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Seasonal Variations of Physiological Characteristics and Thermal Sensation under Identical Thermal Conditions

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Abstract Seasonal variations of human thermal characteristics were inspected in thermal comfort and when constantly indoors. Metabolic rate, tympanic temperature, skin temperature, body fat, body weight and thermal sensation were measured under identical thermal conditions in a chamber over the course of one year. Experiments were carried out for each subject in both summer and winter. Six subjects were measured 35 times in summer and 45 times in winter. one subject was measured weekly for 14 months. Measurements for analyses were taken 40–60 min after entrance into the chamber. Results revealed the following. 1) For all subjects, the metabolic rate, tympanic temperature and body fat were lower in summer than in winter; thigh skin temperatures were higher in summer than in winter. The averaged individual ratio of seasonal difference was 11.9% for metabolic rate, 14.9% for body fat, 1.8% for thigh temperature and 0.53% for tympanic temperature. Seasonal differences of about 10% in metabolic rate were maintained in this study. 2) Seasonal variations of the variables were examined for phase relationships against the outdoor temperature. 2-1) Metabolic rate, thermal sensation, body weight and body fat changed in reverse phase, whereas skin temperature was in-phase. 2-2) Skin temperature lagged by about one month in both summer and winter. Body fat also lagged by about one month in summer, but corresponded to the phase in winter. Metabolic rates were also in-phase in winter but led about three months in summer. Thermal sensations lagged by about three months in winter but were in-phase in summer. Body weight was in-phase in summer and winter. 2-3) Summer disorders were observed particularly in seasonal variations of metabolic rates, tympanic temperature, skin temperatures, and thermal sensation, thereby suggesting that the effect of temperature exposure was altered by air-conditioner use. *J Physiol Anthropol 25(1): 29–39, 2006* http://www.jstage.jst.go.jp/browse/jpa2
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Keywords: seasonal difference, seasonal variation, metabolic rate, skin temperature, tympanic temperature, thermal sensation, circannual rhythm, air-conditioner use

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Introduction

In thermal comfort standards such as the ASHRAE Standard 55-2004 (2004), Thermal Environmental Conditions for Human Occupancy, seasonal differences of an acceptable range between summer and winter are based only on clothing differences. Physiological differences according to seasons are assumed to be as negligible and are not considered. Fanger (1970) mentioned circadian rhythm when developing a thermal index of Predicted Mean Vote, which was introduced in the ISO-7730 standards (1994), but noted that the effect is sufficiently small to be negligible. Moreover, he made no reference to circannual rhythms or seasonal differences of physiological characteristics.

In the area of thermal physiology, however, numerous researchers have reported seasonal variations or circannual rhythms in physiological characteristics. For example, human basal metabolism was reported to be higher in winter and lower in summer by Yoshimura et al. (1976), Sasaki (1979), and Shimaoka et al. (1987). Seasonal differences amounted to approximately 10% for Japanese male subjects. Nevertheless, it must be noted that these results were based on measurements for which thermal conditions were not controlled. Umemiya (2001) estimated that the PMV changes as much as 0.58 units on a seven-point thermal sensation scale in the case of a 10% difference in metabolic rate. To develop a more rational standard of thermal comfort for air-conditioning design, seasonal differences and variations of thermal physiological and psychological characteristics must be examined under identical thermal conditions.

These days it is said that people spend more than 80% of their lives indoors. Because of the spread of air-conditioner use, indoor environments are becoming increasingly comfortable and isolated from outdoor climatic change: consequent physiological and psychological variations have been ignored. Now, rational concerns exist that the human ability of adaptation to environmental changes has weakened. Studies of physiological anthropology are also required in this area.

Nakamura and Okamura (1998) reported the existence of seasonal variations in mean skin temperature and tympanic temperature, each averaged for five male subjects in measurements taken every second month under identical thermal conditions. In this study, seasonal differences and seasonal variations of physiological measurements of metabolic rate, skin temperature, tympanic temperature, body fat, and body weight were measured and investigated under identical thermal conditions throughout the year. Thermal sensations were also measured and analyzed to determine which seasonal difference is related to physiological seasonality. Sasaki (1979) and Shimaoka et al. (1987) discovered phase differences of the metabolic rate against the outdoor temperature and mentioned the effects of temperature exposure on them. Seasonal variations of the measured variables and their relations to outdoor temperature were also examined in an aspect of the phase. This study is intended: 1) to examine the existence of seasonal differences between summer and winter; 2) to identify the magnitude of those differences; 3) to examine the phases of seasonal variations against seasonal climatic change; and 4) to examine effects of temperature exposure, particularly changes by air-conditioner use, on the basis of experiments under identical thermal conditions throughout the year.

Methods

Measured variables

This study measured metabolic rates, skin temperatures of arms, chests, thighs and shins, along with tympanic temperature, body weight, body fat, and thermal sensations.

Expired gas was gathered in a Douglas bag through a mask. Fractions of carbon dioxide and oxygen were measured. The gathered gas in the bag was sucked through a wet flow meter and its volume was measured. A subject inserted a tympanic temperature sensor into the external auditory canal until it touched the tympanic membrane. Both a highly sensitive thermistor probe and an easier touch sensor of thermocouple were used. The thermistor probe was fixed gently with a fine spiral spring to the tympanic membrane. The thermocouple was covered with a cotton ball and did not touch the tympanic membrane directly. After the subject confirmed the touch of the probe, the sensor was affixed to the ear with surgical tape. Subjects practiced attaching the sensors several times before experiments. It has been reported that tympanic temperature was affected by ambient illuminance (Aizawa et al., 1997). Horizontal illuminance at the working plane in front of the subject was 909 lx from four fluorescent tubes on the ceiling, which was within the Japanese Industrial Standard (JIS) recommended illuminance range for office work. Skin temperatures were measured using thermocouples; along with tympanic temperature measurements, they were recorded automatically every 10 s by a data logger. Average temperatures for each minute from 3 min before the start of gathering the expired gas were used for analyses. Thermal sensations were evaluated on a continuous linear rating scale. Subjects checked appropriate points on the Likert scale to report their feelings. The scale was continuous, but graduated as cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2) and hot (+3) at identical intervals. Thermal comfort, sensations of perspiration, thermal acceptability, and local thermal sensation were also recorded to confirm that the subjects were in their thermal neutrality without whole body or local discomfort and perspiration.

Experimental Procedure

The experimental procedure was as follows. Subjects entered the pre-test room in a chamber, where body weight and fat were measured. Subjects changed clothing to a provided ensemble: a short-sleeved cotton shirt, a long cotton jersey, trousers, and socks. The clothing's total thermal insulation was estimated as 0.32 clo. After proceeding to the test room in the chamber and sitting on a wooden chest, skin temperature sensors were affixed to one arm, chest, one thigh and one shin using surgical tape. For the arm, thigh and shin sensors, elastic bandages were bound over the sensors to prevent unexpected detachment. After the skin temperature and tympanic temperature sensors were set, subjects were instructed to spend time reading easy magazines or listening to favorite music, but never to sleep. Thermal sensations were measured at scheduled times. Two minutes at most were required to fill in the questionnaires. A mask was fixed to the subject's head and expired gas was gathered. Fractions of carbon dioxide and oxygen were measured immediately in the chamber. Before release from the experiment, the subject returned to the pre-test room, changed clothing, then measured body weight and body fat again. Volumes of the gathered gas in bags were measured within three hours after the subject was released.

Three experiments

Data were gathered from three experiments using the same chamber. Numbers of subjects, target temperature and humidity, experimental periods and the number of experiments for three experiments are shown in Table 1. Experiments were carried out independently on different occasions and the experimental methods differed in some details among the three. There were some other objects for Experiment I. The experiment was continued after measuring the metabolic rate. Commonly in each experiment, measurements in both summer and winter were available for the same subject and thermal conditions were maintained during the entire year. Regarding Experiment I, 23 tests in summer and 27 in winter were conducted, Experiment II iterations were 6 in summer and 12 in winter. Experiment III was performed 49 times. Results therefore reflect data from 117 experiments.

Different points among the three experiments other than those shown in the table are as follows. 1) Body fat and thermal sensation were not measured in Experiment I. 2) Metabolic rates were measured at 30, 60, 90 and 120 min after entrance in Experiments II and III, whereas they were measured only once at 40 min in Experiment I. 3) Expired gases were gathered for 10 min for Experiment I, but for only

Table 1 Numbers of experiments and experimental conditions

	Season	Experiment I	Experiment II	Experiment III
Number of subjects		3	3	1
Air temperature		25°C	26°C	26°C
Relative humidity		50%	50%	50%
Experimental period (Number of experiments)	Summer	July 17–Aug. 23 1996 (23)	Sep. 24–26 1998 (6)	July 15–Sep. 16 1999 (6)
	Winter	Dec. 5–19 1996 (27)	Feb. 24–26 1998 (6), Feb. 23–27 1999 (6)	Dec. 8–22 1998 (3), Feb. 9–24 1999 (3)
	All season	—	—	Nov. 30 1998–Feb. 7 2000 (49)
Elapsed time of the measurements after the entrance		40 min	30, 60, 90, 120 min	

Table 2 Physical characteristics of the subjects

	Exp.	Age	Height (m)	Weight (kg)	Surface Area (m^2)	BMI
Sub. A	I	22	1.65	50.7	1.56	18.6
Sub. B		35	1.80	77.0	1.96	23.8
Sub. C		21	1.77	73.5	1.92	23.5
Sub. D	II	24	1.68	61.7	1.83	23.5
Sub. E		23	1.72	69.5	1.86	21.9
Sub. F		24	1.77	68.5	1.72	21.9
Sub. G	III	22	1.67	56.2	1.64	20.2

BMI: Body Mass Index = Weight (kg)/{Height (m)}^{2}

3 min for Experiments II and III to spare time in the experimental schedule of gathering the gas at 30 min intervals. 4) Experiments were carried out three times per day in Experiment I in the morning, afternoon and evening at 5 h intervals, whereas they were done once per day in Experiments II and III, for which the subjects entered the chamber at 13:30 pm. 5) Tympanic temperature was measured using a thermistor probe in Experiments I and II, and using a thermocouple in Experiment III. To lighten the burden on subjects, a more convenient touch sensor of thermo-couple was used at the expense of accuracy. 6) Calories of foods that were consumed before the experiments were restricted to 500–900 kcal for Experiment I. However, lunch dishes were specified as 560 kcal of soy-sauce noodles, a piece of bean curd and boiled spinach provided in the dining hall of the university about an hour before entrance for Experiments II and III.

Subjects

Seven male subjects participated in the experiments. Table 2 shows their physical characteristics. Six were in their 20 s; one was over 30 years old. Their Body Mass Index values were between 18.5 and 25.0 and graded as standard in the grading system of the Japan Society for the Study of Obesity. They usually engaged in office work in a study room of the university for more than eight hours per day. They were instructed to sleep normally the night before the experiment and to eat breakfast and not to take heavy physical exercise or consume alcoholic beverages within 24 hours before experiments. Caloric contents of foods consumed before the experiments were restricted. Procedures and risks were explained carefully before the experiments. Each subject gave informed consent to participation.

Methods for the analysis

Mean skin temperature (*MST*) was calculated by Ramanathan's equation (1964).

$$MST = 0.3t_{arm} + 0.3t_{chest} + 0.2t_{thigh} + 0.2t_{shin} \qquad (1)$$

In that equation, t_{arm}, t_{chest}, t_{thigh} and t_{shin} are skin temperatures measured respectively at the arm, chest, thigh and shin.

Metabolic rates were estimated using the following equations.

$$\begin{aligned} M/A &= (0.23V_{CO_2}/V_{O_2} + 0.77) \times 5.88V_{O_2} \\ V_{CO_2} &= V_{ex}(F_{CO_2} - 0.0003) \\ V_{O_2} &= V_{ex}\{(1 - F_{CO_2} - F_{O_2})/0.7904 \times 0.2096 - 0.0003)\} \end{aligned} \qquad (2)$$

Therein, M is the metabolic rate (W), A is the human surface area (m^2), V_{ex} is the volume of expired gas (l/h) converted into the standard condition of 0°C and 1013 hPa. In addition, V_{CO_2} and V_{O_2} respectively represent the volumes of carbon dioxide and oxygen consumption (l/h) in the standard condition, and F_{CO_2} and F_{O_2} respectively represent the fractions of carbon dioxide and oxygen in the expired gas.

Human surface area A was estimated by the following equation, as

$$A = kW^{0.425}H^{0.725}, \qquad (3)$$

where W is the body weight in kilograms and H is the height in centimeters. The value of k is 0.007246 for Japanese by Takahira (1925), but the difference from that calculated by Dubois' equation was less than 1%.

Experiment III was carried out almost every week mainly for clarification of seasonal variation in its phase. A male student agreed to attend weekly experiments as a subject for over 14 months. Experiments were planned every week as a rule, but several of them were cancelled. Those measurements taken of subjects in poor physical condition were disregarded in analyses. Measurements of 49 weeks were obtained from 30 November in 1998 to 9 February in 2000. Averages of both sides of the cancelled or neglected experiments were interpolated. Consequently, a time series of 60 weeks was obtained.

Moving-averages were introduced to filter the fluctuation. Each observation was averaged with the weight of 1 : 6 : 15 : 20 : 15 : 6 : 1, with seven preceding and proceeding observations. In all, 53 observations of moving-averaged values were acquired; 51 for a year were analyzed. The dates were also moving-averaged from 25 December in 1998 to 24 December in 1999. Annual trends were removed by the least-squares method assuming that the trends were a linear function of time. Subsequently, the outcomes were standardized by annual means and standard deviations.

Results and Discussion

Effects of elapsed time after entrance into chamber

In Experiment I, the metabolic rate and thermal sensation were measured only once in an experiment, whereas in Experiments II and III, they were measured at 30, 60, 90 and 120 min after entrance into the chamber. Previous studies using climate chambers, however, have used measurements taken after two or three hours from the time of entrance were used. Rohles and Nevins (1968) found unstable sensations for male subjects during 60–120 min after entrance. Fanger (1970) analyzed thermal sensations at 120, 150 and 180 min after entrance to ensure steady-state conditions because sensations continued to change, even after 90 min. In contrast, the present study analyzed measurements at 60 min after entrance for Experiments II and III because mutual differences between the paired elapsed times of 30, 60, 90 and 120 min were tested using paired t statistics tests. Only differences in tympanic temperatures between 30 and 60 min and between 30 and 90 min were significantly different from zero ($p<0.01$). Significant differences were not apparent between the paired elapsed times for metabolic rate, mean skin temperature and thermal sensation. Moreover, it was advantageous to use data in Experiment I together with data at 60 min in Experiments II and III.

Subjects in this study adapted rapidly to the chamber conditions, probably because they stayed comfortable indoors with a low activity level before experiments and conditions in the chamber were also set around the thermal neutral zone.

Ratio of Seasonal Difference and Ratio of Seasonal Variation

Figure 1 shows seasonal differences between summer and winter within each subject. The ratio of seasonal difference (*RSD*) is defined as the following.

$$RSD(\%)=200\cdot(p_{winter}-p_{summer})/(p_{winter}+p_{summer}) \qquad (4)$$

In that equation, p_{winter} and p_{summer} are the mean values for winter and summer for the same subject. Metabolic rate, tympanic temperature, thigh skin temperature, and body fat had consistent seasonal tendencies for all individual subjects. Table 3 shows mean values for summer and winter, *RSD*, and the seasonal difference by subjects. Here, six were chosen as summer and winter experiments each out of 49 experiments on Subject G in Experiment III.

Metabolic rates were lower in summer than in winter for all seven subjects. The *RSD* ranged from 3.7 to 23.7% among subjects and the average was 11.9%. It would become 10.0% if Subject A were excluded. Seasonal differences of the metabolic rate are discussed further in the following section.

Tympanic temperature was also lower in summer than in winter for all subjects, but the *RSD* values were small and varied between 0.0 and 1.2% among subjects. The average *RSD* for seven subjects was 0.5% and the seasonal difference was 0.19°C. The *RSD* in Subject G was particularly small, perhaps because Subject G alone did not use a high-sensitivity tympanic temperature sensor. Another possible reason was that he attended experiments almost every week for more than a year and had become skilled in inserting the sensor. Averaged *RSD* and seasonal difference would be 0.6% and 0.22°C if Subject G was excluded.

Thigh skin temperature was higher in summer than in winter for all subjects. On the other hand, no consistent tendencies exist in temperatures at other sites or mean skin temperature. Averaged *RSD* and seasonal difference was -1.8% and -0.6°C. Averaged *RSD* and seasonal difference became -1.1% and -0.4°C if Subject B, whose temperature generally decreased in summer, were excluded.

Three of the four subjects evaluated warmer in winter than in summer for the same thermal conditions. The *RSD* values for three subjects were uneven: 7.7, 16.7 and 35.9%. Subject E, who evaluated contrarily to the other subjects for summer and winter in thermal sensations, also responded contrarily to the others in the thermal comfort evaluated.

Body fat increased in winter and decreased in summer for all subjects. However, by chance, fat was not measured for two subjects whose body weight decreased in winter.

Figure 2 shows the moving-averaged time series of the measured variables at 60 min in Experiment III. Annual trends were clearly recognized particularly in body fat and body weight, whereas no such clear trends existed in metabolic rate and thermal sensation. The body weight changed between 54.5 and 58.1 kg and the body fat changed between 12.4 and 16.2% after they had been moving-averaged. It appears as though the subject was pursuing a weight-loss program during the experimental period. For that reason, trends were removed in the following analysis to clarify seasonal variations.

The ratio of seasonal variation (*RSV*) is defined as the following.

$$RSV(\%)=100\cdot(p_{max}-p_{min})/p_{mean} \qquad (5)$$

In that equation, p_{max}, p_{min} and p_{mean} are the annual maximum, minimum and mean of the measured variables, which were moving-averaged. The annual trend was removed.

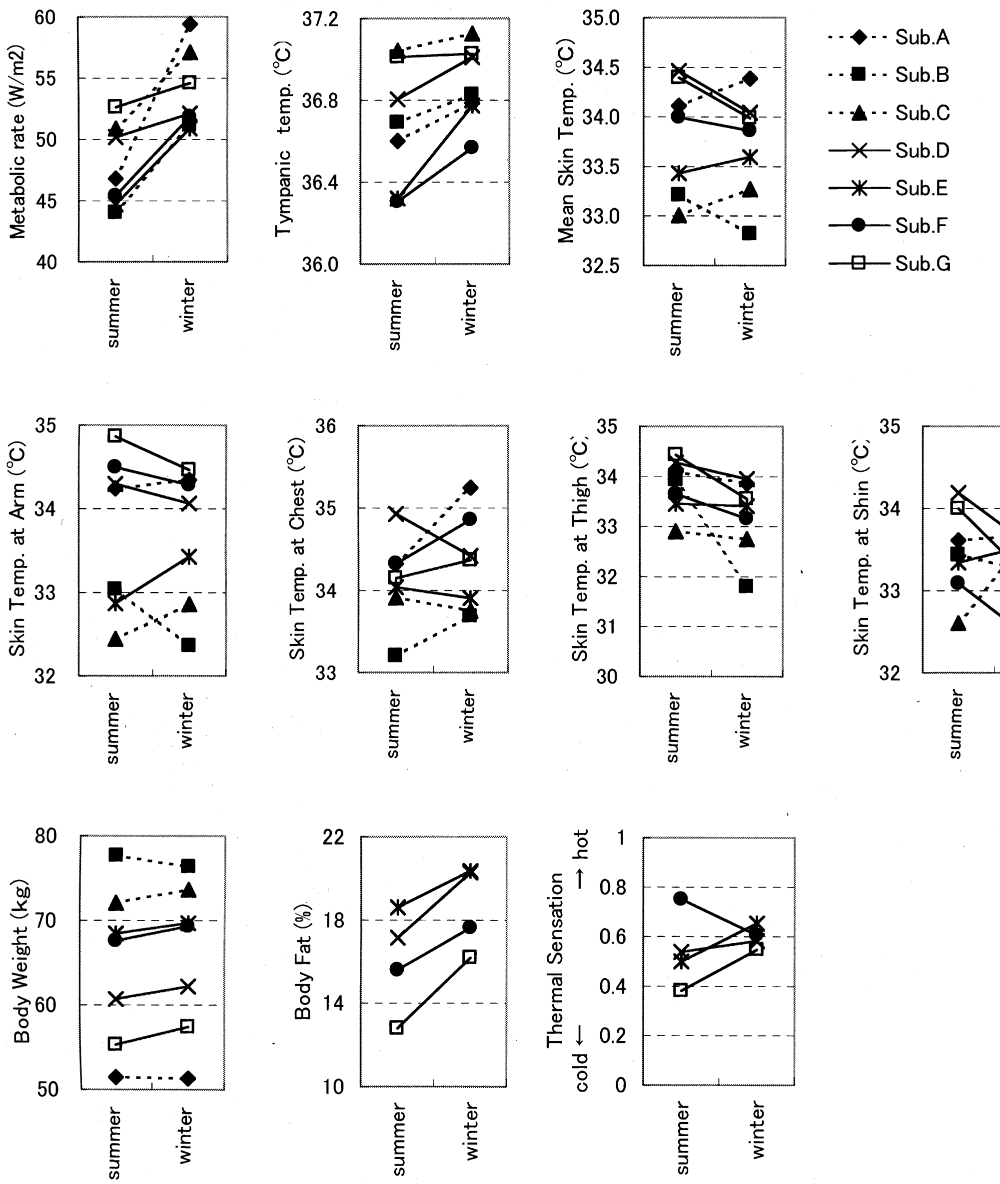

Fig. 1 Seasonal differences of physiological variables and thermal sensation.
Each symbol represents the mean value of each subject for the season. Body fat and thermal sensation were measured only for four subjects. Metabolic rates, tympanic temperature, thigh temperature and body fat had consistent seasonal tendencies for all subjects. See also Table 3.

Table 4 shows values of the annual mean, standard deviation and *RSV* for Experiment III. Average *RSD* for Experiments I and II are also shown for comparison. Here, *RSD* values are shown only for those variables that had consistent seasonal tendencies. Note that Subject G is excluded from the average. The *RSV* values for weekly experiments of Experiment III on Subject G resembled the averaged *RSD* values for 'winter' and 'summer' in Experiments I and II. We therefore infer that the chosen experimental periods as 'winter' and 'summer' in Experiments I and II were appropriate. Tympanic temperature was the only exception that was higher in summer and lower in winter for the time series on Subject G, but *RSD* was positive for the chosen 'winter' and 'summer', as Table 3 shows. It is noteworthy that the value of *RSV* is always positive because of its definition. This contradiction about the tympanic temperature will be explained below.

Outdoor temperature in the table is the daily mean outdoor temperature at a meteorological observatory in Kyoto about 5.0 km south-west from the laboratory. The daily mean outdoor temperature changed between 3.3 and 30.2°C; when moving-averaged, it changed between 4.6 and 28.7°C. Its annual mean was 16.1°C.

Table 3 Ratios of Seasonal Difference

Met. (W/m^2)	Summer	Winter	*RSD* (%)	Difference
Sub. A	46.80	59.40	23.7	12.61
Sub. B	44.03	51.15	15.0	7.13
Sub. C	50.87	57.10	11.5	6.23
Sub. D	50.18	52.10	3.8	1.92
Sub. E	44.70	50.88	12.9	6.19
Sub. F	45.38	51.85	13.3	6.48
Sub. G	52.61	54.56	3.7	1.96
Average	47.79	53.86	11.9	6.07

T_{thigh} (°C)	Summer	Winter	*RSD* (%)	Difference
Sub. A	34.1	33.9	−0.7	−0.2
Sub. B	33.9	31.8	−6.5	−2.1
Sub. C	32.9	32.7	−0.5	−0.2
Sub. D	34.3	33.9	−1.0	−0.3
Sub. E	33.5	33.4	−0.1	0.0
Sub. F	33.7	33.2	−1.5	−0.5
Sub. G	34.4	33.6	−2.6	−0.9
Average	33.8	33.2	−1.8	−0.6

T_{ty} (°C)	Summer	Winter	*RSD* (%)	Difference
Sub. A	36.60	36.79	0.5	0.19
Sub. B	36.69	36.83	0.4	0.13
Sub. C	37.04	37.12	0.2	0.08
Sub. D	36.81	37.01	0.6	0.20
Sub. E	36.32	36.77	1.2	0.45
Sub. F	36.31	36.57	0.7	0.26
Sub. G	37.01	37.03	0.0	0.02
Average	36.68	36.87	0.5	0.19

Fat (°C)	Summer	Winter	*RSD* (%)	Difference
Sub. D	17.2	20.3	16.7	3.1
Sub. E	18.6	20.4	9.0	1.8
Sub. F	15.6	17.6	12.2	2.0
Sub. G	12.8	16.2	23.4	3.4
Average	16.0	18.6	14.9	2.6

$$RSD(\%)=200\cdot(p_{winter}-p_{winter})/(p_{winter}+p_{winter}) \tag{4}$$

Seasonal difference of the metabolic rate

Numerous researchers, mainly of the area of physiology, have investigated seasonal variations of basal metabolism. According to Sasaki (1954), most of them in Japan such as Oti et al. (1932), Fujimoto (1936), Hatakeyama (1941), Ishikawa (1948), Fukuhara (1950) and Sasaki (1954) recognized that basal metabolism increased during the cold season and decreased in warm season. Non-Japanese researchers such as

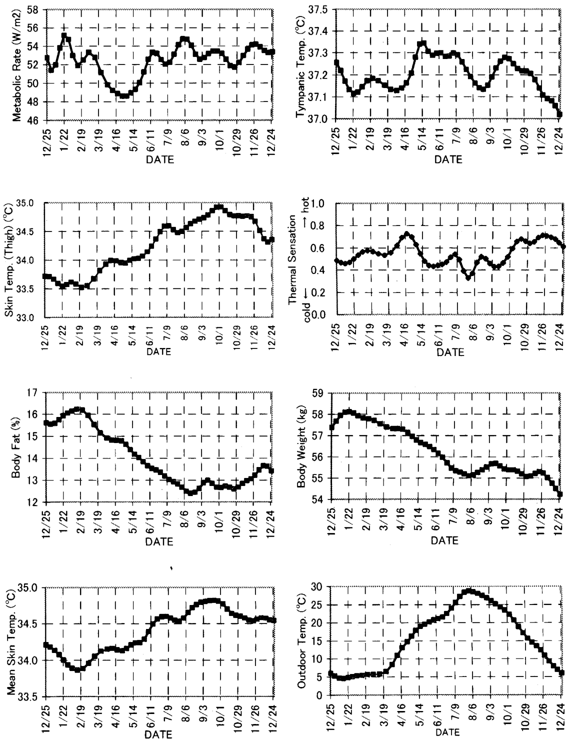

Fig. 2 Seven-week moving-averaged time series of the measurements in Experiment III.

Standardized time series 60 min after entrance are shown. Annual trends were clearly recognized particularly in body fat and body weight, whereas no such clear trends existed in metabolic rate and thermal sensation.

Table 4 Ratios of Seasonal Variation in Experimant III

	Annual Mean	Standard Deviation	*RSV* (%)	*RSD* (%)
Metabolic rate (W/m^2)	52.45	1.69	12.5	13.3
Tympanic temp. (°C)	37.20	0.08	0.9	0.6
Mean skin temp. (°C)	34.4	0.3	2.8	—
Thigh Skin temp. (°C)	34.3	0.4	4.0	−1.7
Thermal sens. (%)*	54.8	10.2	72.6	—
Body fat (%)*	13.8	0.7	17.6	12.6
Body weight (kg)	56.1	0.4	2.5	—
Outdoor temp. (°C)	16.1	8.3	150.2	—

Average *RSD* for Experiments I and II are also shown. Only *RSD* values of the variables of consistent seasonal tendencies are shown. Note that Subject G is excluded in the average.

RSD: Ratio of Seasonal Difference,

$$RSD(\%)=200\cdot(p_{winter}-p_{summer})/(p_{winter}+p_{summer}) \tag{4}$$

RSV: Ratio of Seasonal Variation,

$$RSV(\%)=100\cdot(p_{max}-p_{min})/p_{mean} \tag{5}$$

* Measured only in Experiments II and III.

Palmer et al. (1914), Benedict et al. (1918), Kunde (1923), Hafkesbring et al. (1924), Gessler (1925), and Griffith (1929) found similar seasonal tendencies, but the seasonal differences were smaller. Lindhard (1910), Young (1920) and Gufston et al. (1928) showed opposite seasonal tendencies, and Dubois (1927) and Tilt (1930) reported no seasonal differences. More recently, seasonal differences of basal metabolism in Japanese were 9.7% by Sasaki (1979) and 11.0% by Shimaoka et al. (1987): metabolic rates are higher in winter and lower in summer.

The ratios of seasonal difference in this study were 11.9 and 10.0% without the extreme data. They closely resembled the results of previous studies of Sasaki and Shimaoka et al. It is notable that the result of this study almost agreed with those of other studies even though they measured basal metabolism under natural temperatures that differed by season. Possibly, the effect of thermal environment the exposure on seasonal differences in metabolic rates is negligible. Notwithstanding, the following fact should be considered: seasonal differences in sitting metabolism were generally less than those of reclining basal metabolism: the former was 9% while the latter was 17% in Sasaki (1954).

Sasaki (1979) noted that the seasonal difference of Japanese basal metabolism had been shrinking from nearly 20% immediately after World War II to about 10% in the 1970 s and reported that the seasonal difference in Japanese metabolism was attributable to both Japanese food and climate. He pointed out a change of Japanese food in those thirty years whereby the proportion of carbohydrates and fats changed drastically from 82 to 63% and from 6 to 22% respectively. Yoshimura (1976) confirmed that the effects of dietary composition were greater than those caused by climate because seasonal differences were not recognized in Canadians living in Japan and eating high-fat foods. More recently, Shimaoka et al. (1987) reported seasonal differences of basal metabolism that were averaged for seven young Japanese Self Defense Force officials: they were about 10%. He referred to more recent studies that reported a difference of about 5%. Japanese government research in 1998 concluded that the respective proportions of carbohydrates and fats in food were 58 and 26%. The result of this study, that the seasonal difference was about 10%, supports the conjecture of nutrition as an important factor because the dietary composition changed little from that in the late 1970 s. Since the 1970 s, a difference of about 10% was revealed in the present study even though it has been projected that seasonal differences in metabolic rates were shrinking and would disappear due to dietary composition changes.

Phases of seasonal variations against outdoor temperature

Sasaki (1979) inspected the phase of the basal metabolic rate against the outdoor temperature. He found that the metabolic rate lagged climatic change by about 20 days in the season before summer, whereas it anticipated the climatic change by about 20 days in the season before winter. He estimated that those changes occurred because the body heat production system positively prepared humans against the cold. Shimaoka et al. (1987) found that the metabolic rate changed two months behind the climatic change and attributed it to the change in the thermal environment by air-conditioner use. Apparently, seasonal differences are maintained at about 10%, but the phase might be altered by the thermal environment. From the phase viewpoint, effects of exposure temperature on seasonal variations of physiological and psychological measurements, including metabolic rate, are examined in this section.

Figure 3 shows seasonal variations of Subject G against the outdoor temperature (T_{out}) in Experiment III. The value of T_{out} is overlaid to clarify the phase differences. These series were standardized using the annual means and standard deviations. Zeros in vertical axes represent the annual means. Units in vertical axes represent the widths of the standard deviations. Aside from those for body fat and body weight, figures show measurements at 60 min after entrance. Figure of mean metabolic rates averaged for 60, 90 and 120 min (met234) is also shown for comparison. Figures of other variables are not shown because their seasonal variations did not differ greatly among 60, 90 and 120 min. Table 5 summarizes the phase differences of the variables at 60 min against T_{out}. Approximately, the metabolic rate, thermal sensation, body weight and fat moved in the reverse phase of T_{out}, whereas T_{ty}, T_{thigh} and MST moved in the same phase as T_{out}. Skin temperature lagged by about a month in summer and winter, and fat also lagged by a month in summer but corresponded to that in winter. Metabolic rates also corresponded to the phase in winter, but led about three months in summer. Thermal sensation lagged by about three months in winter, but was in-phase in summer. Body weight corresponded to the phase in both summer and winter. Seasonal variations of respective measurements are as follows.

1) *Metabolic rate*

Metabolic rate fluctuated around the annual mean more intensely than did the other variables. The mean of the final three measurements (met234) moved more gently and the phase was clearer. Instability of measurements might be partly attributable to the technical difficulties posed by gathering the expired gas.

The maximum of the metabolic rate (at 60 min) agreed with the minimum of T_{out}. It is notable that the winter peak occurs at almost the same time as that shown by the result of Sasaki (1979): the basal metabolism was measured every month for 15 subjects and all the maxima calculated by the cosinor method came between 2 January and 19 February. Half of those subjects showed peaks within the seven days of 22–28 January. The summer trough was not as clear as the winter peak. The time series of the metabolic rate was rather positive in summer. Shimaoka et al. (1987) reported that the highest basal metabolism was obtained in April and the lowest in October by monthly measurements and that the lag was extending. Results of this study agreed with the earlier measurements by Sasaki (1979) rather than with the more

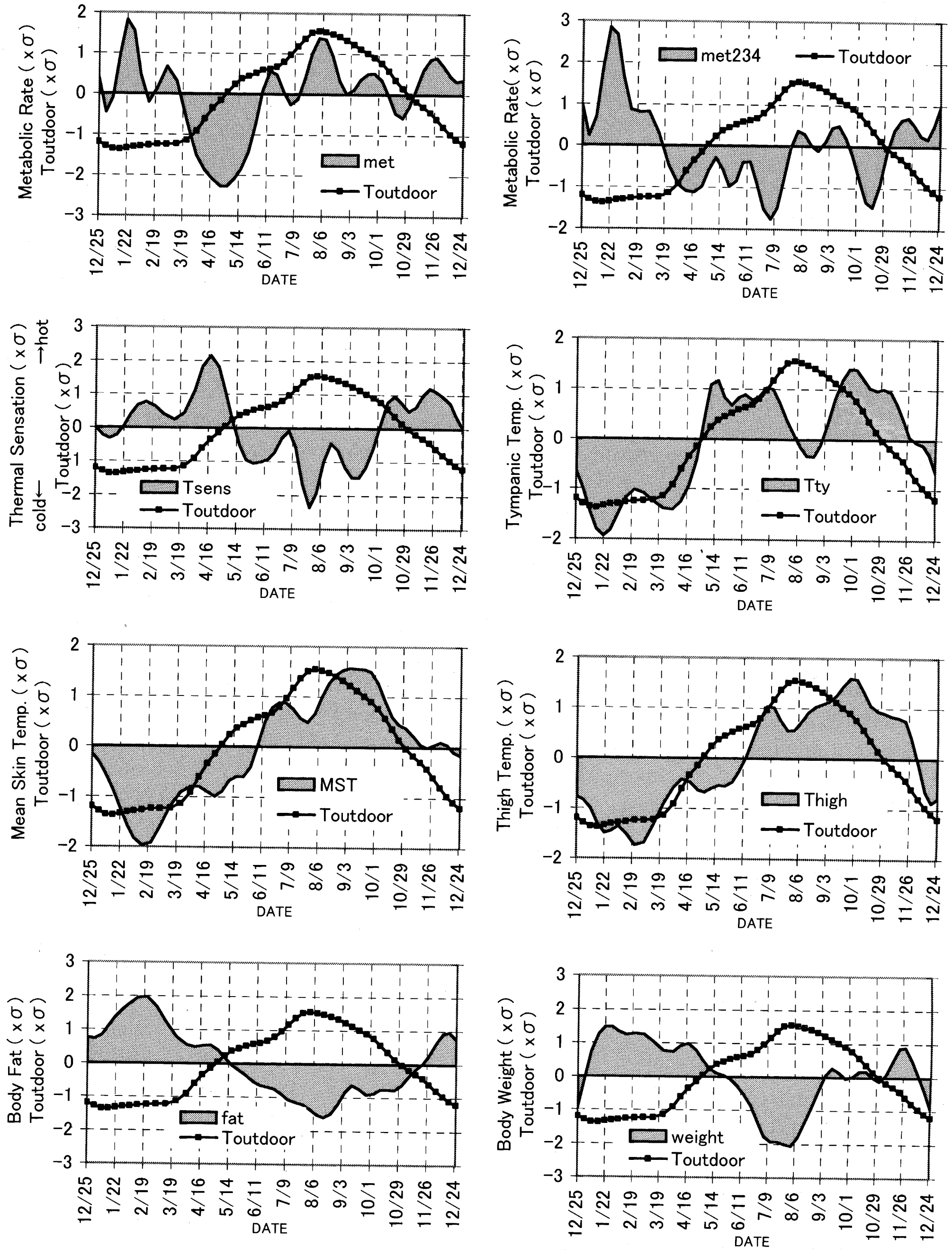

Fig. 3 Seasonal variations of measurements against the outdoor temperature.
Standardized time series 60 min after entrance are shown. Time series of the outdoor temperature ($T_{outdoor}$) is overlaid to clarify the phases. Figure of mean metabolic rates averaged for 60, 90 and 120 min (met234) is also shown. Zeros in vertical axes represent the annual means. Units in vertical axes represent the widths of the standard deviations (σ).

recent results of Shimaoka et al. (1987). Metabolic rates reached a minimum at the beginning of May, three months ahead of the peak of T_{out}. Nevertheless, a large trough in May disappeared for the mean of the last three measurements (met234). On the other hand, data of the maximum metabolic rate of both agreed with the minimum outdoor temperature.

2) *Tympanic temperature*

Figure 3 shows that the winter trough of T_{ty} agreed with the trough of T_{out}, whereas the summer peak was not so clear. The time series of T_{ty} crossed zero at the same time as the series of T_{out} in May. A large trough existed in August and the time series became negative. T_{ty} of Subject G was 0.02°C higher in winter than in summer, but that difference was much smaller

Table 5 Summary of the phase differences against the outdoor temperature

Variables	Date 22-Jan.	 19-Feb.	 16-Apr.	 6-Aug.	 1-Oct.	Phase against T_{out}	Stability	Summer disorder
Outdoor temp.	**minimum**			**maximum**				
Tympanic temp.*	**minimum**				maximum	same	△	◎
Mean skin temp.		minimum			maximum	same	○	○
Thigh Skin temp.		minimum			maximum	same	○	○
Metabolic rate	**maximum**		minimum			reverse	×	○
Body weight	**maximum**			**minimum**		reverse	◎	none
Body fat		maximum		**minimum**		reverse	◎	none
Thermal sensation			maximum	**minimum**		reverse	×	○

Dates of minima and maxima are shown. Bold figures show the accordance with T_{out}. See also Fig. 3.
* Measured using a thermocouple covered with a cotton ball. The probe did not touch the tympanic membrane.

than for other subjects, as shown in Table 3. But the seasonal variation of T_{ty} in Fig. 3 showed the reverse tendency: it was lower in winter and higher in summer for every subject.

Nakamura and Okamura (1998) which used the same type of thermistor probe as used in the present study also found a lower tympanic temperature in summer and a higher one in winter on the basis of every second month's measurements in a chamber kept at 23°C in SET*. Such was not true for individual values, but for the mean values of five subjects. Some doubt remains about the seasonal variation of the tympanic temperature by thermocouple in this study because it did not touch the tympanic membrane, but the seasonal difference was confirmed on the basis of thermistor measurements. Table 3 shows only those values at 60 min from entrance, but it was also true for values at 120 min: they were lower in summer and higher in winter within each subject in T_{ty}. That difference was maintained even at 120 min, whereas seasonal differences in other measurements became inconsistent among subjects at 120 min.

Further research is necessary to explain seasonal differences of tympanic temperature, but T_{ty} and skin temperature apparently move compensatorily to maintain the mean body temperature (T_b) in summer and winter if $T_b=0.8\ T_{ty}+0.2\ T_{thigh}$, where T_{ty} is an index of core temperature and T_{thigh} is that of shell temperature, and where the values in Table 3 are used.

3) *Skin Temperature*

Variation of the local skin temperature is shown only for thigh (T_{thigh}) in Fig. 3 because seasonal differences of other skin temperatures were not consistent among subjects. In Fig. 3, mean skin temperature (MST) moved similarly to T_{thigh}, although MST was also not consistent among subjects. Both moved behind T_{out} about a month and a half and showed troughs in July. An earlier comprehensive research program on mean skin temperature of Japanese males was undertaken by the Research Committee on Physiological Reaction to Climatic Seasonal Changes (1952). In that study, skin temperatures were measured every month without strict control of thermal conditions. It also showed a similar seasonal tendency. It was higher in summer and lower in winter. In the present study, MST and thigh temperature showed a summer trough that was not reported in earlier studies.

4) *Body fat and body weight*

Body fat and weight varied similarly and moved more gently than did other variables. Both became annual means at almost identical times with T_{out} in May and in November, but the body fat peaks and troughs came about a month later than those of T_{out}, whereas body weight agreed with T_{out}.

5) *Thermal sensation*

Thermal sensation changed approximately in reverse phase to T_{out}, but the time series went to zero several times. The summer trough coincided with the peak of T_{out} in August, whereas the largest peak occurred not in winter, but in April. It is reasonable to infer that subjects feel warmer in winter when the metabolic rate is higher if the thermally neutral point shifts as the metabolic rate changes. Seasonal differences in thermal sensation and metabolic rates shown in Fig. 1 support that conjecture. However, seasonal variations are shown in detail in Fig. 3: they did not move in the reverse phase, particularly in winter, suggesting that the change of thermal sensation is not explained only by the change of metabolic rate.

Figure 4 compares seasonal variations of the thermal sensation by elapsed time from entrance into the chamber. Seasonal differences lessened as time elapsed, but amounted to about 1.8 units on the seven-point Likert scale, even for the 120 min series. Umemiya (2001) calculated that the difference of PMV was 0.58 for the 10% change of metabolic rate, which was much less than that measured in the present study. This low value suggests that some other physiological or psychological characteristics than metabolic rate change seasonally for thermal regulation, even under the same thermal conditions. They affect thermal sensation.

The sensations voted immediately before entrance, $T_{sens}0$,

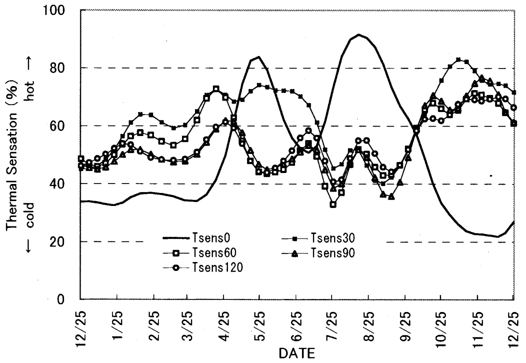

Fig. 4 Seasonal variations of thermal sensation by elapsed time. $T_{sens}30$, 60, 90 and 120 represents the thermal sensation 30, 60, 90 and 120 min after entrance into the chamber respectively. $T_{sens}0$ represents the thermal sensation immediately before entrance.

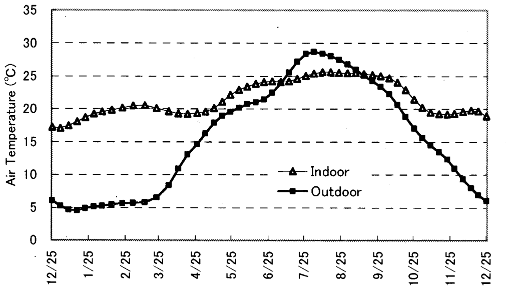

Fig. 5 Seasonal variations of the indoor and outdoor temperatures. Indoor temperature was measured in one university study room in the building where the subjects usually spent more than eight hours a day.

are also shown. They reflect the subjects' daily thermal sensation because the laboratory outside the chamber was free from air-conditioning and the subject voted with seasonal clothing. Although it showed a large trough in July, $T_{sens}0$ moved concomitant with variation of T_{out}. In the trough period, sensations at 60, 90 and 120 min moved almost in the reverse phase against $T_{sens}0$; one peak occurred at almost simultaneously with the large trough of $T_{sens}0$.

Summer disorder in variation

Figure 5 shows the moving-averaged indoor temperature in one university study room in the building where the subjects usually spent more than eight hours a day. It changed between 17.1 and 25.6°C in a year and changed in a 'trapezoidal' shape during May–October. It remained around 25°C from June through September despite the rapid change of T_{out}. Instead, the inclines on both sides of the plateau were steep and showed the effects of air-conditioner use.

Results demonstrated that seasonal variations did not always reflect sinusoidal curves, as T_{out} did. Particularly at the hight of summer, measurements broke out of rhythm. The metabolic rate had a peak, T_{ty} had a large trough, and MST and T_{thigh} showed summer troughs. Thermal sensations before the entrance also went out of rhythm in summer. These disorders indicated the potential influencing factor of summer exposure temperatures by air-conditioner use. Seasonal variations of indoor temperatures were kept small. Occupants were protected from exposure to extreme changes of the outdoor environment. On the other hand, it is worth considering that remaining in comfort and a constant environment in summer might engender summer disorders or sudden changes in physiological and psychological characteristics.

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References

Aizawa S, Tokura H (1997) Exposure to bright light for several hours during the daytime lowers tympanic temperature. Int J Biometeorol 41: 90–93

American Society of Heating, Refrigerating and Air-conditioning Engineers (2004) ASHRAE Standard 55-2004, Thermal environmental conditions for human occupancy. ASHRAE, Inc., Atlanta, 5

Fanger PO (1970) Thermal comfort–Analysis and application in environmental engineering. McGraw-Hill, New York, 75, 93

Fuller WA (1976) Introduction to statistical time series. John Wiley & Sons, New York

Griffith FR (1929) Studies in human physiology I. The metabolism and body temperature (oral) under basal conditions. Am J Physiol 87: 602

ISO (1994) Moderate thermal environments–Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. ISO-7730: 1–2

Nakamura Y, Okamura K (1998) Seasonal variation of sweating responses under identical heat stress. J Physiol Anthropol 17: 167–172

Ramanathan NL (1964) A new weighting system for mean surface temperature of the human body. J Appl Physiol 19: 531–533

Research Committee on Physiological Reaction to Climatic Seasonal Change, the 7th division of Scientific Research Aid Board, Department of Education, Japan (1952) Seasonal variations of skin temperature distribution of Japanese male adults. Jpn J Med Prog 89: 121–136 [*In Japanese*]

Rohles FR Jr, Nevins RG (1968) Short duration adaptation to comfortable temperatures. ASHRAE Trans 74: IV.1.1–IV.1.4

Sasaki T (1954) Seasonal variation in basal metabolism and resting metabolism, with particular reference to a climatic element of temperature. Bul Const Med Res Inst, Kumamoto Univ 4: 439–452 [*In Japanese*]

Sasaki T (1979) Trend of basal metabolism in the Japanese population. Metab Disease 16: 3–12 [*In Japanese*]

Shimaoka A, Machida K, Kumae T, Sugawara K, Kurakake S, Okamura N, Suemune J (1987) Seasonal variation of basal metabolism. Jpn J Biometeorol 24: 3–8 [*In Japanese*]

Takahira H (1925) Measurement and formation of body surface area of Japanese. Rep Imperial Govern Inst Nutr 1: 61–95

Umemiya N, Okamura K, Nakamura Y (2000) Seasonal Difference of the Resting Metabolism in Neutral Temperature. Biometeorology and Urban Climatology at the Turn of the Millennium–Selected papers from the Conference ICB-ICUC '99, World Meteorological Organization TD-No.1026: 143–148

Umemiya N (2001) Seasonal difference of neutral temperature based on the measured metabolic rate. Proc 7th Int Building Performance and Simulation Association Conference, Building Simulation 2001: 781–787

Yoshimura H (1976) Physiological studies on human acclimatization to tropical climates. Southeast Asian Studies 13: 602–640 [*In Japanese*]

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