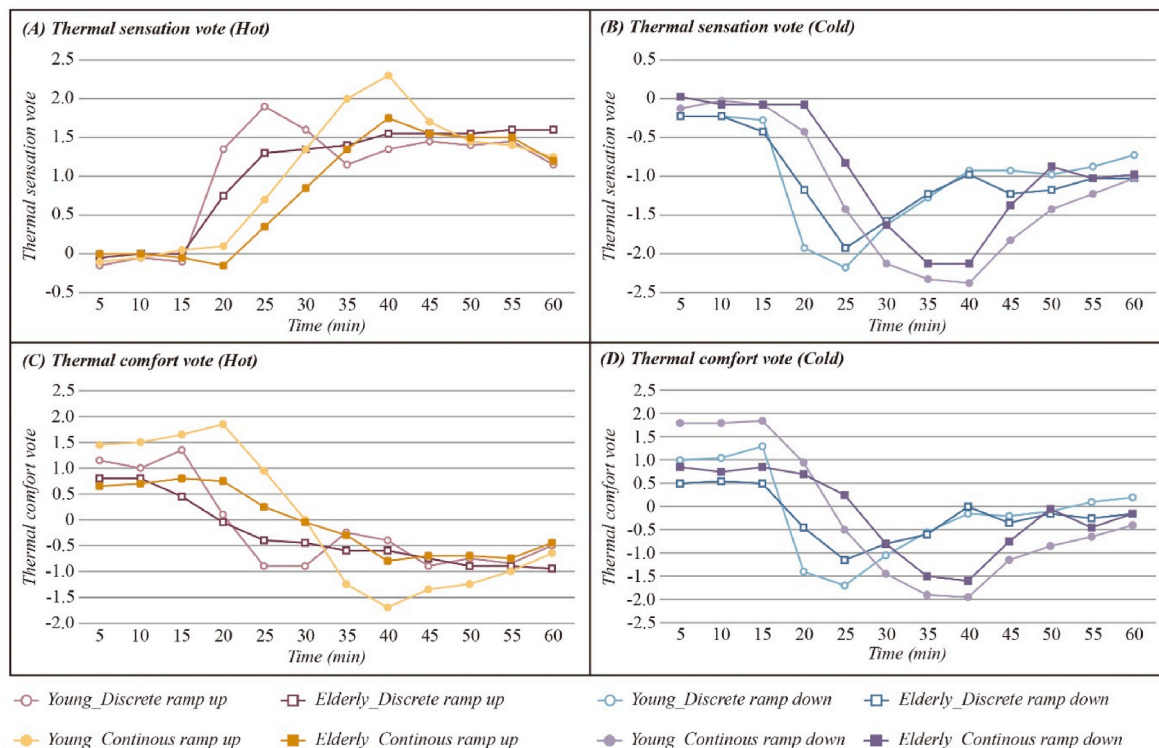


Fig. 7. Temporal dynamics of psychological responses under temperature ramps.

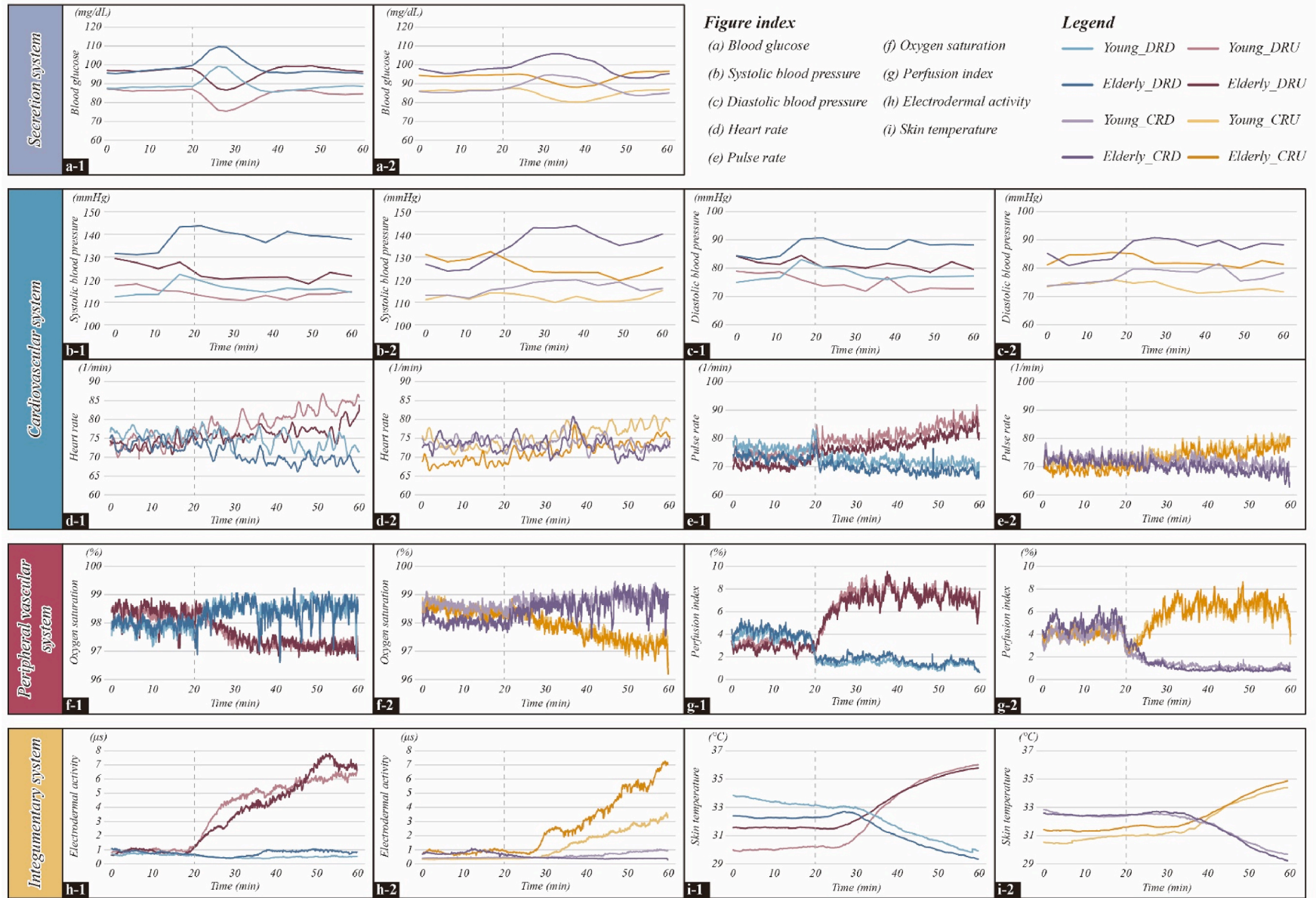


Fig. 8. Temporal dynamics of physiological responses under temperature ramps.

the continuous ramp.

Lastly, EDA and SKT in the integumentary system tended to increase or decrease continuously without clear recovery or stabilization after overshooting according to the temperature ramp. Both EDA and SKT increased in the temperature ramp-up condition. However, EDA slightly increased or decreased in the temperature ramp-down condition, while SKT decreased. The analysis found that in the temperature ramp-up condition, the discrete ramp had a significantly higher peak value than the continuous ramp. It was also found that the residual trend of EDA and SKT showed plateauing phenomena with gradual decreases in slope after overshooting.

3.2. Thermoregulatory response under the temperature ramp

3.2.1. Thermoregulation in the secretion system

SM Table S1 summarizes overshooting and recovery time in BG to temperature ramps. As a result, there was no statistically significant difference (i.e., $p < 0.05$) in overshooting between young and elderly subjects. That is, a significant age difference in thermoreceptor responses was not observed through the change of BG. However, there was a statistically significant age difference in the recovery time of BG under the discrete temperature ramp. In the DRU condition, the BG of young subjects (9.3 ± 2.49 min) recovered to the initial state approximately 4.8 min faster than elderly subjects (14.1 ± 6.71 min). Similarly, in the DRD condition, the BG of young subjects (10.6 ± 5.92 min) recovered approximately 8.2 min faster than elderly subjects (18.8 ± 6.48 min). In other words, young subjects maintained relatively better homeostasis of BG against the discrete ramp than elderly subjects.

In addition, overshooting of BG of all subjects was relatively distinct in the discrete ramp. Overshooting in the ramp-up condition was more than 3 times greater in DRU (-1.75 ± 0.69) than in CRU (-0.5 ± 0.21). Likewise, in the ramp-down condition, overshooting was about 2.5 times greater in DRD (2.01 ± 0.74) than in CRD (0.75 ± 0.38). That is, in the discrete ramp condition, thermoreceptor responses became relatively more active among all subjects. At the same time, DRD (14.9 ± 7.36 min) recovered to the original state approximately 4.4 min faster than CRD (19.3 ± 7.05 min). This is because overshooting became a lot steeper in DRD, and gradual overshooting lasted a little longer in CRD, resulting in a difference in recovery time.

The recovery time of BG was relatively delayed in the ramp-down condition compared to the ramp-up condition. In the discrete ramp condition, recovery time was delayed by 3.2 min in DRD (14.8 ± 7.11 min) compared to DRU (11.6 ± 5.82 min). Similarly, in the continuous ramp condition, recovery time was delayed by 3.7 min in CRD (17.6 ± 7.0 min) compared to CRU (13.9 ± 4.64 min). Therefore, it can be confirmed that the homeostasis of BG is relatively low in a cold environment rather than a hot environment. It was also confirmed that overshooting was more than 1.5 times higher in DRD (0.77 ± 0.38) than in DRU (0.5 ± 0.21).

3.2.2. Thermoregulation in cardiovascular system

SM Table S2 synthesizes the overshooting and variability in HR to temperature ramps. There was a statistically significant age difference in overshooting of HR under the temperature ramp-up condition (i.e., DRU and CRU). In the DRU condition, overshooting of HR in young subjects (0.44 ± 0.28) was approximately 1.6 times greater than that of elderly subjects (0.25 ± 0.19). Similarly, in the CRU condition, overshooting of HR in young subjects (0.40 ± 0.26) was about 1.6 times larger than that of elderly subjects (0.25 ± 0.11). Additionally, in the discrete ramp condition, there was a statistically significant age difference in the variability of HR. In the DRU condition, the variability of young subjects' HR (96.94 ± 45.70) was larger than that of elderly subjects' HR (64.20 ± 42.37). Even in the DRD condition, the variability of young subjects' HR (143.62 ± 67.22) was larger than that of the elderly subjects' HR (92.89 ± 71.39). In other words, the variability of young subjects was greater than that of elderly subjects, which suggests that

the autonomic neural control of heart rate was more active among young subjects.

Additionally, there was no statistically significant difference in overshooting and the variability of HR according to the ramp type. However, there was a statistically significant difference in the variability according to the ramp direction. In addition, the variability was higher in the discrete ramp-down condition and the continuous ramp-down condition. Specifically, DRD (119.68 ± 73.75) was 1.5 times larger than DRU (81.10 ± 46.46), and CRD (105.99 ± 59.06) was 1.4 times larger than CRU (77.46 ± 25.99).

SM Table S3 summarizes the overshooting and variability in PR to temperature ramps. The findings revealed that there was a statistically significant difference in overshooting of PR between young and elderly subjects under the continuous ramp condition. In the CRU condition, overshooting of PR was greater in young subjects (0.37 ± 0.19) than in elderly subjects (0.26 ± 0.98). Similarly, in the CRD condition, overshooting of PR was larger in young subjects (-0.38 ± 0.23) than in elderly subjects (-0.23 ± 0.17). That is, the thermoreceptor response of PR was relatively more sensitive in the condition of change to a hot environment for young subjects than for elderly subjects. In addition, there were statistically significant differences in the variability under all temperature ramps, and the variability of young subjects was higher than that of elderly subjects in all temperature ramp conditions.

Meanwhile, statistically significant differences according to the ramp type were found in the overshooting in ramp-down conditions. DRD (0.67 ± 0.83) showed more than two times greater overshooting than CRD (0.30 ± 0.21). In addition, a statistically significant difference according to the ramp direction was found only in overshooting of the discrete ramp. Specifically, DRU (0.27 ± 0.15) was about two times less than DRD (0.64 ± 0.79). There was no statistically significant difference in variability according to the ramp type and direction.

3.2.3. Thermoregulation in the peripheral system

SM Table S4 outlines the overshooting and stabilization time in OS to temperature ramps. The results demonstrate a statistically significant age difference in overshooting of OS between under DRD and CRU conditions. Specifically, in the DRD condition, overshooting of OS in young subjects (0.106 ± 0.084) was about 3 times larger than that of elderly subjects (0.034 ± 0.034). In the CRU condition, overshooting of OS in young subjects (-0.051 ± 0.024) was about 1.5 times larger than that of elderly subjects (-0.035 ± 0.022). Additionally, in the discrete ramp condition, there was a statistically significant difference in the stabilization time of OS between young and elderly subjects. In the DRU condition, the OS of young subjects (16.0 ± 7.58 min) stabilized approximately 6.6 min faster than elderly subjects (22.6 ± 8.65 min). Similarly, in the DRD condition, the OS of young subjects (14.0 ± 7.70 min) stabilized approximately 10.2 min faster than elderly subjects (24.2 ± 9.38 min). That is, the thermoreceptor response of OS to rapid temperature changes was relatively more sensitive, and homeostasis was better in young subjects than in elderly subjects.

In addition, the stabilization time of OS of all subjects was further delayed in the continuous ramp with gradual temperature changes. In the ramp-up condition, stabilization time was further delayed 12.08 min in CRU (31.32 ± 4.82 min) than in DRU (19.24 ± 8.45 min). Similarly, in the ramp-down condition, stabilization time was further delayed 6.85 min in CRD (25.85 ± 7.87 min) than in DRD (19.0 ± 9.96 min). At the same time, overshooting of OS was twice as larger in DRU (-0.082 ± 0.069) than in CRU (-0.042 ± 0.024).

Likewise, the stabilization of OS was relatively delayed under the continuous ramp-up condition. In the continuous ramp condition, stabilization time was further delayed by 4.6 min in CRU (30.6 ± 5.55 min) than in CRD (26.0 ± 7.87 min).

SM Table S5 presents the overshooting and stabilization time in PI to temperature ramps. The findings indicate a statistically significant difference in overshooting of PI between young and elderly subjects under the ramp-up condition. Specifically, in the DRU condition, overshooting

of PI in young subjects (0.341 ± 0.154) was about 1.5 times larger than that of elderly subjects (0.228 ± 0.117). In the CRU condition, overshooting of PI was about 1.5 times greater in young subjects (0.32 ± 0.12) than in elderly subjects (0.192 ± 0.107). That is, the thermoreceptor response of PI was relatively sensitive among young subjects in the condition of change to a hot environment. On the other hand, there was no statistically significant difference in stabilization time between young and elderly subjects.

In addition, the stabilization time of PI of all subjects was relatively delayed in the continuous ramp with gradual temperature changes. In the ramp-up condition, stabilization time was further delayed 4.4 min in CRU (19.3 ± 8.26 min) than in DRD (14.9 ± 5.98 min).

Likewise, the stabilization time of PI was relatively delayed in the continuous ramp-up condition of change to a hot thermal environment. In the discrete ramp condition, stabilization time was further delayed about 4.8 min in DRU (14.8 ± 6.29 min) than in DRD (10.0 ± 10.1 min). Similarly, in the continuous ramp condition, stabilization time was further delayed by 6.7 min in CRU (19.7 ± 8.56 min) than in DRD (13.0 ± 8.96 min).

3.2.4. Thermoregulation in the integumentary system

SM Table S6 reveals the overshooting and residual trend in EDA to temperature ramps. There was no statistically significant age difference in overshooting which means no significant age difference in thermoreceptor response. However, there was a statistically significant age difference in residual trend of EDA under the discrete ramp condition. In the DRU condition, residual trend of EDA in elderly subjects (0.325 ± 0.362) was about 2.5 times larger than that of young subjects (0.131 ± 0.178). Similarly, in the DRD condition, residual trend of EDA was about 4 times greater in elderly subjects (0.004 ± 0.006) than in young subjects (0.001 ± 0.006).

Also, overshooting of EDA of all subjects was relatively prominent under the ramp-up condition. In the discrete ramp condition, overshooting was more than 13 times greater in DRU (0.279 ± 0.557) than in DRD (0.02 ± 0.033), while residual trend was about 40 times larger in DRU (0.197 ± 0.258) than in DRD (0.005 ± 0.004). Similarly, in the continuous ramp condition, the intensity of overshooting was more than 10 times greater in CRU (0.149 ± 0.288) than in CRD (0.014 ± 0.019), while that of residual trend was about 44 times larger in CRU (0.222 ± 0.441) than in CRD (0.005 ± 0.006).

SM Table S7 shows the findings on the overshooting and residual trend in SKT to temperature ramps. There were statistically significant age differences in overshooting under the discrete ramp condition. In the DRU condition, overshooting of SKT in young subjects (0.177 ± 0.995) was about 1.5 times larger than that of elderly subjects (0.106 ± 0.125). Similarly, in the DRD condition, overshooting of SKT was about 2.5 times greater in elderly subjects (-0.037 ± 0.095) than in young subjects (-0.094 ± 0.054).

Moreover, overshooting of SKT of all subjects was prominent under the discrete ramp condition. Overshooting in the ramp-up condition was more than 1.5 times greater in DRU (0.157 ± 0.099) than in CRU (0.091 ± 0.074). Also, in the ramp-down condition, it was more than 1.5 times larger in DRD (0.093 ± 0.046) than in CRD (0.062 ± 0.035). On the contrary, residual trend of SKT of all subjects was relatively prominent in the continuous ramp condition. In the ramp-up condition, residual trend was 1.5 times greater in CRU (0.158 ± 0.074) than in DRU (0.112 ± 0.099). Also, in the ramp-down condition, it was 1.5 times larger in CRU (0.147 ± 0.053) than in DRU (0.099 ± 0.037).

Likewise, overshooting of SKT was relatively prominent under the ramp-up condition. In the discrete ramp condition, overshooting was more than 1.5 times greater in DRU (0.160 ± 0.099) than in DRD (0.093 ± 0.047). Similarly, in the continuous ramp condition, overshooting was about 1.5 times greater in CRU (0.09 ± 0.074) than in CRD (0.062 ± 0.034).

4. Discussions

4.1. Thermoregulatory responses and mechanism

Among the nine types of physiological responses obtained through the experiment, overshootings were observed in seven types of physiological responses, except for SBP and DBP. This empirical evidence supports the theoretical mechanism of the overshooting phenomenon in thermoregulation, which suggests that when thermoreceptors detect temperature changes, there is an immediate increase in their firing rate.

Moreover, in comparison with the temperature ramp direction, overshooting occurred in the same direction for HR, PR, PI, EDA, and SKT, whereas overshooting occurred in the opposite direction for BG and OS. Specifically, in the temperature ramp-down condition, BG seemed to temporarily rise while increasing metabolism to maintain body temperature. In addition, HR and PR decreased with blood vessel constriction to prevent heat loss while decreasing blood volume, thus affecting OS and PI. Contrary to the general physiological theory that both OS and PI decrease under the temperature ramp-down condition, the data trend of OS measured in this experiment increased. This is because respiratory activity becomes active while increasing sympathetic nerve activity to temporarily maintain body temperature in a cold environment. Meanwhile, EDA and SKT tended to decrease with peripheral vessel constriction. In the temperature ramp-up condition, these thermoregulatory responses and mechanisms acted in inverse. Specifically, BG temporarily decreased as blood vessels dilated and sweat was released to promote heat dissipation. In addition, HR and PR increased as blood circulation was accelerated to secrete sweat. Despite the general theory that OS and PI increase due to blood circulation, the data trend of OS was the opposite of what was expected. It can be assumed that the reason is a decrease in dissolved oxygen concentration or a lack of oxygen because of reduced blood flow. In addition, EDA increased due to sweat release, and SKT increased with blood circulation activated.

In the wake of the overshooting, a tendency to recover back to the initial state was observed in these physiological responses, as the control center and effectors worked to restore body temperature to normal range. However, there was a difference in the degree of recovery to the initial state depending on the system of effectors. BG that belongs to the secretion system tended to immediately recover to the initial state after overshooting due to the temperature ramp. HR and PR that belong to the cardiovascular system tended to recover to the initial state or stabilize at the peak point where overshooting occurred, while OS and PI that belong to the peripheral vascular system showed stabilization at the peak point. Meanwhile, EDA and SKT that belong to the integumentary system did not reach stabilization during the observation time. However, since the plateauing phenomenon occurs in which the range of change gradually decreases, stabilization is expected if the temperature change lasts for a long period.

4.2. Age differences in thermoregulation

The analysis found a statistical age difference in the thermoregulatory mechanism of nine types of physiological responses observed throughout the experiment. In particular, this difference was more prominent in the recovery or stabilization phenomenon rather than overshooting. Firstly, a significant difference in overshooting was found in HR, PR, OS, PI, and SKT, and overshooting was steeper in young subjects than in elderly subjects. This suggests that the thermoreceptor response of the young subject is relatively more sensitive. Secondly, all significant differences in recovery or stabilization phenomena were observed only in the discrete ramp. It took more time for elderly subjects to recover BG to the initial state after overshooting than young subjects. Similarly, more time was required for stabilization for elderly in OS. These results showed that maintaining homeostasis against thermoregulatory response was relatively more effective among young subjects. It was also observed that the residual trend of EDA, the slope of the 40–60

min period, was less smaller for young subjects than elderly, which can be interpreted that stabilization being faster among young subjects. Thirdly, the variability of HR and PR was more significantly higher in young subjects. This suggests sympathetic nerve activity in thermoregulation was more active among younger subjects.

Through these findings, it can be inferred that elderly individuals are more likely to be at risks under temperature ramps than young individuals. Regarding thermoregulation, steep overshootings can be positively interpreted as indicative of a well-functioning thermoregulatory mechanism with sufficiently robust signals transmitted to the brain under temperature ramps. In this regard, elderly individuals may encounter more challenges in thermoregulatory mechanisms as their overshootings appear to be weaker compared to younger. However, there is also possibility where steep overshootings becoming triggers of symptoms such as strokes as they are instant and intensive responses themselves. While young individuals may be more capable of handling intensive loads generated during the process of thermoregulation, precautions should be exercised. Also, recovery or stabilization is another important feature in thermoregulation aspect. Unlike overshootings, recovery or stabilization takes a certain period of time and thus, can affect human body significantly. Moreover, recovery or stabilization time serves as an indicator of the proper functioning of homeostasis. Therefore, it can be deduced that elderly individuals have more troubles in thermoregulations with weaker overshootings and longer recovery or stabilization time. Furthermore, the age difference in thermoregulatory response was more evident in discrete ramp conditions than in continuous ramp conditions. This means that elderly individuals are more vulnerable to thermoregulatory disorders than young individuals in summer and winter, with extreme outdoor and indoor temperatures. In addition, elderly individuals have lower sensitivity of thermoreceptor response than young individuals, showing passive thermoregulatory response required for body temperature regulation. Thus, elderly individuals may be at risk when exposed to extreme and discrete ramps due to insufficient thermoregulatory response. In addition, another problem arises that the recovery or stabilization of the thermoregulatory response is delayed compared to young individuals. For example, as residual trend of EDA is greater than that of young individuals, continuous sweat secretion leads to excessive water loss.

4.3. Thermoregulation differences under various temperature ramps

The most significant difference in thermoregulatory response according to the temperature ramp type (i.e., discrete and continuous) and direction (i.e., up and down) was found in BG and SKT. Firstly, a significant difference in temperature ramp type was prominent in BG, OS and SKT. Depending on the temperature ramp type, BG showed steeper overshooting under the discrete ramp condition, and OS took more time to stabilize under the continuous ramp condition. Meanwhile, SKT showed significant differences in overshooting and residual trend under all temperature ramps. Compared to EDA that belongs to the same integumentary system, overshooting of SKT was slightly more consistent.

Secondly, significant differences in the temperature ramp direction were clearly shown in BG, HR, PI, EDA, and SKT. It is noted that whether discrete or continuous, ramp-down conditions slowed the recovery time of BG. The variability of HR was about twice as large in a cold environment, and the stabilization time of PI in the ramp-up condition took longer than the ramp-down condition. Both overshooting and residual trend of EDA showed significant differences. These results suggest that as EDA is closely related to sweating, a dynamic change occurs, especially in the ramp-up condition. However, there was an intentional difference of approximately 3 °C in absolute values between the temperature ramp-up and down. This disparity could have caused slight distortions in the experimental results and corresponding comparative analysis (i.e., between the temperature ramp-up and down). If the ramps in both directions were equally formed, it is assumed that there would be

slight changes in physiological values. Nevertheless, since this comparative analysis focused on thermoregulatory features rather than raw values, any alterations in the analysis are expected to be insignificant, and the overall trend is highly likely to remain consistent.

4.4. Recommendations for elderly individuals under temperature ramps

To this end, recommendations for elderly individuals' health under temperature ramps are suggested as follows:

First, in the seasons like summer and winter, it is necessary to prevent exposure to the discrete ramp and buffer the temperature ramp. In addition, gradual temperature control is essential before or after going out or when entering another indoor space where the cooling or heating does not work properly. Meanwhile, various methods of buffering the temperature difference between outdoor and indoor space can reduce the burden on homeostasis to maintain the body temperature of elderly individuals. For example, with the recent development of smart technology capable of remotely controlling the indoor environment, temperature control has been made to immediately relieve hotness or coldness when people enter the room after going out. However, since increasing the temperature ramp for instant relief of thermal discomfort may cause an excessive load on thermoregulation in homeostasis, gradual control is required for the heating or cooling system. When the outside is extremely hot or cold, efforts are also needed for people to control the temperature between the indoor and the outside temperature for a certain period before and after going out. Specifically, insufficient thermoregulatory responses can lead to disorders such as heatstroke or hypothermia [56,57].

Second, elderly individuals diagnosed with diabetes or pre-diabetes should pay more attention to situations where the temperature drops rather than situations where the temperature rises. According to the study's findings, BG's recovery time was delayed in situations where the temperature dropped. Therefore, elderly individuals who have difficulties stably maintaining the homeostasis of BG should be careful not to be exposed to a rapid temperature drop when the intensity of overshooting increases and the recovery time is long. According to the results Baker and Dawson(1986), 43% of patients hospitalized for diabetes had pathological disorders associated with hypothermia [58]. Another research showed that hypothermia was identified in 23.4% of patients with severe hypoglycemia [59].

Third, rather than manual control, automatic control of the heating and cooling system is recommended for elderly individuals. Elderly individuals' overshooting was found to have a lower intensity than young individuals. The elderly individual's thermoreceptor seems to be relatively insensitive to the temperature ramp stimulus. This is consistent with the result of the perceived thermal sensation examined in the previous studies as well as the findings of this study [21–23]. In other words, elderly individuals have weak thermoregulation for the temperature ramp and lack the ability to recognize and control it properly [24]. Moreover, elderly individuals with diseases associated with cognitive decline, such as dementia, or suffer from physical discomfort, have difficulty controlling appropriate temperature and thus are likely to develop thermoregulatory disorders. Therefore, it is recommended that elderly individuals use automatic control systems such as smart heating and cooling system that detects and reflects recent outdoor temperature.

5. Conclusions

The aging population is leading to an emerging interest in the health and well-being of elderly individuals, whose health is more likely to be threatened by extreme climates. This study investigated the age differences in thermoregulatory responses under temperature ramps.

20 young and 20 elderly subjects participated in experiments, during which physiological and psychological responses were collected. The temperature ramps varied in four types: (i) discrete ramp-up; (ii)

discrete ramp-down; (iii) continuous ramp-up; and (iv) continuous ramp-down. The thermoregulatory features were extracted from each physiological response and statistical analysis was conducted to discover significant differences between ages and ramp types and directions. The main findings of this study are as follows:

- Thermoregulatory features, specifically overshooting and recovery or stabilization, were discovered in physiological responses.
- There were statistically significant differences between young and elderly subjects' overshooting and recovery or stabilization time.
- Elderly subjects have insensitive thermoreceptors with smaller overshootings, and recovery and stabilization time also took longer than younger subjects.
- Types and directions of ramp temperature impact thermoregulatory responses.

Based on the main findings of this study, recommendations for elderly individuals regarding temperature ramps were suggested. It is recommended that elderly individuals avoid discrete temperature ramps that extreme outdoor temperatures can form. Also, as they have weaker thermoregulatory responses, methods to buffer the temperature ramps were suggested. Elderly individuals with diabetes have to be cautious about exposure to cold environments. These recommendations can contribute to enhancing the health and well-being of the elderly.

However, this study has some limitations. First, more significant differences could have been found if the ramp-down conditions were more extreme. Due to concerns about elderly individuals' health issues, the temperature has only ramped down to 14–17 °C. In the winter, temperature differences indoors and outdoors can be over 20 °C, so this ramp might be much more threatening to elderly individuals. Second, there were limitations that were yielded from equipment used to measure physiological responses. For instance, E4 wristband could only measure the local skin temperature whereas more reliable data could have been obtained if various local skin temperatures were collected. Also, unlike other continuous measuring equipment, blood pressure (BP) monitors could only measure discrete values. This could possibly affect the data quality, and if BP had been appropriately measured, the overshooting and stabilization phenomena might have been observed.

CRedit authorship contribution statement

Dahyun Jung: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation. **Hakpyeong Kim:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Jongbaek An:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Taecheon Hong:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.buildenv.2023.110760>.

Nomenclature

BG	Blood glucose level
BP	Blood pressure
CGMS	Continuous glucose monitoring system
CRD	Continuous ramp-down
CRU	Continuous ramp-up
DBP	Diastolic blood pressure
DRD	Discrete ramp-down
DRU	Discrete ramp-up
EDA	Electrodermal activity
HR	Heart rate
IRB	The institutional review board
OS	Oxygen saturation
PI	Perfusion index
PMV	Predicted mean vote
PR	Pulse rate
SBP	Systolic blood pressure
SDNN	Standard deviation of nn interval
SKT	Skin temperature
TCV	Thermal comfort vote
TSV	Thermal sensation vote
WHO	World health organization

References

- [1] Announcement of the Results of the 2022 Survey on the Reality of Solitary Deaths, 2022. https://www.mohw.go.kr/react/al/sal0301vw.jsp?PAR_MENU_ID=04&MENU_ID=0403&page=1&CONT_SEQ=374084. (Accessed 23 May 2023).
- [2] T.A. Kato, N. Shinfuku, N. Sartorius, S. Kanba, Loneliness and Single-Person Households: Issues of Kodokushi and Hikikomori in Japan, 2017.
- [3] U. Nations, World Population Ageing 2015, ST/ESA/SER. A/390, 2015.
- [4] W.H. Organization, World Report on Ageing and Health, World Health Organization, 2015.
- [5] C. Iniguez, F. Ballester, J. Ferrandiz, S. Pérez-Hoyos, M. Sáez, A. López, Relation between temperature and mortality in thirteen Spanish cities, *Int. J. Environ. Res. Publ. Health* 7 (2010) 3196–3210.
- [6] P. Vaneckova, P.J. Beggs, C.R. Jacobson, Spatial analysis of heat-related mortality among the elderly between 1993 and 2004 in Sydney, Australia, *Soc. Sci. Med.* 70 (2010) 293–304.
- [7] Hot Weather Safety for Older Adults, National Institute on Aging. (n.d.). <https://www.nia.nih.gov/health/hot-weather-safety-older-adults> (accessed May 23, 2023).
- [8] Cold Weather Safety for Older Adults, National Institute on Aging. (n.d.). <https://www.nia.nih.gov/health/cold-weather-safety-older-adults> (accessed May 23, 2023).
- [9] B.W. Olesen, K.C. Parsons, Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730, *Energy Build.* 34 (2022) 537–548. <https://www.sciencedirect.com/science/article/pii/S037877880200004X>. (Accessed 23 May 2023).
- [10] A.A. Romanovsky, Thermoregulation: some concepts have changed. Functional architecture of the thermoregulatory system, *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 292 (2007) R37–R46.
- [11] D. Wendt, L.J.C. Van Loon, W.D. Marken Lichtenbelt, Thermoregulation during exercise in the heat: strategies for maintaining health and performance, *Sports Med.* 37 (2007) 669–682.
- [12] K. Nakamura, Central circuitries for body temperature regulation and fever, *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 301 (2011) R1207–R1228.
- [13] K. Nakamura, S.F. Morrison, A thermosensory pathway that controls body temperature, *Nat. Neurosci.* 11 (2008) 62–71.
- [14] H. Liu, J. Liao, D. Yang, X. Du, P. Hu, Y. Yang, B. Li, The response of human thermal perception and skin temperature to step-change transient thermal environments, *Build. Environ.* 73 (2014) 232–238.
- [15] A.P. Gagge, J.A.J. Stolwijk, J.D. Hardy, Comfort and thermal sensations and associated physiological responses at various ambient temperatures, *Environ. Res.* 1 (1967) 1–20.
- [16] A.P. Gagge, J.A.J. Stolwijk, B. Saltin, Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures, *Environ. Res.* 2 (1969) 209–229.
- [17] H. Hensel, K. Schafer, Thermoreception and Temperature Regulation in Man, Springer, 1984.
- [18] Y. Li, The science of clothing comfort, *Textil. Prog.* 31 (2001) 1–135.

- [19] K. Nagano, A. Takaki, M. Hirakawa, Y. Tochihiro, Effects of ambient temperature steps on thermal comfort requirements, *Int. J. Biometeorol.* 50 (2005) 33–39.
- [20] Y. Zhang, J. Zhang, H. Chen, X. Du, Q. Meng, Effects of step changes of temperature and humidity on human responses of people in hot-humid area of China, *Build. Environ.* 80 (2014) 174–183.
- [21] J. van Hoof, L. Schellen, V. Soebarto, J.K.W. Wong, J.K. Kazak, Ten questions concerning thermal comfort and ageing, *Build. Environ.* 120 (2017) 123–133, <https://doi.org/10.1016/j.buildenv.2017.05.008>.
- [22] K. Natsume, T. Ogawa, J. Sugeno, N. Ohnishi, K. Imai, Meteorology Preferred Ambient Temperature for Old and Young Men in Summer and Winter, 1992.
- [23] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, J. Toftum, M.H. de Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, *Indoor Air* 20 (2010) 273–283, <https://doi.org/10.1111/j.1600-0668.2010.00657.x>.
- [24] K.J. Collins, A.N. Exton-Smith, C. Doré, Urban hypothermia: preferred temperature and thermal perception in old age, *Br. Med. J.* 282 (1981) 175–177.
- [25] P. Roelofs, Healthy ageing: differences between elderly and non-elderly in temperature sensation and dissatisfaction, *Intell. Build. Int.* 9 (2017) 123–136, <https://doi.org/10.1080/17508975.2015.1063474>.
- [26] S. Guergova, A. Dufour, Thermal sensitivity in the elderly: a review, *Ageing Res. Rev.* 10 (2011) 80–92, <https://doi.org/10.1016/j.arr.2010.04.009>.
- [27] D. Tuinse Novieto, Adapting a Human Thermoregulation Model for Predicting the Thermal Response of Older Persons, 2013.
- [28] J. Knight, Y. Nigam, Exploring the anatomy and physiology of ageing. Part 1—The cardiovascular system, *Nurs. Times* 104 (2008) 26.
- [29] C.T. Minson, S.L. Wladkowski, A.F. Cardell, J.A. Pawelczyk, W.L. Kenney, Age Alters the Cardiovascular Response to Direct Passive Heating, 1998. <http://www.jap.org>.
- [30] E.J. Van Someren, R.J. Ray-Mann, E.J. Scherder, H.A. Daanen, D.F. Swaab, Physiology of aging invited review: aging and human temperature regulation, *Exerc. Sport Sci. Rev.* 17 (1997) 205–213, <https://doi.org/10.1152/japphysiol.00202.2003-This>.
- [31] D. Novieto, Y. Zhang, D.T. Novieto, Towards thermal comfort prediction for the older population: a review of aging effect on the human body IESD-Fiala model View project towards thermal comfort prediction for the older population: a review of aging effect on the human body, n.d. <https://www.researchgate.net/publication/267385764>.
- [32] Y. Der Jiang, C.H. Chang, T.Y. Tai, J.F. Chen, L.M. Chuang, Incidence and prevalence rates of diabetes mellitus in Taiwan: analysis of the 2000–2009 nationwide health insurance database, *J. Formos. Med. Assoc.* 111 (2012) 599–604, <https://doi.org/10.1016/j.jfma.2012.09.014>.
- [33] K. Natsume, T. Ogawa, J. Sugeno, N. Ohnishi, K. Imai, Meteorology Preferred Ambient Temperature for Old and Young Men in Summer and Winter, 1992.
- [34] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, J. Toftum, M.H. de Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, *Indoor Air* 20 (2010) 273–283, <https://doi.org/10.1111/j.1600-0668.2010.00657.x>.
- [35] V. Soebarto, H. Zhang, S. Schiavon, A thermal comfort environmental chamber study of older and younger people, *Build. Environ.* 155 (2019) 1–14, <https://doi.org/10.1016/j.buildenv.2019.03.032>.
- [36] C. Dore, A.N. Exton-Smith, Urban hypothermia: preferred temperature and thermal perception in old age, *Br. Med. J.* 282 (1981) 175–177, <https://doi.org/10.1136/bmj.282.6259.175>.
- [37] Z. Wang, H. Yu, Y. Jiao, X. Chu, M. Luo, Chinese older people's subjective and physiological responses to moderate cold and warm temperature steps, *Build. Environ.* 149 (2019) 526–536, <https://doi.org/10.1016/j.buildenv.2018.12.058>.
- [38] Y. Wu, Z. Zhang, H. Liu, B. Li, B. Chen, R. Kosonen, J. Jokisalo, Age differences in thermal comfort and physiological responses in thermal environments with temperature ramp, *Build. Environ.* 228 (2023), <https://doi.org/10.1016/j.buildenv.2022.109887>.
- [39] B. Kingma, A. Frijns, W. Van, M. Lichtenbelt, *The Thermoneutral Zone: Implications for Metabolic Studies*, 1975.
- [40] H. Kim, D. Jung, H. Choi, T. Hong, Advanced prediction model for individual thermal comfort considering blood glucose and salivary cortisol, *Build. Environ.* 224 (2022), <https://doi.org/10.1016/j.buildenv.2022.109551>.
- [41] H. Pallubinsky, L. Schellen, B.R.M. Kingma, B. Dautzenberg, M.A. van Baak, W. D. van Marken Lichtenbelt, Thermophysiological adaptations to passive mild heat acclimation, *Temperature* 4 (2017) 176–186, <https://doi.org/10.1080/23328940.2017.1303562>.
- [42] J. Wu, Z. Hu, Z. Han, Y. Gu, L. Yang, B. Sun, Human physiological responses of exposure to extremely cold environments, *J. Therm. Biol.* 98 (2021), <https://doi.org/10.1016/j.jtherbio.2021.102933>.
- [43] Z. Wu, N. Li, S. Schiavon, Experimental evaluation of thermal comfort, SBS symptoms and physiological responses in a radiant ceiling cooling environment under temperature step-changes, *Build. Environ.* 224 (2022), <https://doi.org/10.1016/j.buildenv.2022.109512>.
- [44] X. Jia, B. Cao, Y. Zhu, A climate chamber study on subjective and physiological responses of airport passengers from walking to a sedentary status in summer, *Build. Environ.* 207 (2022), <https://doi.org/10.1016/j.buildenv.2021.108547>.
- [45] C. Kuroki, K. Godai, M. Hasegawa-Moriyama, T. Kuniyoshi, A. Matsunaga, Y. Kanmura, T. Kuwaki, Perfusion index as a possible predictor for postanesthetic shivering, *J. Anesth.* 28 (2014) 19–25, <https://doi.org/10.1007/s00540-013-1658-9>.
- [46] Z. Wang, H. Yu, M. Luo, Z. Wang, H. Zhang, Y. Jiao, Predicting older people's thermal sensation in building environment through a machine learning approach: modelling, interpretation, and application, *Build. Environ.* 161 (2019), <https://doi.org/10.1016/j.buildenv.2019.106231>.
- [47] Y. Bai, Y. Zhang, Z. Wei, Y. Wang, Experimental study on human comfort responses after simulated summer commutes with double transients of temperature and metabolic rate, *Build. Environ.* 221 (2022), <https://doi.org/10.1016/j.buildenv.2022.109253>.
- [48] M.S. Qasim, D.S. Bari, Ø.G. Martinsen, Influence of ambient temperature on tonic and phasic electrodermal activity components, *Physiol. Meas.* 43 (2022), <https://doi.org/10.1088/1361-6579/ac72f4>.
- [49] Y. Lee, C. Chun, Association between physiological signal from wearable device and alertness of office workers, *Healthy Buildings 2021—Europe*, in: *Proceedings of the 17th International Healthy Buildings Conference 21–23 June 2021*, 2021.
- [50] H. Kim, T. Hong, Determining the optimal set-point temperature considering both labor productivity and energy saving in an office building, *Appl. Energy* 276 (2020), <https://doi.org/10.1016/j.apenergy.2020.115429>.
- [51] J. Kim, H. Kim, T. Hong, Automated classification of indoor environmental quality control using stacked ensembles based on electroencephalograms, *Comput. Aided Civ. Infrastruct. Eng.* 35 (2020) 448–464, <https://doi.org/10.1111/mice.12515>.
- [52] Ageing (n.d.), https://www.who.int/health-topics/ageing#tab=tab_1. (Accessed 23 May 2023).
- [53] S. McKinley, M. Levine, Cubic Spline Interpolation, n.d.
- [54] Different Uses of Moving Average (MA), (n.d.).
- [55] J. Sztajzel, *Heart Rate Variability: a Noninvasive Electrocardiographic Method to Measure the Autonomic Nervous System*, 2004.
- [56] Y. Epstein, R. Yanovich, Heatstroke, *N. Engl. J. Med.* 380 (2019) 2449–2459, <https://doi.org/10.1056/NEJMr1810762>.
- [57] R.H. Fox, I.C. Macdonald, P.M. Woodward, Accidental hypothermia and impaired temperature homeostasis in the elderly, *Br. Med. J.* 1 (1977) 353–356, <https://doi.org/10.1136/bmj.1.6057.353>.
- [58] J.E. Baker, J.A. Dawson, Risk of hypothermia in elderly patients with diabetes, *Br. Med. J.* 293 (1986) 416–418, <https://doi.org/10.1136/bmj.293.6544.416>.
- [59] C. Tran, K. Gariani, F.R. Herrmann, L. Juan, J. Philippe, O.T. Rutschmann, U. M. Vischer, Hypothermia is a frequent sign of severe hypoglycaemia in patients with diabetes, *Diabetes Metab.* 38 (2012) 370–372, <https://doi.org/10.1016/j.diabet.2012.03.005>.