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Human response to the indoor environment under fluctuating temperature

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The effect on humans of a 6-hour long exposure to cyclic fluctuating air temperature was examined. The tested fluctuating pattern consisted of a gradual sweep-up +2.0°C over 40 minutes and a rather abrupt sweep-down –2.0°C over 20 minutes, within the temperature ranges of 26–28°C and 27–29°C. The experiment on cyclic fluctuating air temperature demonstrates that the thermal dissatisfaction rate for cyclic fluctuating air temperature control between 26°C–28°C is lower than that for constant air temperature control at 26°C, while consuming less energy. Moreover, occupant stress levels measured by salivary alpha-amylase, and subjective fatigue levels under cyclic fluctuating air temperature show that similar or even lower distinct results can be achieved with fluctuating air temperature control compared with constant air temperature control.

Introduction

To reduce CO_2 emissions and electricity consumption during the summer, the government of Japan encourages offices to use less air-conditioning by setting office temperatures higher and encourages office workers to dress down. This leads many offices to set their temperatures at 28°C, which is the upper limit recommended by the Act on Maintenance of Sanitation in Buildings (the requirement of architecture in Japan). However, considering that the labor costs of employees exceed building energy costs by a factor of 100, energy reduction should not be achieved by sacrificing employee productivity. Roelofsen (2002) showed that the indoor environment has the biggest influence on productivity in relation to job stress and job dissatisfaction. Various research studies have shown that discomfort imposed by the thermal environment is related to productivity reduction (de Dear et al. 2013). In a previous field study in Japan, the room temperature that maximized workers' performance was estimated to be 25.7°C, based on a survey of over 350 workers in an office building, after conformity of subjective and objective performance was confirmed with limited numbers of human participants (Tawada et al. 2010); this is in accordance with the research of Pilcher et al. (2002) showing that performance by sedentary occupants peaked across a temperature range from 21.1°C to 26.6°C. Association between thermal discomfort and reduced performance was supported by neurobehavioral research results (Lan and Lian, 2009; Lan et al., 2009).

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Besides the widely used method of constant air temperature control, fluctuating air temperature control between the value required for saving energy and that required for occupant satisfaction has the potential to provide both energy savings and occupant thermal satisfaction. Comfort and work performance under ambient temperature fluctuations of varying amplitudes and periods were examined by Wyon et al. (1973). These researchers concluded that large ambient temperature swings could have a positive effect on human performance, but could also increase discomfort depending on the tested conditions. However, most of the tested combinations of temperature amplitude and period were designed for laboratory or personal control systems (e.g., the distance between participant and inlet air was 70 cm), and are not easy to reproduce in office buildings with widespread variable air volume (VAV) air-conditioning outlets in their ceilings. It was also concluded that longer-term studies would be necessary because the participants experienced some conditions for only 24 minutes. Rohles et al. (1980) investigated thermal sensation and comfort under more practical cyclical changes (with amplitudes of about 1°C to 5.5°C) around various base temperatures (around 18°C–29°C) with rather low cyclic rates (0.3 to 1.5 cycles/hour). The authors concluded that changes will be perceived as acceptable as long as the rate of change does not exceed 3.3°C/h and the peak to peak difference (amplitude) is not more than 3.3°C. Each temperature fluctuating pattern was tested four times; from an initial steady state, temperature was increased twice and decreased twice, but did not include consecutive cycles.

According to ASHRAE standard 55-2013, if the period of the fluctuation cycle exceeds 15 minutes, the variation is treated as a drift or ramp. Berglund and Gonzalez (1978) concluded that the response to a temperature ramp of 0.5°C/h when wearing normal clothing for summer was nearly constant indicating that participants probably did not even notice the temperature was slowly rising from 25°C to 27°C. A gradual increase in indoor temperature provides a more comfortable transition than an abrupt increase (Shinozuka et al. 2011). On the other hand, a rapid temperature decrease, which allows rapid removal of the heat load accumulated in the human bodies, was shown to be important in a previous study demonstrating that cold shock contributed to enhancement of comfort upon entering the indoor environment from a hot outdoor environment (Chikamoto and Hashimoto 2008).

This study aimed to reveal the potential of cyclic fluctuating air temperature with sweep control (ramp control) as a means of increasing occupant comfort and decreasing energy consumption in office buildings with VAV air-conditioning system. In view of the typical working hours, excluding lunch or break time, the effects of fluctuating air temperature control with a 6-hour period versus constant air temperature control on human physiological and psychological conditions were investigated. Energy consumption under the two air temperature-control methods was also compared.

Methods

Methodology

A human participant experiment was carried out to investigate the human response to fluctuating air temperature. Targeting an application for on-site situations (e.g., office buildings), the main temperature range for fluctuating air temperature was set to 26°C–28°C considering the typical temperature set point for occupant comfort is 26°C and the recommended upper limit for office buildings is 28°C in Japan. Thermal environment of 26°C and 28°C was calculated to be predicted mean vote (PMV) = 0.20 and PMV = 0.87, with the typical values for the summer in the region where the study was conducted and for built environment with VAV air-conditioning systems (clothing insulation = 0.5 clo, activity level = 1.1 met, air velocity = 0.1 m/sec, humidity = 50%). The temperature 26°C is close to 25.7°C, at which the performance of office occupants is optimum, according to a field study conducted in the same region (Tawada et al. 2010). In the study by Tawada et al., PMV at the optimum temperature is considered to be 0.15, which is close to the value of 0.20, which was calculated with the averages of the measured and visually judged values in the paper (clothing insulation = 0.5 clo, activity level = 1.1 met, air velocity = 0.1 m/sec, humidity = 56%). Both of the experiments in this study and in the study of Tawada et al. (date of analysis target; July 25th and August 1st) were conducted under similar outdoor thermal conditions in the summer. Simulating office workers' typical working hours, 9:00–17:00, participants were exposed to fluctuating air temperature with a 6-hour period while performing tasks. Because the fluctuating cycle was set to 1 hour, the 6-hour period was comprised of six cycles. The participants were removed from the fluctuating air temperature condition during lunch, breaks, and measurement times. The experiment was conducted for 6 days, once or twice a week for 1 month, with the same group of participants. Results were evaluated based on the unit of a day, considering the application (i.e., exposure of occupants to daylong fluctuating temperature).

An asymmetric sweep up-down air temperature fluctuation pattern, consisting of a 40-minute gradual temperature increase to save on energy consumption and suppress occupants' thermal discomfort and a 20-minute abrupt temperature decrease to give the occupants a feeling of coolness and to rapidly decrease thermal discomfort, was employed. In a temperature increase to save on energy consumption, a faster rate of change is better because it contributes to decreased cooling energy but it should be determined to the extent it suppresses the occupants' thermal discomfort moderately. A 40-minute sweep-up in a temperature range 26°C–28°C (the peak to peak difference 2.0°C), 3°C/h was almost in accordance with ASHRAE standard 55-2013; the maximum operative temperature change were 1.1°C/0.25 h and 1.7°C/0.5 h because adjacent chamber were controlled at the maximum of the fluctuating temperature range (refer to Temperature control cases and the Results section). This was also in accordance with the conclusion of Rohles et al. (1980), that acceptable changes were under 3.3°C/h, with a peak-to-peak difference of 3.3°C. Real offices with VAV air-conditioning systems, cooling a room stably from 28°C to 26°C typically requires around 15 minutes, mainly because of thermal mass and internal heat generation. As an abrupt temperature decrease, a 20-minute sweep-down was selected because this duration approximates the reproducible rapid cooling at on-site situations.

This study aimed to investigate the positive and negative effects of cyclic fluctuating temperature on humans and on air-conditioning energy consumption. In the experiment, occupant thermal sensation, thermal satisfaction, performance, and stress and fatigue levels were examined.

Thermal chamber

The experiment was conducted in a climate-controlled chamber (Figure 1a) in summer (August), in a suburb of Tokyo, Japan. The indoor temperature of the main chamber (8 m long, 15 m wide, and 3.0 m high) was controlled by VAV air-conditioning outlets in its ceiling. There were six chambers adjacent to the four walls, floor and ceiling that surrounded the main chamber. The temperature of the chambers was also controlled.

Participants

The participants in the experiment were healthy men and women (university students) with body mass indices (BMI [kg / m^2] = weight [kg] / (height [m])^2) within the standard range (18.5 < BMI < 24). The number of participants was between 12 and 16 depending on the day (some subjects could not attend all of the days). Participants wore their own clothing, but clothing insulation was controlled at around 0.5 clo. Consumption of food and drinks during the experiment was also controlled. All participants consumed the same lunch each day of the experiment, and drank only 1 or 2 bottles (500 mL/bottle) of green tea per day, which were stored

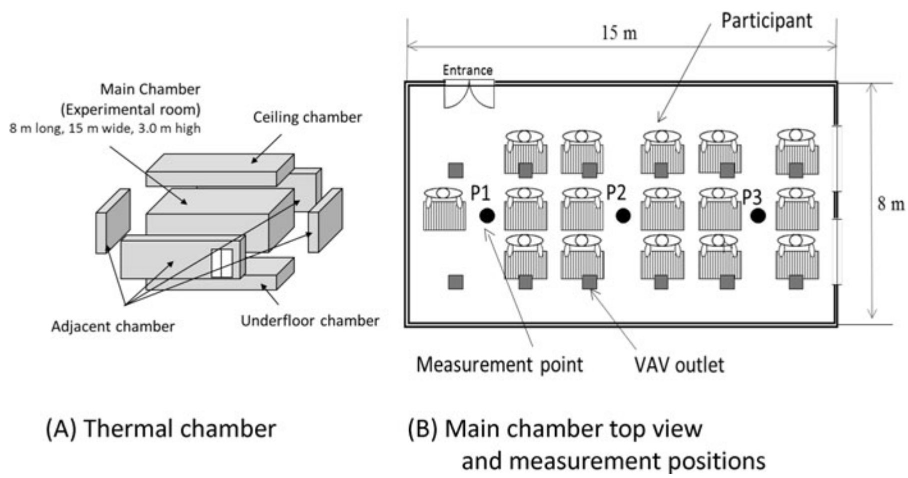

Fig. 1. Thermal chamber, top view and measurement positions in the main chamber.

at room temperature for more than 1 day before they were consumed.

Temperature control cases

The temperature control procedures (cases) are shown in Figure 2. Except for one fluctuating case, which was used for comparison, the temperature range of the control cases was between 26°C and 28°C. The temperature range for the fluctuating case for comparison was between 27°C and 29°C. The case period was 120 minutes. Case-26c, Case-27c, and Case-28c were constant temperature control cases. For these cases, temperatures in both the main chamber and adjacent chambers were held at 26°C, 27°C, and 28°C. Case-27v and Case-28v were fluctuating temperature control cases. Both Case-27v and Case-28v consisted of 60-minute cyclic temperature fluctuations (each case had two fluctuation cycles). The temperature range for Case-27v was 27°C ± 1°C (26°C–28°C) and the range for Case-28v was 28°C ± 1°C (27°C–29°C). In one cycle of a fluctuating temperature control case, the temperature swept up from its minimum to its maximum in the first 40 minutes, and for the next 20 minutes, the temperature swept down from its maximum to its minimum. In the fluctuating cases, the temperature of adjacent chambers was held at maximum of the fluctuating temperature range (i.e., 28°C for Case-27v and 29°C for Case-28v).

Each control case corresponds to one session (see the following subsection). Sessions were repeated three times a day.

Experimental procedure

Simulating the typical office workers' activity, participants arrived at the building every day of the experiment by 8:45 am. After they sat in the waiting room for 15 minutes, they entered the climate chamber at 9:00 am, and were seated at their work spaces, which included a desk, a chair and a personal computer (PC). The procedure is shown in Figure 2. There was a demonstration period while the participants sat at their

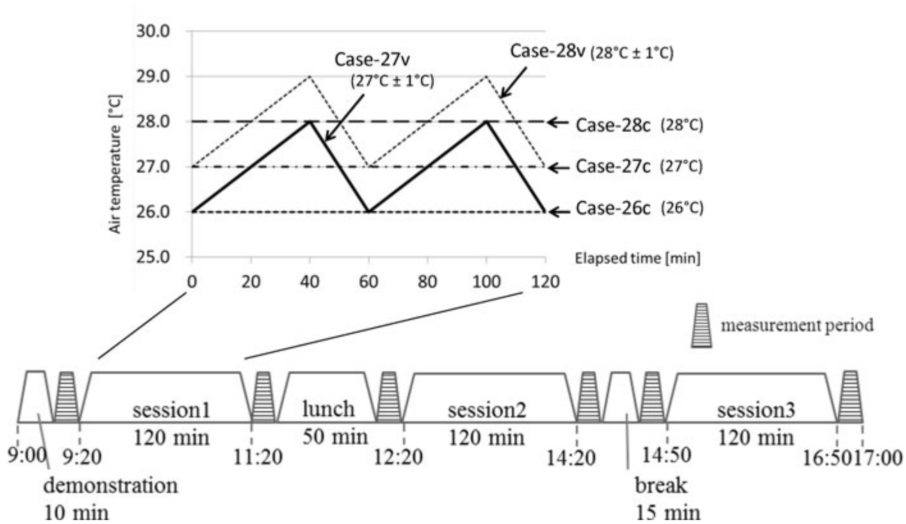

Fig. 2. Temperature control cases and experiment procedure.

Table 1. Measurement.

Category (height)	Interval [min]	Instrument (company)
Air temperature (0.1, 0.6, 1.1 m)	1	Type-T thermocouple data logger NR-1000 (Keyence)
Globe temperature (1.1 m)	1	Globe thermometer (SIBATA Scientific Technology)
Relative humidity (1.1 m)	1	Temp/humidity data logger TR-72Ui (T&D)
Air velocity (1.1 m)	1	Climomaster Model 6533-01 (Kanomax)
CO_2 concentration (1.1 m)	20	IAQ Monitor Model 2211 (Kanomax)

desks in the morning, during which they received an explanation about the day's schedule under a constant temperature equals to the starting air temperature of the day's case. Morning questionnaire surveys were conducted during this period to confirm that participants' physical conditions were normal. There were pre-session and post-session measurement periods (5 or 10 minutes in duration) which were used to check the participants' physiological and psychological conditions under a constant temperature equal to the starting or ending air temperature of the day's case.

Participants spent 20 minutes (10 minute demonstration period and 10 minute pre-session measurement period) under a constant temperature environment before the first session of the day and had three sessions in a day. The first session was in the morning and the second and the third sessions were in the afternoon. Lunch time (50 minutes) was between the first and the second session. Break time (15 minutes) was between the second and third sessions. During the break time, participants were not given tasks. They took rested quietly and went out of the chamber only for their personal needs.

Measurements

Physical measurements

Air temperature, globe temperature, relative humidity, air velocity, and CO_2 concentration were measured at a height of 1.1 m at specific intervals (Table 1). Measurement positions are shown in Figure 1b. The air temperatures at the height of 0.1 m and 0.6 m were also measured at each measurement position. Because of physical placement restrictions, measurements at 1.1 m were set as representative values after prior confirmation of differences in measured values between 0.6 and 1.1 m. Differences between values during the experiment are presented in the Results section. Air velocity was an average of 60 values measured every second for the previous minute. Average CO_2 concentration was 600 ppm. During the experiment, all lights were turned on and the lighting conditions were not changed. The representative value of illuminance was found by measuring a few of the participants' desks; the value was 700 lx. Other measurement results are shown in the Results section.

Physiological and psychological parameter measurements

- To investigate occupant stress levels, the concentration of salivary alpha-amylase was measured (Salivary amylase monitor, Nipro Co., Japan) during pre-session and post-session measurement periods, as described in Figure 2. Amylase monitoring has been examined and assessed to be valid and reliable (Shetty et al. 2011; Yamaguchi et al. 2003, 2004, 2006). Salivary alpha-amylase activity, a well-known stress indicator, increases when the participant feels uncomfortable and/or responds negatively to an external stimulus that is considered to be related with fatigue due to the continuous need for bodily thermoregulation in response to fluctuating temperature. In the range of 10–230 kU/l, the coefficient of variation was less than 9% and the accuracy was $R^2 = 0.989$ by linear regression analysis (Shetty et al. 2011).
- Two types of questionnaire surveys were conducted to measure psychological parameters.
- A questionnaire on Subjective Symptoms of Fatigue proposed by Japan Society of Occupational Health (JSOH); participants completed the questionnaire during pre- and post-session measurement periods.
- Questionnaires on thermal satisfaction and thermal sensation

During each session, participants completed psychological questionnaires that posed questions about thermal sensation and thermal satisfaction every 10 minutes. For the thermal sensation questionnaire, participants stated a number between –3.0 and +3.0 according to the thermal sensation scale shown in Figure 3. For the thermal satisfaction questionnaire, participants chose "dissatisfied" or "satisfied."

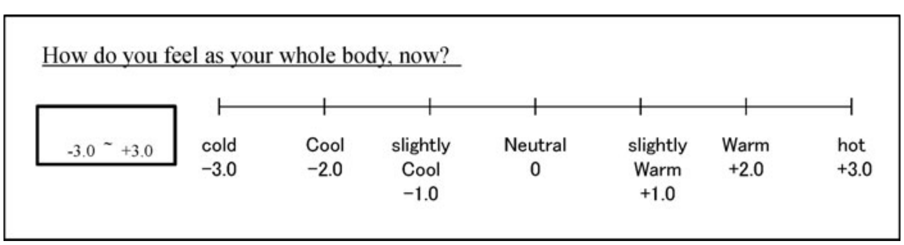

Fig. 3. Questionnaire of thermal sensation.

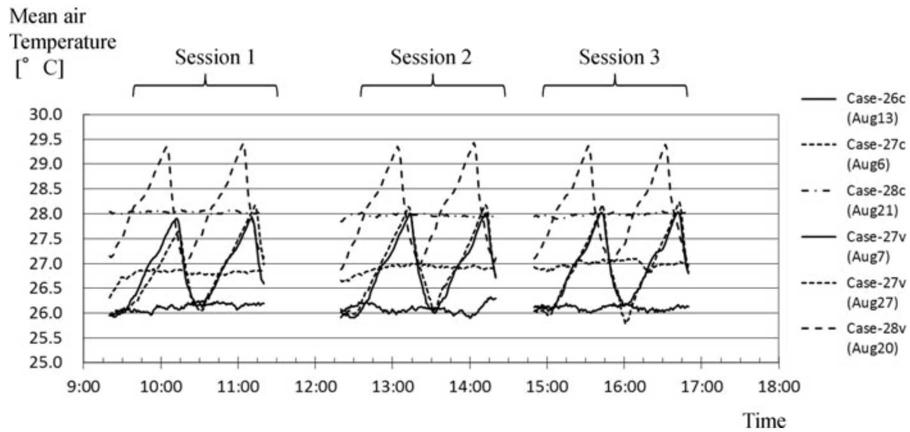

Fig. 4. Trend of floor mean air temperature of the cases.

Performance measurement

Two types of performance tasks, text typing and number place puzzle, were employed as performance measurement tasks. All tasks were performed on a PC and the results were saved in a database. For text typing, participants were asked to type successive sections of text. A section consisted of approximately 50 words. The texts were taken from a collection of speeches in English to avoid necessity for Japanese character conversion of which performance varies widely according to each participant's ability. Typing speed and error rate were evaluated. The number place puzzle is a logic-based, combinatorial number-placement puzzle. Participants were asked to solve six questions in 10 minutes. The numbers of correct answers were evaluated. Participants alternated between two tasks (text typing and number place puzzle) in turn every 20 minutes and continued this repeatedly during the sessions.

Analysis

Evaluation was conducted based on the unit of a day being considering the application for on-site situations (i.e., exposure of occupants to daylong fluctuating temperature). The results of 2 days of testing (Aug 7th and 27th) for the same Case-27v are also presented in the following results to confirm agreement between them. Parametric data were presented as mean and standard deviation in tables and graphs. Comparisons between session-mean values and standard deviations for the cases are shown for physical measurements, thermal sensation, thermal dissatisfaction, stress level, and fatigue level as follows. Student's t-test was used to determine significant differences for stress level, and fatigue level; $p < 0.05$ was considered significant. Analysis was done after excluding data of participants considering the attendance issues. In analysis for stress level and fatigue level, more exclusion conditions describing in each section were considered.

Results

Conditions tested

Figure 4 shows floor mean air temperature trends for all cases. The trends fit well with the case design. Figure 5 shows mean air temperatures at three heights (0.1, 0.6, and 1.1 m), mean air velocity (1.1 m), and mean operative temperature (1.1 m) for p1, p2, and p3 (Figure 1b). Standard deviations of the fluctuating cases were greater because they included variation caused by temperature fluctuation control. The vertical differences in mean air temperatures between both 0.1 and 1.1 m, and 0.6 and 1.1 m were under 0.3°C except for p1. Those for p1 were also under 0.6°C. Mean air velocities at 1.1 m height for p1 were higher than those for p2 and p3, but all values were under 0.15 m/s. According to ASHRAE standard 55-2013, operative temperature was calculated as the mean of the average air temperature and mean radiant temperature. Mean operative temperature for p3 was higher than that for p1 and p2 by 0.5°C at most. Table 2 shows the floor mean physical measurement data at 1.1 m height by day. The following analyses are based on the floor mean physical measurement data at 1.1 m height. Slopes of operative temperature for increases in fluctuating cases (i.e., Case-27v and Case-28v) were about 0.6°C–0.8°C/0.25 h, 1.2°C–1.6°C/0.5 h, respectively, both of which are permitted in ASHRAE standard 55-2013, with maximum values of 1.1°C/0.25 h and 1.7°C/0.5 h.

Thermal sensation

Figure 6a is a comparison between mean PMV (0.5 clo, 1.1 met) and mean thermal sensation according to the thermal sensation questionnaire completed every 10 minutes. Analysis for thermal sensation was done with the data of 12 participants. Although all mean thermal sensations were lower than mean PMVs, and thermal sensation for Case-27c was slightly greater, trends among the cases were similar and reflected differences in the case designs. Figure 6b shows ratios of daily thermal sensation divided into seven domains. Thermal sensation ratios for Case-27v were thought to be between those of Case-26c and Case-27c. Figure 7 shows session mean rate of thermal sensation divided into three domains (cold-side under –0.5, hot-side over 0.5, and nearly neutral between –0.5 and 0.5). Rates of both cold-side and hot-side thermal sensation for Case-27v were between those for Case-26c and Case-27c. Rates of nearly neutral thermal sensation for Case-27v were 65 and 71% were similar to or greater than those for Case-26c and Case-27c.

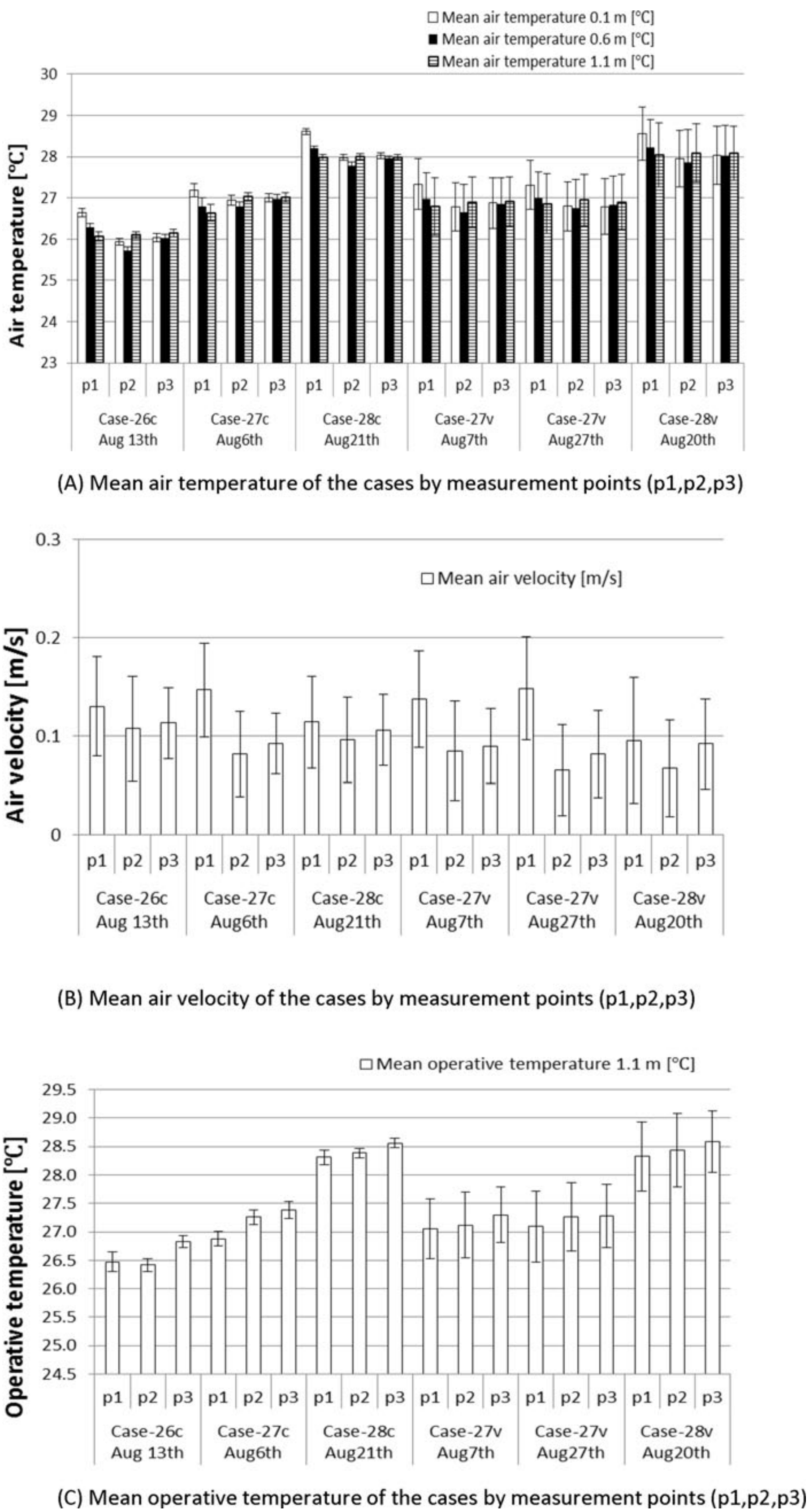

Fig. 5. Physical measurement results.

Table 2. Results of physical measurement.[1,2]

Case	Date	Session	Air temperature [°C]	Globe temperature [°C]	Operative temperature [°C]	Air velocity [m/s]	Relative humidity [%]
Case-26c	Aug 13th	1	26.1 ± 0.1	26.7 ± 0.2	26.7 ± 0.2	0.12 ± 0.05	48 ± 1
		2	26.1 ± 0.1	26.6 ± 0.3	26.5 ± 0.2	0.12 ± 0.05	48 ± 1
		3	26.1 ± 0.1	26.6 ± 0.3	26.5 ± 0.2	0.11 ± 0.04	48 ± 1
Case-27c	Aug 6th	1	26.8 ± 0.3	27.2 ± 0.3	27.1 ± 0.2	0.10 ± 0.04	43 ± 4
		2	26.9 ± 0.2	27.2 ± 0.3	27.2 ± 0.3	0.11 ± 0.05	38 ± 1
		3	27.0 ± 0.1	27.3 ± 0.2	27.2 ± 0.2	0.11 ± 0.05	38 ± 1
Case-28c	Aug 21th	1	28.0 ± 0.1	28.5 ± 0.2	28.5 ± 0.1	0.10 ± 0.05	42 ± 1
		2	28.0 ± 0.1	28.4 ± 0.1	28.4 ± 0.1	0.11 ± 0.05	42 ± 1
		3	28.0 ± 0.1	28.5 ± 0.2	28.4 ± 0.8	0.10 ± 0.04	42 ± 1
Case-27v	Aug 7th	1	26.9 ± 0.6	27.2 ± 0.5	27.1 ± 0.5	0.10 ± 0.05	44 ± 2
		2	26.8 ± 0.7	27.2 ± 0.6	27.1 ± 0.6	0.11 ± 0.05	45 ± 2
		3	26.9 ± 0.6	27.3 ± 0.5	27.2 ± 0.5	0.10 ± 0.05	45 ± 1
Case-27v	Aug 27th	1	26.8 ± 0.6	27.2 ± 0.6	27.1 ± 0.6	0.10 ± 0.06	41 ± 2
		2	27.0 ± 0. 7	27.3 ± 0.6	27.3 ± 0.6	0.10 ± 0.06	45 ± 2
		3	26.9 ± 0.7	27.3 ± 0.6	27.2 ± 0.6	0.10 ± 0.06	45 ± 2
Case-28v	Aug 20th	1	28.1 ± 0.7	28.6 ± 0.6	28.5 ± 0.6	0.06 ± 0.04	41 ± 2
		2	28.1 ± 0.7	28.5 ± 0.6	28.4 ± 0.6	0.09 ± 0.06	42 ± 2
		3	28.1 ± 0.7	28.5 ± 0.6	28.4 ± 0.6	0.10 ± 0.06	42 ± 2

[1]Mean ± SD.
[2]SD contains air temperature fluctuation according to the case condition.

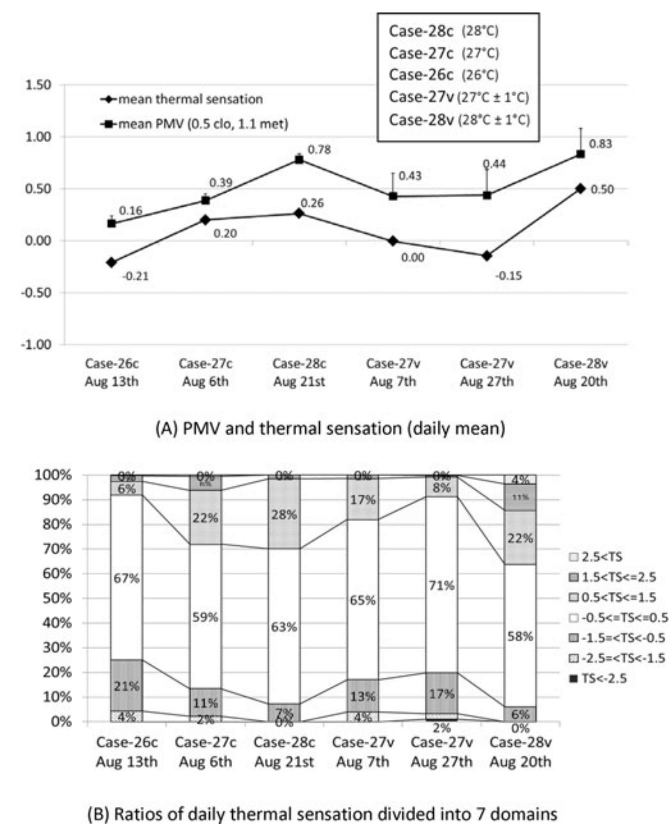

Fig. 6. Thermal sensation.

Thermal dissatisfaction

Figure 8 shows session mean rate of thermal dissatisfaction according to thermal satisfaction questionnaire completed every 10 minutes. Analysis for thermal dissatisfaction was done with the data of 12 participants. Under the environment of constant temperatures of 26, 27, and 28°C (Case-26c, Case-27c, Case-28c, respectively), the rate of thermal dissatisfaction increased as the temperature increased. For the high temperature cases of Case-28v and Case-28c, the rate of thermal dissatisfaction was high (around 20%) and nearly double the values of those of other cases. The rate of thermal dissatisfaction for Case-27v were under 10% and there was good agreement between the results of two days for Case-27v. The upper plot shows the relation between PPD calculated from daily average PMV in

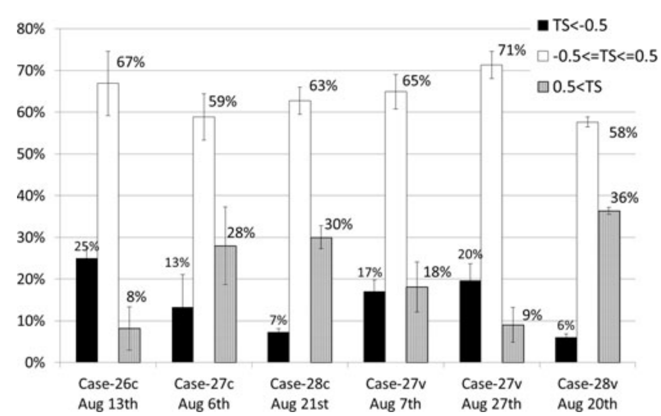

Fig. 7. Rate of thermal sensation (session mean).

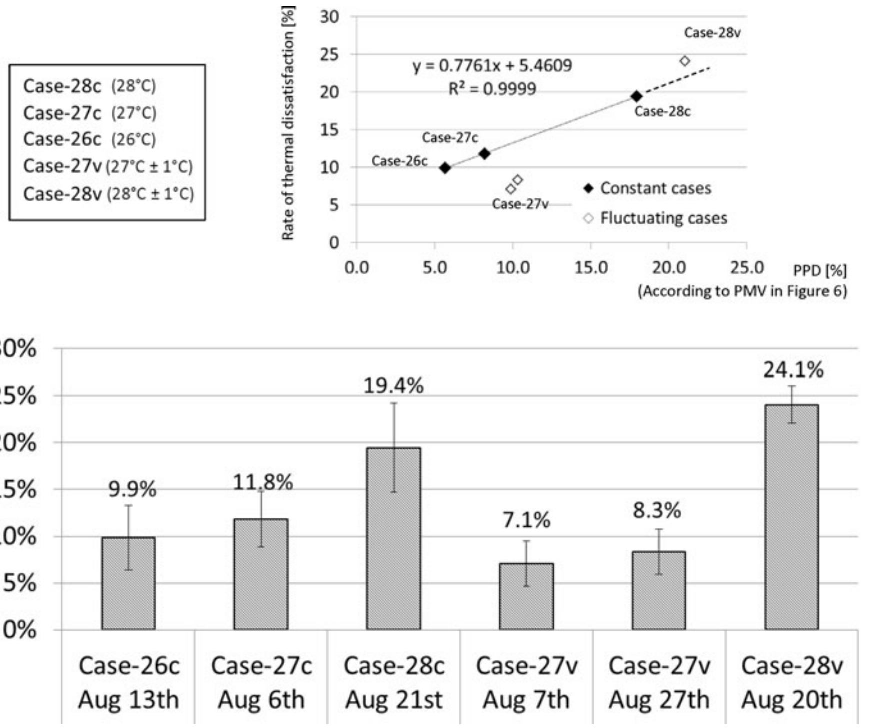

Fig. 8. Rate of thermal dissatisfaction (session mean).

Figure 6 and the session mean rate of thermal dissatisfaction. The eqation shows linear relation between them for the constant cases. The rate of thermal dissatisfaction for Case-27v were under the linear relation line and were lower than those of all other cases. On the other hand, the rate of thermal dissatisfaction for Case-28v were above the linear relation line. Considering the temperature range was between 26°C and 28°C, the rate of thermal dissatisfaction for Case-27v were thought to be low level compared with those for the constant cases.

Performance

After removing learning effects by building each participant model described by a Power law function, results were still seemed to depend strongly on elapsed numbers of session or date not on the cases. Because the experiment was conducted intermittently on 6 days in 1 month, there seemed to be other effects besides normal learning effect. The number place puzzle is a logic-based puzzle and thought to be less affected by elapsed time than text typing (simple task). With Spearman's correlation test, participants who had a *P*-value under 0.2 (participants who were thought to be less affected by leaning effect) were extracted and analyzed. The numbers of correct answers for the number place puzzle are compared in Figure 9. The results of the cases in each session are shown in date order to confirm learning effect. No statistically significant differences were found between the cases.

Stress level

Concentration of salivary amylase relates to the stress level of participants. Figure 10a shows the daily results of post-session mean concentration of salivary amylase for each case. The constant temperature cases show higher concentration of salivary amylase than the fluctuating temperature cases. The trends for session-based mean concentration of salivary amylase for constant temperature cases (Case-26c, Case-27c, and Case-28c) and fluctuating temperature cases (Case-27v and Case-28v) are presented in Figure 10b. In Figure 10b analysis, the mean concentrations of salivary amylase were calculated after all fluctuating data and all constant data were pooled separately. Participants who had loss of data even once, who had a value over 40 kU/L at the morning measurement (before the first session), who had alcohol the night before, or who did not have breakfast were excluded. The stress level was considered high when the value was over 40 kU/L. In both second and third afternoon sessions, the mean concentration of salivary amylase under fluctuating temperature was lower than that under

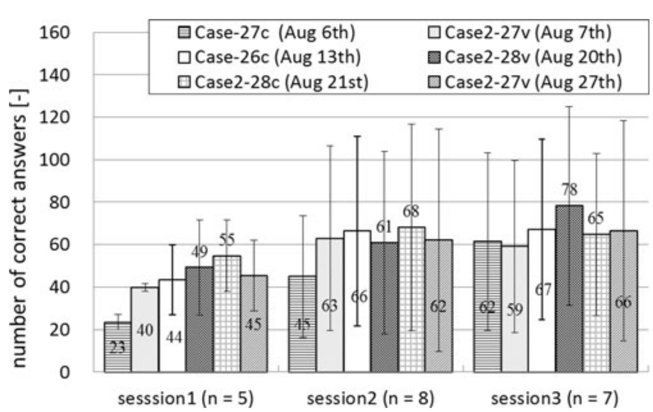

Fig. 9. Performance results of the number place puzzle task.

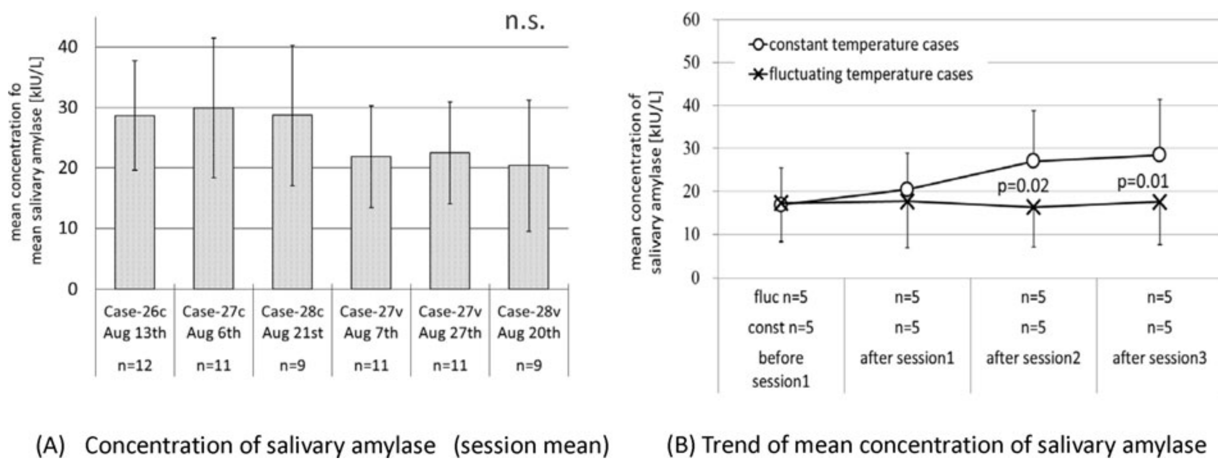

Fig. 10. Stress level (concentration of salivary amylase).

constant temperature. *P*-values were 0.02 after the second session and 0.01 after the third session. Taking into account the individual variations in the changing rates, individual normalized values, sAMYn = (sAMYi – sAMYmin) / (sAMYmax – sAMYmin), were also analyzed (sAMY: salivary alpha-amylase activity, sAMYi: sAMY for individual measurement, sAMYn: normalized value of sAMYi, sAMYmax: maximum sAMY for individual measurement, sAMYmin: minimum sAMYi for individual measurement). The results showed the same tendency as that shown in Figure 10b. The *P*-values were <0.01 after the second session and 0.02 after the third session (graph not shown). Although concentration of salivary amylase is known to be affected not only by thermal stress but also by many other factors, the stress level under fluctuating temperature was similar to or even lower than that under constant temperature.

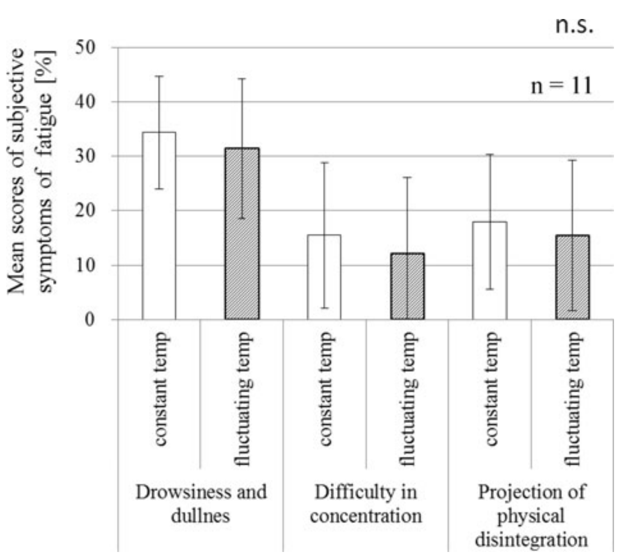

Fig. 11. Subjective fatigue levels as measured by the JSOH questionnaire.

Subjective fatigue level

Three factors "drowsiness and dullness," "difficulty in concentration," and "projection of physical disintegration" were evaluated from responses to the JSOH questionnaire on subjective symptoms of fatigue. Figure 11 shows the daily results of mean scores using questionnaire completed for subjective symptoms of fatigue. Similar to stress level analysis, the scores were calculated after all fluctuating data and all constant data of session-mean scores for each participant were pooled separately. Participants who had loss of data even once were excluded. The scores for fluctuating temperature tended to be lower than those for constant temperature but they were not significant.

Energy consumption

Cooling air-conditioning energy consumptions for the experimental time for a day (120 minutes $\times$ 3 sessions) for Case-26c, Case-27v, and Case-27c, which had comparable values for thermal sensation and thermal dissatisfaction, are compared (Table 3). The value of energy consumption is the total value of the air-handling unit (AHU) heat quantity and fan energy (fan energy was converted to heat quantity multiplied by a coefficient from electricity to heat quantity). Reheating energy for dehumidification was excluded and the value was corrected depending on the enthalpy of the outside air (in this correction, the base condition of the outside air was temperature 30°C and humidity 70%). Compared with Case-26c, the en-

Table 3. Comparison of energy consumptions.

Case	Energy consumption [MJ/h]	Energy reduction compared with Case-26c [%]
Case-27c	74	7.8
Case-27v	76	4.6
Case-26c	80	

ergy consumption of Case-27c and Case-27v was reduced by 7.8 and 4.6%, respectively. Case-27c had a smaller value than Case-27v because there was less energy consumption from the fans. However, there was still a reduction of close to 5%, compared with Case-26c.

Discussion

This study revealed that fluctuating air temperature control has the potential to achieve not only a reduction of energy consumption but also an increase in occupant thermal satisfaction. Compared with constant temperature control at 26°C, fluctuating temperature control between 26°C–28°C was associated with lower air-conditioning energy consumption. Because energy consumption data was from trial calculations in a thermal chamber (i.e., experimental facility), long-term data from on-site studies are needed.

The effects of 6-hour-long fluctuating air temperatures on humans have been investigated. A temperature increase rate of 40-minute for saving on energy consumption with suppressing occupants thermal discomfort was in accordance with both ASHRAE standard 55-2013 and the conclusion of Rohles et al. (1980); a temperature decrease rate of 20-minute for rapidly decreasing hot-side thermal discomfort was determined by the duration approximates the reproducible rapid cooling at on-site situations.

Salivary amylase was tested to examine whether the fluctuating temperature environment increased participant stress levels because of the continuous need for bodily thermoregulation. However, the measurements showed that participant stress level under the fluctuating temperature cases was similar or even lower distinct than stress levels under constant temperature cases. Concentration of salivary amylase is affected not only by thermal stress level but by many other factors; the stress level under fluctuating temperature was similar to or at least not higher with that under constant temperature, after exclusion data for participants who had possible factors other than thermal stress influencing the concentration of amylase. The results of the JSOH questionnaire on subjective symptoms of fatigue showed that the fatigue level for the fluctuating temperature environment did not increase significantly compared with that for the constant temperature environment. Moreover, rates of nearly neutral thermal sensation (thermal sensation between –0.5 and 0.5) for the fluctuating temperature between 26°C and 28°C were close to the rate for the constant temperature at minimum temperature (26°C) of the fluctuating temperature range. The session average rate of dissatisfaction for the fluctuating temperature was the lowest at under 10% even though temperatures for the fluctuating temperature were higher than 27°C for half of the cycle period. Figure 12 shows the typical trend of average thermal sensation every 10 minutes for fluctuating temperature control between 26°C–28°C (Case-27v). Thermal sensation of the second fluctuating cycle was greater than in the first cycle for all sessions (data not shown). Wyon et al. (1973) found skin temperature increased up to 2°C with temperature fluctuation. A maximum skin temperature rise of 2°C was observed with 2°C peak-to-peak fluctuations and a 32-minute fluctuating cycle. Although they did not test cycles longer than 32 minutes, the result suggest that the time lag between vasodilation and slower vasoconstriction elevates skin temperature and enhances the ability of the body to lose heat, resulting in a decrease of some of the negative effects of higher temperature. Verification of this hypothesis is not possible in the present study because skin temperature was not measured.

An asymmetric sweep up-down pattern consisting of a gradual temperature increase and a rather abrupt temperature decrease was employed. To control the rate of temperature increase, the sweep-up times of longer than 40 minutes, that were employed, were changed gradually and were expected to lower occupant dissatisfaction rate (Berglund and Gonzalez 1978, Shinozuka et al. 2011). However, it must be noted that when the internal heat load (imposed by people, PCs, lighting, etc.) in an air-conditioning zone is high, cooling energy may be consumed during the temperature increase to suppress an unwanted rapid sweep-up rate. To control the rate of temperature decrease, it should be noted that rapid decrease rates may increase both cold-side dissatisfaction and energy consumption. If the above hypothesis is correct, cold thermal sensation might overshoot quicker than under normal body conditions with extreme temperature decreases.

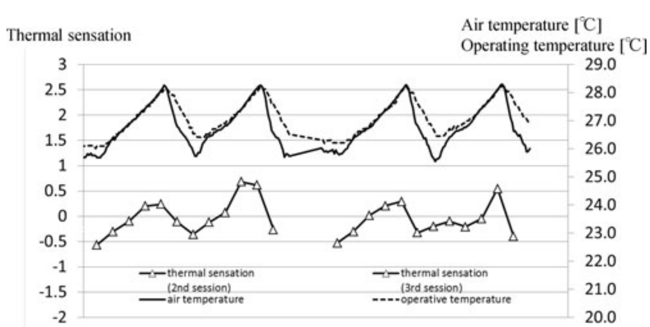

Fig. 12. Trend of thermal sensation during temperature fluctuation (an example of Case-27v).

Conclusions

Fluctuation of air temperature within 2°C above 26°C (26°C–28°C) achieved with an asymmetric sweep up-down pattern (sweep-up over 40 minutes; sweep-down over 20 minutes) was compared to a constant air temperature of 26°C.

- Air-conditioning energy consumption was reduced by about 5%.
- Daily mean (session mean) rate of participants' thermal dissatisfaction was under 10% and similar to or slightly lower.
- Participants' performance was not significantly affected.

Fluctuating temperature environment (26°C–28°C and 27°C–29°C) was compared to environment of constant air temperatures (26°C, 27°C and 28°C).

- Participants' objective indicator of stress (salivary amylase) reduced significantly.
- Participants' fatigue levels were not significantly affected.

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References

ASHRAE. 2013. *ANSI/ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy*. Atlanta: ASHRAE

Berglund, L.G., and R.R. Gonzalez. 1978. Application of acceptable temperature drifts to build environments as a mode of energy conservation. *ASHRAE Transactions* 84(1):110–21.

Chikamoto, T., and N. Hashimoto. 2008. Study on air-conditioning control which considers human comfort corresponding to thermal environment change from outdoor to indoor. *Proceedings of Sustainable Building 2008, Melbourne, Australia, September 21-25*, pp. 212–221.

de Dear, R., T. Akimoto, E. Arens, G. Brager, C. Candido, K.W. Cheong, B. Li, N. Nishihara, S.C. Sekhar, S. Tanabe, J. Toftum, H. Zhang, and Y. Zhu. 2013. Progress in thermal comfort research over the last twenty years. *Indoor Air* 23(6):442–61.

Lan, L., and Z. Lian. 2009. Use of neurobehavioral tests to evaluate the effects of indoor environment quality on productivity. *Building and Environment* 44(11):2208–17.

Lan, L., Z. Lian, L. Pan, and Q. Ye. 2009. Neurobehavioral approach for evaluation of office workers' productivity: The effects of room temperature. *Building and Environment* 44(8):1578–88.

Pilcher, J.J., E. Nadler, and C. Busch. 2002. Effects of hot and cold temperature exposure on performance: a meta-analytic review. *Ergonomics* 45(10):682–98.

Roelofsen, P. 2002. The impact of office environments on employee performance: The design of the workplace as a strategy for productivity enhancement. *Journal of Facilities Management* 1(3): 247–64.

Rohles, F.H., G.A. Milliken, D.E. Skipton, and I. Krstic. 1980. Thermal comfort during cyclical temperature fluctuations. *ASHRAE Transactions* 86(2):125–40.

Shetty, V., C. Zigler, T.F. Robles, D. Elashoff, and M. Yamaguchi. 2011. Developmental validation of a point-of-care, salivary α-amylase biosensor. *Psychoneuroendocrinology* 36(2):193–9.

Shinozuka, T., T. Ikaga, C. Kaseda, and H. Ueda. 2011. Modeling of thermal comfort based on physiological and psychological parameters. *Proceedings of Roomvent 2011, Trondheim, Norway*, June 19-22, 2011, CD-ROM.

Tawada, T., T. Ikaga, S. Murakami, S. Uchida, and H. Ueda. 2010. The total effect on performance and energy consumption causes by office's thermal environment. *Journal of Environmental Engineering (Transaction of AIJ)* 75(648):213–9.

Wyon, P.D., T. Asgeirdottir, P. Kjerulf-Jensen, and P.O. Fanger. 1973. The effects of ambient temperature swings on comfort, performance, and behavior. *Archives de Sciences Physiologiques* 27(4): A441–58.

Yamaguchi, M., M. Deguchi, J. Wakasugi, S. Ono, N. Takai, T. Higashi, and Y. Mizuno. 2006. Hand-held monitor of sympathetic nervous system using salivary amylase activity and its validation by driver fatigue assessment. *Biosensors & Bioelectronics* 21(7): 1007–14.

Yamaguchi, M., M. Kanemaru, T. Kanemori, and Y. Mizuno. 2003. Flow-injection-type biosensor system for salivary amylase activity. *Biosensors & Bioelectronics* 18(5–6):835–40.

Yamaguchi, M., T. Kanemori, M. Kanemaru, N. Takai, Y. Mizuno, and H. Yoshida. 2004. Performance evaluation of salivary amylase activity monitor. *Biosensors & Bioelectronics* 20(3):491–7.