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Authors	Wataru Umishio, Toshiharu Ikaga, Yoshihisa Fujino, Shintaro Ando, Tatsuhiko Kubo, Yukie Nakajima, Naoki Kagi, Tanji Hoshi, Masaru Suzuki, Kazuomi Kario, Takesumi Yoshimura, Hiroshi Yoshino, Shuzo Murakami
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Full length article



## Spatial and temporal indoor temperature differences at home and perceived coldness in winter: A cross-sectional analysis of the nationwide Smart Wellness Housing survey in Japan

Wataru Umishio<sup>a,b,\*</sup>, Toshiharu Ikaga<sup>b</sup>, Yoshihisa Fujino<sup>c</sup>, Shintaro Ando<sup>d</sup>, Tatsuhiko Kubo<sup>e</sup>, Yukie Nakajima<sup>f</sup>, Naoki Kagi<sup>a</sup>, Tanji Hoshi<sup>g</sup>, Masaru Suzuki<sup>h</sup>, Kazuomi Kario<sup>i</sup>, Takesumi Yoshimura<sup>j</sup>, Hiroshi Yoshino<sup>k</sup>, Shuzo Murakami<sup>l</sup>, on behalf of the Smart Wellness Housing survey group

<sup>a</sup> Department of Architecture and Building Engineering, School of Environment and Society, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8552, Japan

<sup>b</sup> Department of System Design Engineering, Faculty of Science and Technology, Keio University, Yokohama, Kanagawa 223-8522, Japan

<sup>c</sup> Department of Environmental Epidemiology, Institute of Industrial Ecological Sciences, University of Occupational and Environmental Health, Japan, Kitakyushu, Fukuoka 807-8555, Japan

<sup>d</sup> Department of Architecture, Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Fukuoka 808-0135, Japan

<sup>e</sup> Department of Public Health and Health Policy, Graduate School of Biomedical and Health Sciences, Hiroshima University, Hiroshima, Hiroshima, 734-8551, Japan

<sup>f</sup> Nikken Sekkei Research Institute, Chiyoda-ku, Tokyo 101-0052, Japan

<sup>g</sup> Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

<sup>h</sup> Department of Emergency Medicine, Ichikawa General Hospital, Tokyo Dental College, Ichikawa, Chiba 272-8513, Japan

<sup>i</sup> Division of Cardiovascular Medicine, Department of Medicine, Jichi Medical University School of Medicine, Shimotsuke, Tochigi 329-0498, Japan

<sup>j</sup> University of Occupational and Environmental Health, Kitakyushu, Fukuoka 807-8555, Japan

<sup>k</sup> Tohoku University, Sendai, Miyagi 980-8577, Japan

<sup>l</sup> Institute for Built Environment and Carbon Neutral for SDGs, Chiyoda-ku, Tokyo 102-0093, Japan

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## ABSTRACT

Residents themselves are responsible for controlling their living environment, and their perception of coldness is important to protect their health. Although previous studies examined the association between perceived coldness and indoor temperature, they did not consider the spatial-temporal differences in indoor temperatures. This study, conducted in Japan, measured indoor temperatures in 1,553 houses across several rooms (living room, changing room, and bedroom) and heights (at 1 m above the floor and near the floor) over two weeks and obtained the perceived coldness from 2,793 participants during winter. Results showed substantial temperature differences between rooms (horizontal differences): 3.8 °C between living and changing rooms, and 4.1 °C between living rooms and bedrooms. The average vertical and diel (evening-morning) temperature differences in the living room were 3.1 °C and 3.0 °C, respectively. Regional analysis revealed that the Tohoku region experienced larger horizontal and diel indoor temperature differences, primarily due to its practice of intermittent and partial heating in living rooms only, in contrast to Hokkaido's approach of heating the entire house continuously. Despite Hokkaido's comprehensive heating system, it exhibited the largest vertical temperature difference of 5.1 °C in living rooms, highlighting the insufficiency of heating alone and the necessity for enhanced thermal insulation. The multivariate logistic regression analyses showed that average temperatures and vertical temperature differences were associated with perceived coldness, while horizontal and diel differences did not show a significant association, further emphasizing the importance of improved thermal insulation. Moreover, factors like individual attributes (age and gender), and lifestyle choices (meal quantity, exercise

**Abbreviations:** ANSI, American National Standards Institute; ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; BMI, body mass index; BP, blood pressure; CASBEE, Comprehensive Assessment System for Building Environment Efficiency; CI, confidence interval; HDD, heating degree days; ISO, International Organization for Standardization; JPY, Japanese yen; MLIT, Ministry of Land, Infrastructure, Transport and Tourism; OR, odds ratio; PD, percentage of dissatisfied; SWH, Smart Wellness Housing; WHO, World Health Organization.

\* Corresponding author at: Department of Architecture and Building Engineering, School of Environment and Society, Tokyo Institute of Technology, W8-11, 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8552, Japan.

E-mail address: [umishio.w.aa@m.titech.ac.jp](mailto:umishio.w.aa@m.titech.ac.jp) (W. Umishio).

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habits, alcohol consumption, and clothing amount) were significantly associated with coldness perception. Notably, older adults were less likely to perceive coldness but more vulnerable to the health impacts of low temperatures, underscoring the necessity of not solely relying on human perception for indoor temperature management to protect cold-related health problems.

## 1. Introduction

The World Health Organization's (WHO) Housing and health guidelines (WHO, 2018) have highlighted the health hazards associated with low indoor temperatures. These findings emphasize the significant impact that inadequate thermal conditions can have on health outcomes. After the issuance of the WHO guidelines, a systematic literature review (Janssen et al., 2023) also showed that exposure to low indoor temperatures was associated with negative outcomes in cardiovascular health (Saeki et al., 2014; Saeki et al., 2015; Umishio et al., 2019; Umishio et al., 2020a; Umishio et al., 2021) and respiratory health (Ishimaru et al., 2022; Mu et al., 2017). Furthermore, the review indicated that older residents, who tend to spend more time at home, are more vulnerable to cold temperatures. Given the global trend of an aging population, it becomes increasingly important to acknowledge that health issues arising from low indoor temperatures represent a significant public health concern.

In Japan, which has been experiencing a super-aged society ahead of the rest of the world, the Housing Quality Assurance Act was revised in 2022 to establish higher thermal insulation performance standards for newly built houses. Yet, the more than 60 million existing houses in Japan are not regulated under these new standards. In our previous study (Umishio et al., 2020b), we reported on the indoor temperature conditions of 2,190 existing houses in Japan, revealing that over 90 % of these homes did not meet the WHO guideline's recommended minimum indoor temperature of 18 °C, indicative of a poor living environment. Therefore, addressing these living environment issues in Japan is urgent.

Our aforementioned analysis of indoor thermal conditions was limited to objective data from actual measurements, and we did not explore whether residents were accurately perceiving their poor thermal environment as inadequate. Indeed, since residents themselves are responsible for controlling their living environment, their perception of coldness is of importance. This perception significantly influences appropriate behavioral thermoregulation, such as operating heating devices or increasing clothing layers. The perceived coldness may be affected by the spatial and temporal differences in indoor temperatures. For example, spatial distribution may impact the perceived coldness due to variations in the density of temperature receptors across different body parts and the presence of both clothed and exposed areas. Additionally, in Japan, where intermittent heating is common, the significant temporal variation in room temperature could also be a contributing factor to the perceived coldness. Although numerous prior studies (Daniel et al., 2019; Fan et al., 2017; Heidari and Sharples, 2002; Pérez-Fargallo et al., 2018; Rijal, 2018; Rijal, 2021; Singh et al., 2010; Xu et al., 2018; Yin et al., 2022) have investigated the relationship between indoor temperature and perceived coldness in residential buildings in real-world settings, there are few cases where analyses have focused on the spatial-temporal indoor temperature variations in addition to the temperature itself. Furthermore, a recent study (Hou et al., 2023) examined the spatial-temporal heterogeneity of indoor and outdoor temperatures, considering factors like latitude and season, and their relationship with thermal sensation. However, it did not take into account the spatial-temporal heterogeneity inside the house and during the day.

Therefore, the present paper aims to organize information regarding the spatiotemporal distribution of indoor temperatures (differences between rooms, vertical differences, and diel variations) and to elucidate the relationship between these indoor temperature indices and perceived coldness. We utilized data from the Smart Wellness Housing (SWH) survey, a nationwide survey in Japan, which was specifically

designed to examine the association between the housing environment and the health status of residents.

## 2. Methods

### 2.1. Geographical and climate area classification in Japan

For the interpretation of the results, the 47 prefectures and eight geographical regions of Japan are illustrated in Fig. 1. Additionally, there is another set of areas - eight climate areas - classified based on the heating degree days (HDD<sub>18-18</sub>) value, as depicted in Fig. 2. Since the SWH survey began in 2014, we used the climate area classification that was in place at that time. The required insulation standards have been defined for each climate area. In our analysis, we included these zones as a variable labeled 'climate area'. Table A1 presents a simplified version of the climate area classification at the prefectural level. A more comprehensive classification at the municipal level has been detailed in another publication (MLIT, 2014).

### 2.2. Study design

The SWH survey targeted households planning to improve their home insulation. This non-randomized controlled trial was structured with groups based on whether participants chose to conduct insulation retrofitting, as shown in Fig. A1. We collected data on the housing environment and residents' health both before and after the retrofitting. The study protocol and informed consent procedure were approved by the ethics committee of the Hattori Clinic Institutional Review Board. Participants were enrolled in the study after providing written consent for participation and data publication. This study is registered at <https://www.umin.ac.jp/ctr/> (Trial No. UMIN000030601).

The main focus of our study was the health impact of insulation retrofitting. Therefore, our inclusion criteria were: (1) a plan to undertake insulation retrofitting, (2) being aged 20 years or older, and (3) living in a pre-retrofitting house that did not comply with the 'S' (Supreme) standards of Japan's 'Act on the Promotion of Dissemination of Long-Lasting Quality Housing' (Building Research Institute, 2023). Participants were recruited through construction companies throughout all 47 prefectures of Japan. Two participants per household (generally a husband and wife pair) were asked to conduct actual measurements.

We analyzed cross-sectional data of the baseline (pre-insulation retrofitting) survey during the winter months (November–March) from 2015 to 2019. We excluded data from 2014, which had been included in our previous paper (Umishio et al., 2020b), because the near-floor temperature measurements (described in the next section) started from 2015. We specifically focused on pre-retrofitting data to reflect the actual condition of houses in Japan, most of which have a low insulation level (MLIT, 2021).

### 2.3. Indoor temperature measurement and questionnaire

Indoor temperature and relative humidity at 1 m above the floor were measured in the living room, changing room (where residents typically change clothes) and bedroom at 10-min intervals over a two-week period (TR-72wf; T&D Corp.). Additionally, indoor temperature near the floor was measured using sensors (TR-51i; T&D Corp.) placed on the floor in these three rooms during the same period. Data obtained from this measurement was defined as the 0 m temperature in our study. Detailed specifications of the sensors are shown in Table A2. For the

placement of these data loggers, we instructed participants to place them neither in direct sunlight nor close to heat sources such as heating equipment, refrigerators, or televisions. We also asked participants to measure blood pressure (BP) after getting out of bed in the morning (during 4 AM–10 AM), and before getting into bed in the evening (during 5 PM–2 AM).

Subjective perceptions of coldness in each room were assessed through a questionnaire using the Comprehensive Assessment System for Building Environment Efficiency (CASBEE) Housing Health Checklist (Japan Sustainable Building Consortium, 2011). This checklist is designed to evaluate health-related aspects of housing from the residents' viewpoint. It includes questions like: How often do you feel cold in the living room during heating in winter? How often do you feel cold in the changing room in winter? How often is your sleep in the bedroom disturbed due to coldness in winter? Responses were initially recorded on a four-point scale: 'often,' 'sometimes,' 'rarely,' and 'never.' They were later grouped into a two-point scale, with 'feeling coldness' including 'often' and 'sometimes,' and 'not feeling coldness' including 'rarely' and 'never.' We also asked individual attributes (age, sex, weight, household income), and lifestyle choices (meal quantity, regular exercise, current smokers and drinkers, clothing patterns). Household income was categorized into low (<2 million Japanese yen (JPY)), middle (2–6 million JPY), and high (≥6 million JPY) brackets in accordance with the National Health and Nutrition Survey by the Ministry of Health, Labour and Welfare. Clothing patterns were selected from multiple-choice options, and the amount of clothing worn was calculated according to ISO 7730 (ISO, 2005) and ANSI/ASHRAE Standard 55 (ASHRAE, 2013) (Fig. A2).

In addition, we conducted a diary survey where participants recorded their wake-up and bedtime hours, as well as the amount of time spent at home each day. This information was used to deduce the indoor temperatures when participants were at home and during sleep.

#### 2.4. Definition of spatial–temporal indoor temperature differences

We defined spatial and temporal indoor temperature differences, with the following equations:

$$\text{Horizontal difference} = \text{Temp}_{\text{RoomA.1m}} - \text{Temp}_{\text{RoomB.1m}} \tag{1}$$

$$\text{Vertical difference} = \text{Temp}_{\text{RoomA.1m}} - \text{Temp}_{\text{RoomA.0m}} \tag{2}$$

$$\text{Diel difference} = \text{Temp}_{\text{RoomA.1m.Eve.}} - \text{Temp}_{\text{RoomA.1m.Mor.}} \tag{3}$$

Where  $\text{Temp}_{\text{RoomA.1m}}$  and  $\text{Temp}_{\text{RoomB.1m}}$  denote the temperatures in Room A and Room B, respectively, at 1 m above the floor;  $\text{Temp}_{\text{RoomA.0m}}$  represents the temperature in Room A near the floor;  $\text{Temp}_{\text{RoomA.1m.Eve.}}$  and  $\text{Temp}_{\text{RoomA.1m.Mor.}}$  are the temperatures in Room A at 1 m above the floor in the evening and morning when participants measured BP. For the calculation of horizontal and vertical temperature differences, average temperatures during the occupancy were extracted from the diary survey. 'During the occupancy' refers to the time when participants were awake and at home for the living room and changing room, and the time when they were sleeping for the bedroom.

#### 2.5. Statistical analysis

The association between perceived coldness, indoor temperature indices, individual attributes, and lifestyle was analyzed by multivariate logistic regression models. The dependent variable was whether feeling coldness or not, and the model was developed with the following independent variables: indoor temperature indices (average temperature, horizontal difference, vertical difference, and diel difference), individual attributes (age, duration of residence in the house, body mass index (BMI), sex, and household income), and lifestyle choices (meal quantity, exercise, smoking, drinking, and amount of clothes). All independent variables were included in the analysis simultaneously. Climate area was

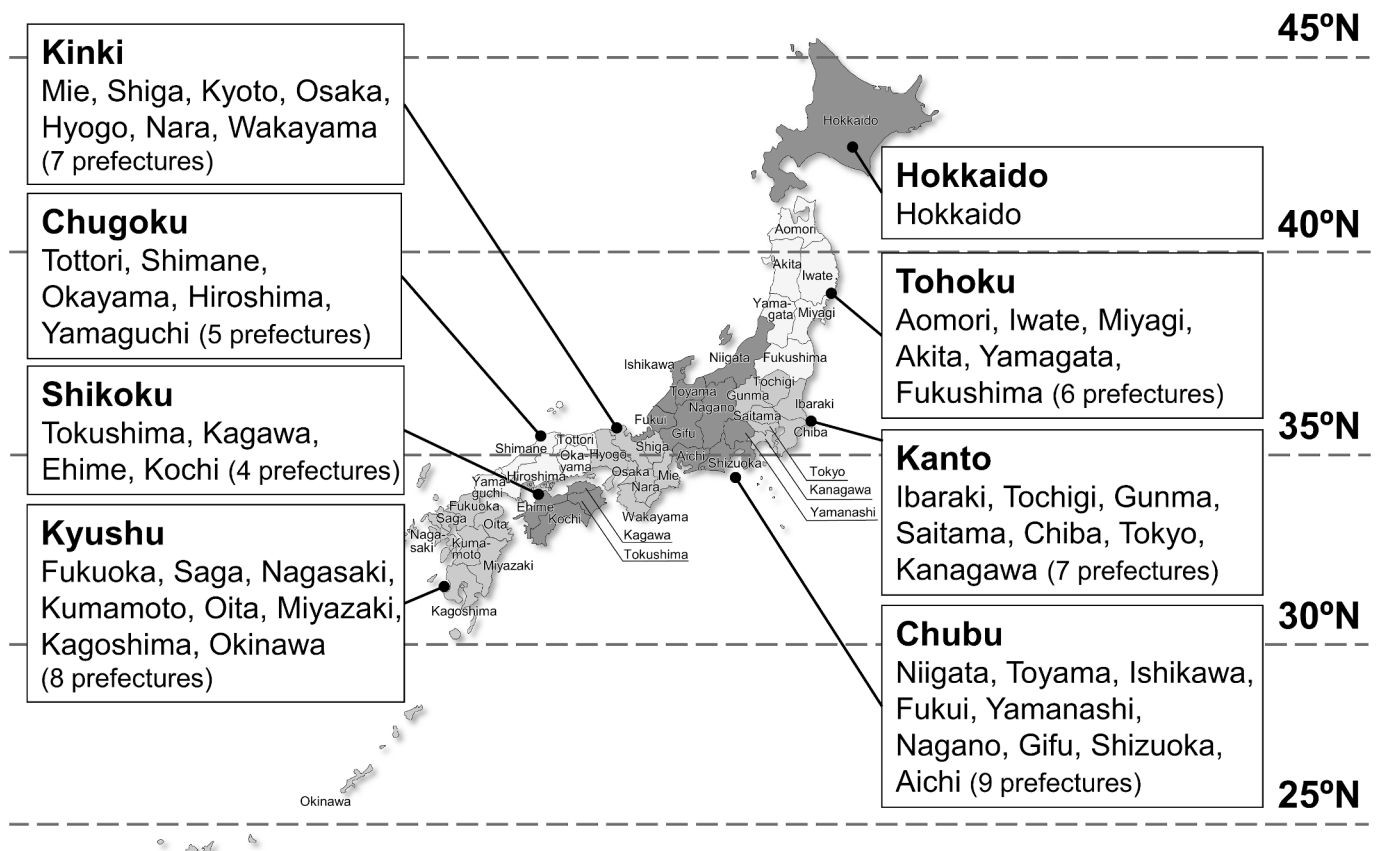


Fig. 1. 47 prefectures and eight geographical regions in Japan.

adjusted in the models. All P values were two-sided, and a two-sided P value less than 0.05 was considered statistically significant. All analyses were performed using SPSS Ver. 26 (SPSS Inc., Chicago, Illinois, USA).

### 3. Results and discussion

#### 3.1. Indoor temperatures and spatial-temporal indoor temperature differences

A total of 1,631 households and 2,951 participants responded to the survey, and valid data were obtained from 1,553 households and 2,793 participants by excluding participants who did not answer perceived coldness or missed indoor temperature measurements.

Table 1 shows the indoor temperatures in the living room, changing room and bedroom at 0/1 m above the floor in each period. The average living room, changing room, and bedroom temperature at 1 m above the floor during the occupancy were 16.9 °C, 13.1 °C, and 12.8 °C, respectively. In all three rooms, the average indoor temperatures near the floor were lower than those at 1 m above the floor. Additionally in all rooms, the average indoor temperatures in the morning were lower than those in the evening.

Table 2 summarizes the spatial-temporal variations in indoor temperatures. On average, there was a horizontal difference of 3.8 °C between the living room and the changing room, and 4.1 °C between the living room and the bedroom. In Japan, the living room is typically designated as the heating room, while the changing room is considered a non-heating room. As a result, the living room's temperature was higher than that of the changing room. Additionally, indoor temperature in the living room was higher than that in the bedroom, as heating devices are typically switched off at night. Vertical temperature differences in the living room, changing room, and bedroom were 3.1 °C, 1.4 °C, and 0.9 °C, respectively. The vertical temperature difference in the living room (the heating room) was significant due to the natural tendency of warm air to rise and cold air to descend. The largest diel temperature difference between morning and evening occurred in the living room because it is customary in Japan to turn off heating devices during the night, and indoor temperatures tend to decrease with a decrease in

**Table 1**  
Indoor temperatures in the living room, changing room and bedroom.

Room	Height	Period†	Ave [°C]	SD [°C]
Living room	1 m above the floor	during the occupancy	16.9	3.5
		in the morning	15.3	4.2
	near the floor (0 m)	in the evening	18.3	3.7
		during the occupancy	13.8	3.3
Changing room	1 m above the floor	in the morning	12.1	3.6
		in the evening	14.7	3.3
	near the floor (0 m)	during the occupancy	13.1	3.9
		during the occupancy	11.0	4.1
	1 m above the floor	in the morning	13.4	3.9
		in the evening	11.7	3.5
Bedroom	1 m above the floor	during the occupancy	10.3	3.7
		in the morning	11.8	3.6
	near the floor (0 m)	in the evening	12.8	3.9
		during the occupancy	12.3	4.2
	1 m above the floor	in the morning	14.2	4.2
		in the evening	11.9	3.5
near the floor (0 m)	during the occupancy	11.2	3.6	
	in the evening	12.7	3.6	

† 'During the occupancy' refers to the time when participants were awake and at home for the living room and changing room, and the time when they were sleeping for the bedroom. 'In the morning' and 'in the evening' denote the times when participants measured their blood pressure: in the morning (after getting out of bed) and in the evening (before going into bed).

outdoor temperatures.

Fig. 3 displays scatter plots showing spatial-temporal differences in indoor temperatures across different houses. About 90 % of the houses exhibited horizontal temperature differences greater than 0 °C, indicating that the changing room and bedroom were generally colder than the living room. In terms of vertical differences, living room temperatures near the floor were colder than those at 1 m above the floor in 96 %

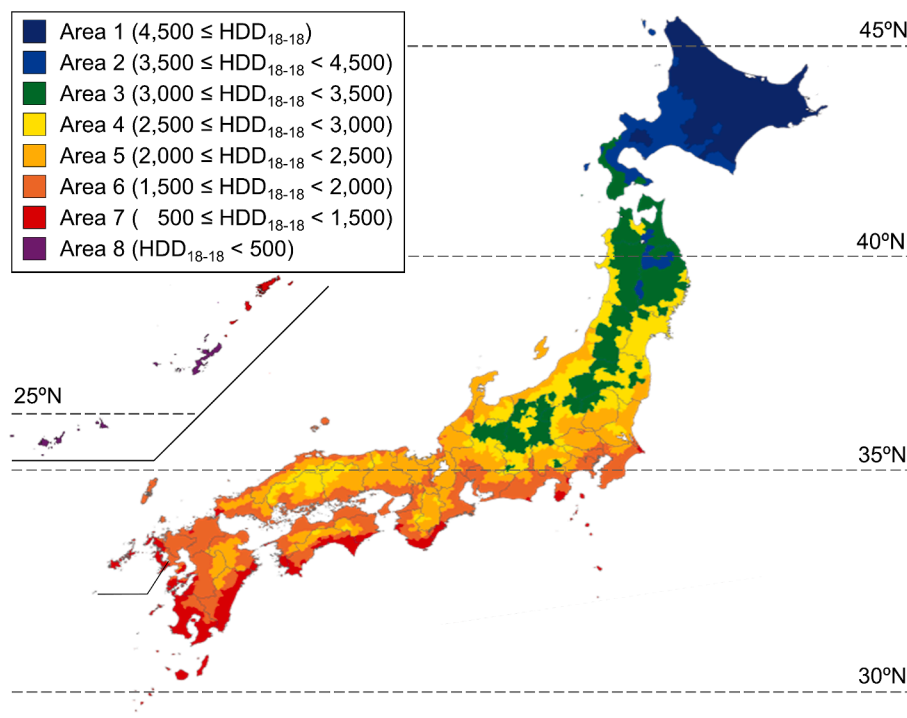


Fig. 2. Eight climate areas in Japan as of 2014.

**Table 2**  
Spatial-temporal indoor temperature differences.

Indoor temperature differences	Ave [°C]	SD [°C]
Spatial difference		
Horizontal difference		
Living room and changing room	3.8	3.6
Living room and bedroom	4.1	3.7
Changing room and bedroom	0.3	3.4
Vertical difference		
Living room at 1 m above the floor and near the floor (0 m)	3.1	2.3
Changing room at 1 m above the floor and near the floor (0 m)	1.4	1.7
Bedroom at 1 m above the floor and near the floor (0 m)	0.9	1.7
Temporal difference		
Diel difference		
Living room temperature in the evening and morning	3.0	2.8
Changing room temperature in the evening and morning	2.3	1.8
Bedroom temperature in the evening and morning	1.9	2.4

of houses. According to the guidelines for vertical air temperature differences in ISO 7730 (ISO, 2005) and ANSI/ASHRAE Standard 55 (ASHRAE, 2013), 31.6 % of houses fell into Class A (less than 2 °C difference), 20.7 % into Class B (less than 3 °C difference), and 16.7 % into Class C (less than 4 °C difference). The remaining 31.0 % did not even meet the criteria for Class C. Measurements were taken at heights of 1 m and 0 m in this study while the guidelines specify that vertical temperature differences should be measured at heights of 1.1 m and 0.1 m. Although it is important to note this discrepancy, vertical temperature differences may affect thermal comfort levels. Regarding diel differences, living room temperatures in the morning were colder than those in the evening in 91.0 % of the houses. These spatial-temporal differences in indoor temperatures well reflected the traditional heating use in Japan (partial intermittent heating in the living room only and heating devices are typically switched off at night).

Fig. 4 shows the average living room and changing room temperature at 1 m above the floor and horizontal difference in each prefecture. In the Tohoku region, four out of five valid prefectures experienced a temperature difference of more than 5 °C between two rooms. This is presumed to be due to the low outdoor temperatures in the Tohoku region, resulting in lower indoor temperatures in the non-heating room such as the changing room. Indeed, the average changing room temperatures were below 10 °C in 3 prefectures in the Tohoku region, and the lowest temperature was observed in Akita prefecture. Fig. 5 displays the average living room and bedroom temperature and horizontal difference in each prefecture. A similar trend to that shown in Fig. 4 was observed, where a large temperature difference occurred in the Tohoku region, with the lowest bedroom temperature being recorded in Fukushima prefecture (9.3 °C). Fig. 6 indicates the results of vertical temperature differences in the living room in each prefecture. The largest vertical temperature difference of 5.1 °C was observed in Hokkaido, which has the lowest outdoor temperatures in Japan and the only region where continuous heating is common. In this survey, we recruited houses with relatively low insulation levels. Consequently, relying solely on heating is insufficient to raise temperatures at floor level, emphasizing the necessity of improving the thermal insulation of houses. Fig. 7 shows the diel difference of the living room temperature in the morning and evening in each prefecture. In the evening, about half (21 out of 41 valid prefectures) had the average living room temperatures above 18 °C. However, in the morning, only Hokkaido had the average living room temperatures above 18 °C due to the continuous heating, indicating the difficulty of temperature management in the morning. However, morning temperature management is important because indoor temperature in the morning was strongly associated with BP compared to the evening (Umishio et al., 2019) and cardiovascular events, which are partially caused by raised BP, occur frequently in the

morning (Cohen et al., 1997; Elliott, 1998; Muller et al., 1989; Omama et al., 2006). In an integrated evaluation of these figures, houses in the Tohoku region exhibited larger horizontal and diel differences in indoor temperatures. This is primarily attributed to the heating practices. Despite having the second lowest outdoor temperatures in Japan, following Hokkaido, the Tohoku region differs from Hokkaido in its approach to heating. In Tohoku, heating is typically intermittent and partial in the living room only, unlike the continuous heating to the entire house observed in Hokkaido.

### 3.2. Perceived coldness in living room, bedroom, and changing room

Table 3 shows the characteristics of 2,793 participants in the SWH survey. The average age was 57 years, and about half were men. The average duration of residence in a house was 25 years. The average amount of clothes while awake and that during sleep were 0.97 clo and 0.76 clo, respectively. About 40 % of residents had high household income ( $\geq 6$  million JPY); about 15 % of the respondents had a larger meal quantity than the average person; and about 30 % of participants exercised regularly. Current smokers and drinkers made up about 15 % and 55 %, respectively. More than half of residents lived in Area 6.

Fig. 8 displays the frequency of feeling coldness in three different rooms. Approximately 70 % of residents felt coldness in the living room, 90 % in the changing room, and 40 % in the bedroom. Interestingly, despite the living room's temperatures being 4.1 °C higher than those in the bedroom, residents reported feeling coldness more frequently in the living room. This phenomenon can be attributed to participants using bedclothes in addition to clothing.

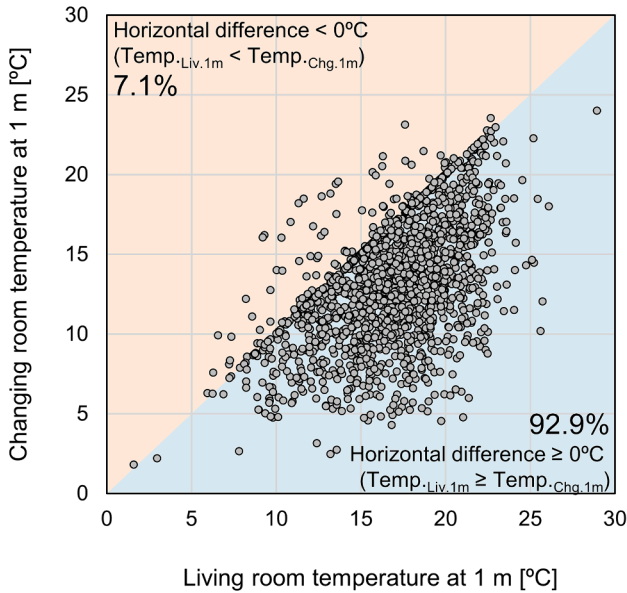
### 3.3. Association between indoor temperature indices and perceived coldness

The average indoor temperatures for each category of perceived coldness are shown in Fig. 9. In all rooms, there was a tendency for indoor temperatures to be higher when the frequency of feeling coldness was lower. However, the overall means of average indoor temperatures were 17.8 °C in the living room, 14.7 °C in the changing room, and 13.6 °C in the bedroom when residents reported 'never feeling coldness.' Significantly, even the overall mean of 'average' living room temperatures during occupancy fell short of the WHO's recommended 'minimum' temperature of 18 °C, underscoring the prevalence of inadequate indoor thermal conditions in Japan. The lower temperatures in the changing room may be attributed to a general acceptance of non-heated rooms, while in the bedroom, they may be due to the use of bedclothes, as previously mentioned.

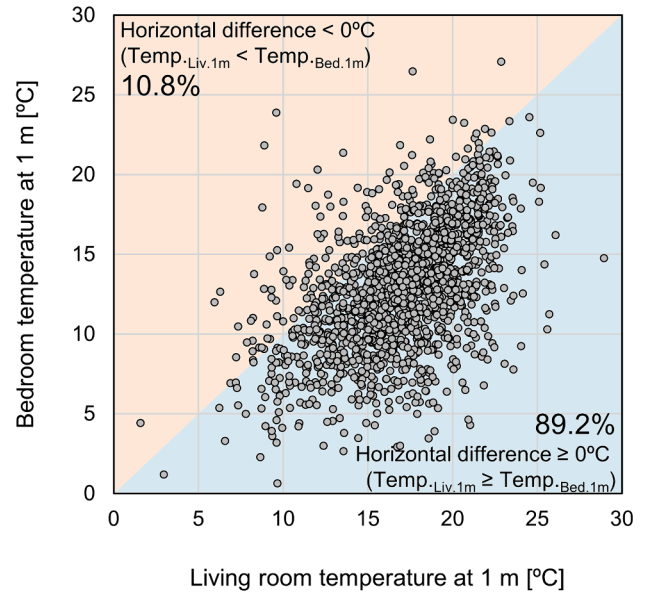
The results of multivariate logistic regression analyses are shown in Table 4. Regarding indoor temperature indices, both average indoor temperatures and vertical temperature differences were associated with perceived coldness. However, the horizontal temperature differences between rooms and diel variations were not. These results were consistent across all three rooms. ISO 7730 (ISO, 2005) and ANSI/ASHRAE Standard 55 (ASHRAE, 2013) indicate that the percentage of dissatisfied (PD) individuals increases with an increase in vertical temperature difference, a finding supported by a previous study (Möhlenkamp et al., 2019) that reviewed literature on PD and vertical temperature gradients. These previous findings are generally based on results in climate chambers. The present study, however, showed the same relationship in a real-world setting.

Regarding individual attributes, older residents were significantly less likely to feel coldness. An earlier review has revealed that aging is associated with a progressive decrease in thermal perception, evidenced by the need for increased thermal detection thresholds in the elderly (Guergova and Dufour, 2011). However, BP in older residents was vulnerable to changes in indoor temperature (Umishio et al., 2019), indicating that indoor temperature at home could be 'silent killer' for the elderly. Females reported feeling cold more frequently in the

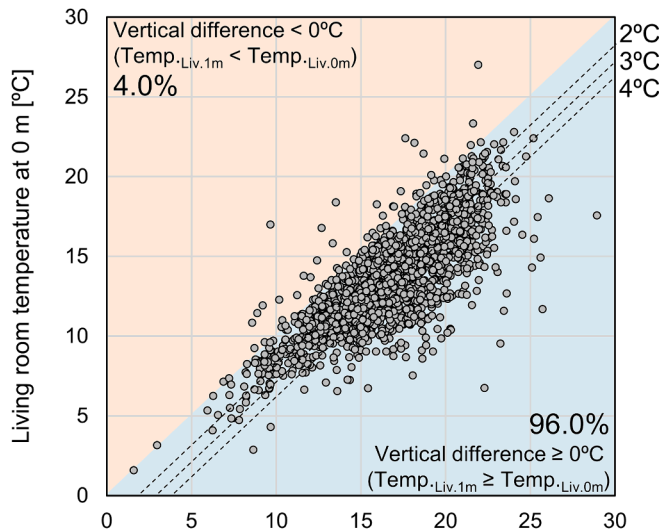
A) Horizontal difference (Living room vs Changing room)



B) Horizontal difference (Living room vs Bedroom)



C) Vertical difference (1 m vs 0 m)



D) Temporal difference (Evening vs Morning)

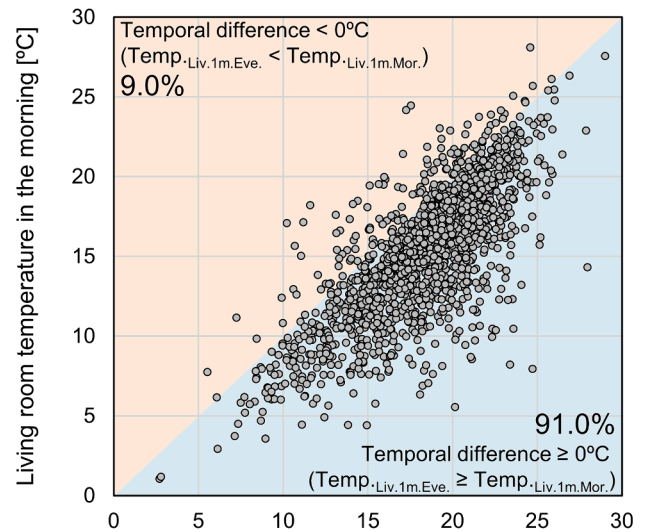


Fig. 3. Scatter plots of spatial-temporal variations in indoor temperatures in each house.

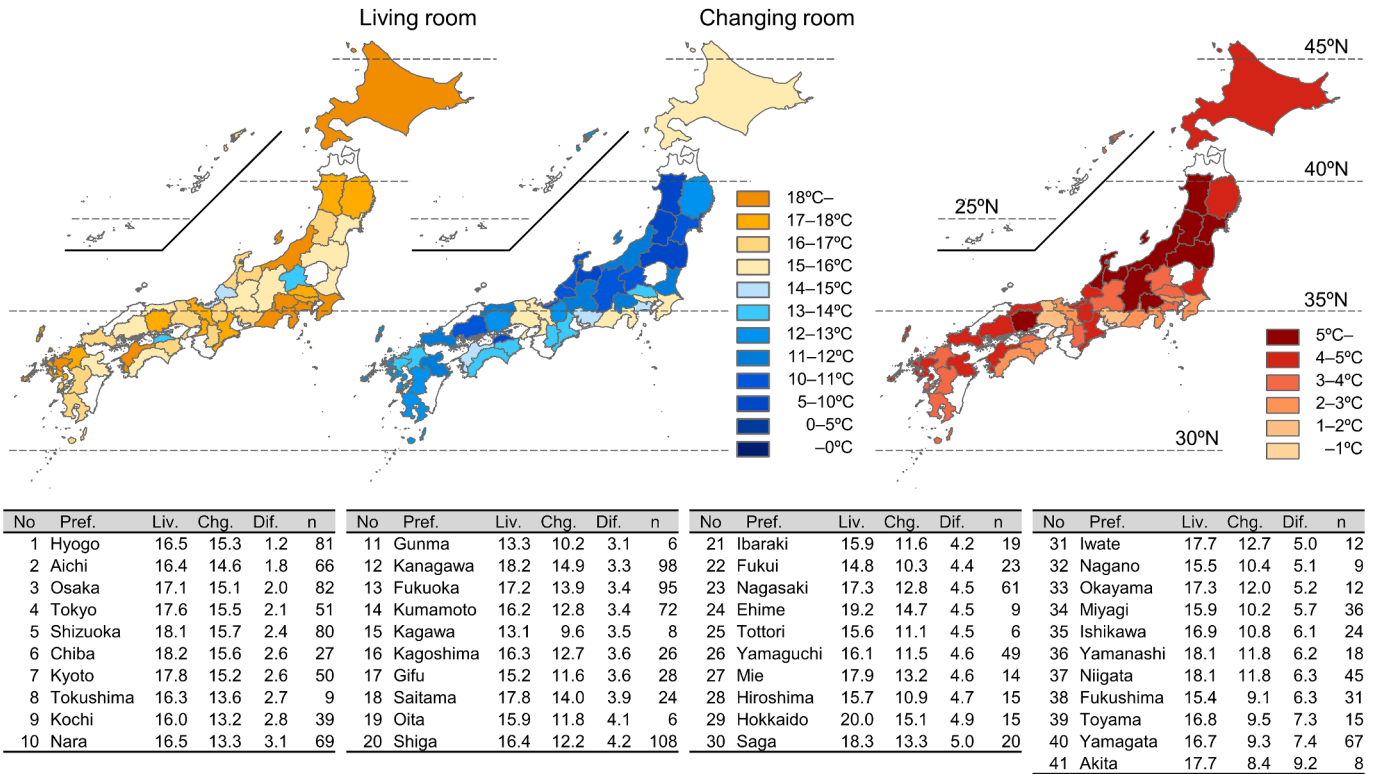
changing room and bedroom than males. This is partly attributed to females having less muscle mass compared to males, which results in a lower metabolic rate. This result is consistent with the previous study conducted in the chamber, which indicated that females felt colder and less comfortable than males at cool temperatures below 18 °C (Yang et al., 2021).

In terms of lifestyle choices, there was a significant association between the quantity of meals consumed and perceived coldness. The odds ratios for the group with higher food consumption reporting coldness were 1.71 [95 % confidence interval (CI): 1.29–2.27] in the living room and 1.37 (95 % CI: 1.08–1.74) in the bedroom. Feeling coldness might enhance food intake to increase diet-induced thermogenesis. In fact, it is well established that there is a strong link between environmental temperature and food intake: in colder conditions, more food is required to maintain the core body temperature (Brobeck, 1948; Macari et al., 1983). Compared to the group that rarely exercises, the odds ratios for the regular exercise group experiencing coldness were 0.78 (95 % CI:

0.63–0.96) in the living room, 0.62 (95 % CI: 0.46–0.85) in the changing room, and 0.79 (95 % CI: 0.64–0.96) in the bedroom. The regular exercise group may possess more muscle mass, which could result in a lower frequency of feeling coldness. The odds ratio for current drinker was 1.43 (95 % CI: 1.05–1.95) in the changing room. A previous study showed that higher alcohol consumption caused peripheral artery disease (Larsson et al., 2020), potentially worsening blood circulation and thus promoting peripheral coldness. The odds ratio for the amount of clothes worn was significant in the changing room and bedroom. Residents wearing a larger amount of clothing experienced a greater discrepancy in sensory temperature – the temperature a person perceives – upon removing their clothes in the changing room. This might lead to an increased sensation of coldness. In the bedroom, due to the reduction in metabolic rate during sleep, the influence of clothing amount, which is another human factor affecting thermal sensation besides metabolic rate, was more pronounced.

Living and changing room temperature at 1 m above the floor

Spatial difference (horizontal)

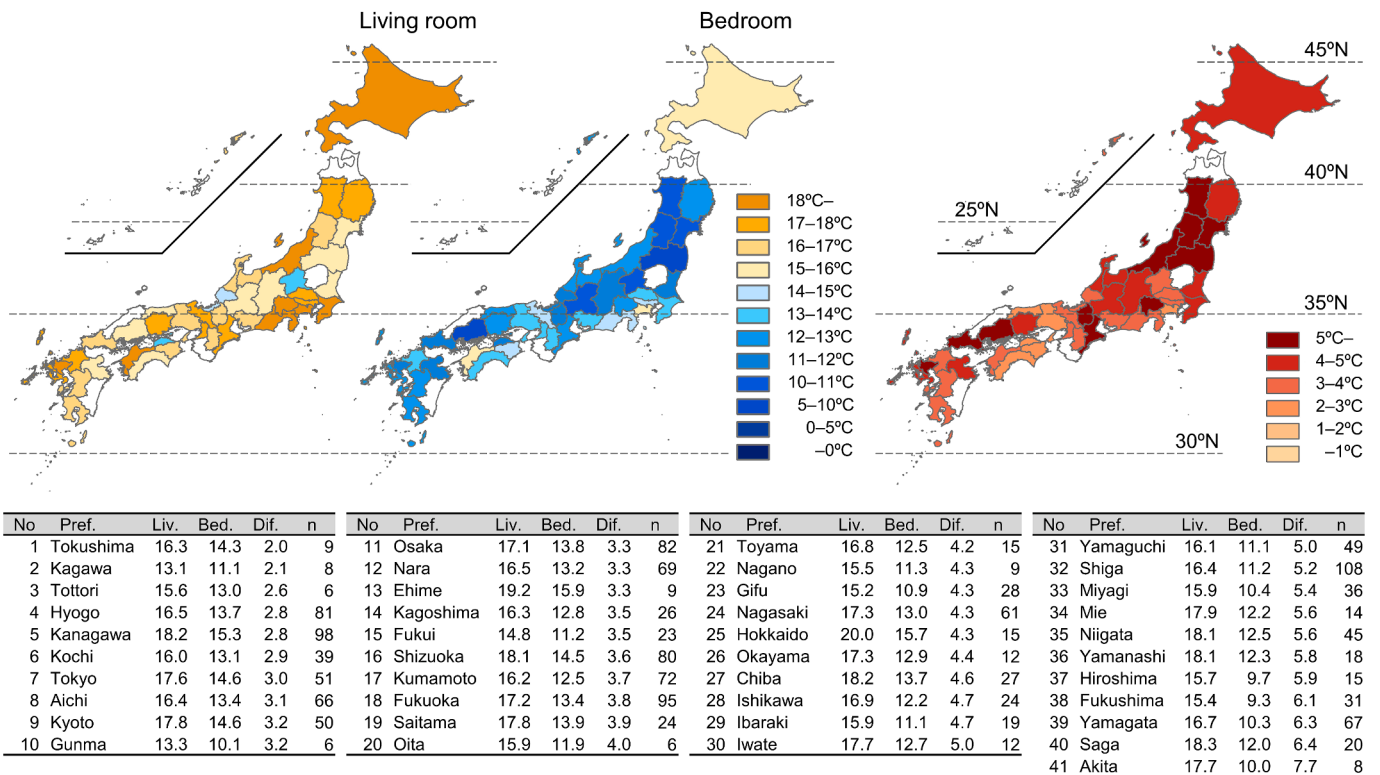


Six prefectures (Aomori, Tochigi, Wakayama, Shimane, Miyazaki, and Okinawa) were not included because of the small sample size (n≤5).

Fig. 4. Horizontal temperature difference between living room and changing room for each prefecture.

Living room and bedroom temperature at 1 m above the floor

Spatial difference (horizontal)

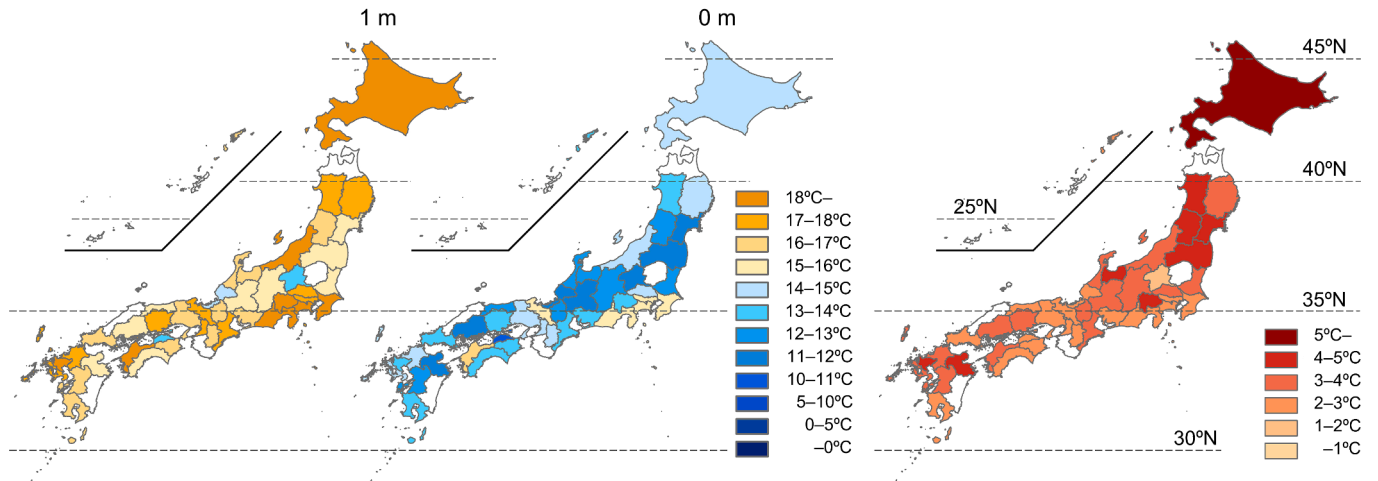


Six prefectures (Aomori, Tochigi, Wakayama, Shimane, Miyazaki, and Okinawa) were not included because of the small sample size (n≤5).

Fig. 5. Horizontal temperature difference between living room and bedroom for each prefecture.

Living room temperature at 1 m above the floor and near the floor (0 m)

Spatial difference (vertical)



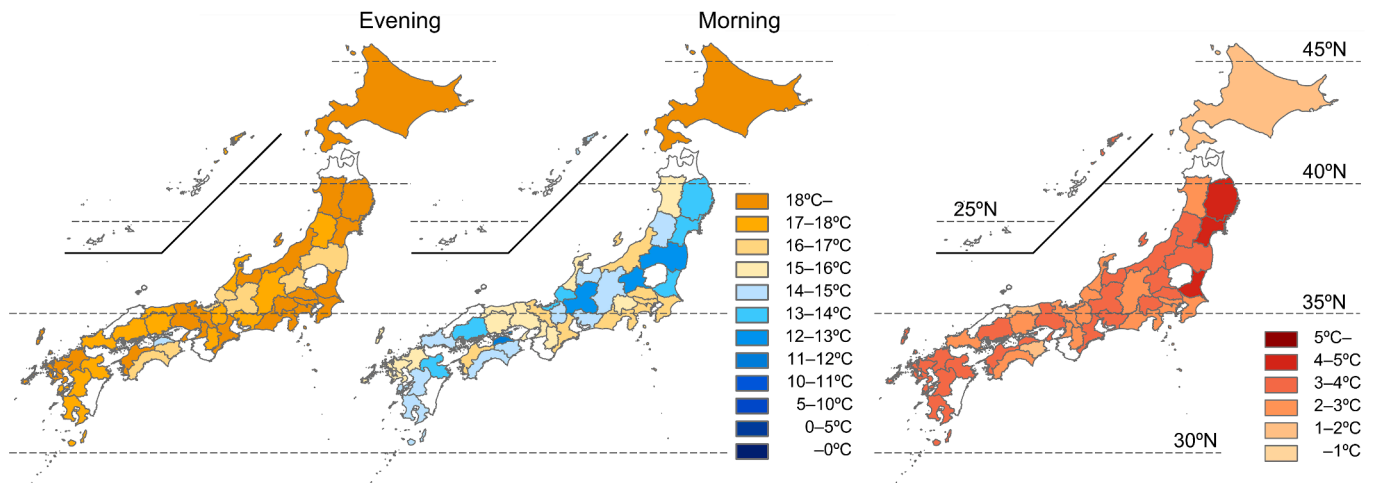
No	Pref.	1 m	0 m	Dif.	n	No	Pref.	1 m	0 m	Dif.	n	No	Pref.	1 m	0 m	Dif.	n	No	Pref.	1 m	0 m	Dif.	n						
1	Gunma	13.3	11.7	1.6	6	11	Shizuoka	18.1	15.4	2.7	80	21	Fukuoka	17.2	14.1	3.1	95	31	Ishikawa	16.9	12.9	4.0	24						
2	Kagawa	13.1	10.9	2.2	8	12	Tottori	15.6	12.9	2.7	6	22	Kumamoto	16.2	12.9	3.2	72	32	Okayama	17.3	13.3	4.0	12						
3	Kochi	16.0	13.7	2.3	39	13	Fukui	14.8	12.0	2.8	23	23	Nagano	15.5	12.3	3.2	9	33	Oita	15.9	11.9	4.0	6						
4	Nara	16.5	14.1	2.4	69	14	Kagoshima	16.3	13.5	2.8	26	24	Iwate	17.7	14.1	3.5	12	34	Yamanashi	18.1	14.0	4.1	18						
5	Kanagawa	18.2	15.8	2.4	98	15	Chiba	18.2	15.4	2.8	27	25	Ibaraki	15.9	12.3	3.6	19	35	Toyama	16.8	12.6	4.2	15						
6	Hyogo	16.5	14.1	2.4	81	16	Yamaguchi	16.1	13.3	2.8	49	26	Shiga	16.4	12.8	3.6	108	36	Yamagata	16.7	12.4	4.2	67						
7	Tokyo	17.6	15.2	2.5	51	17	Aichi	16.4	13.6	2.9	66	27	Gifu	15.2	11.5	3.6	28	37	Fukushima	15.4	11.1	4.3	31						
8	Osaka	17.1	14.5	2.6	82	18	Ehime	19.2	16.2	3.0	9	28	Hiroshima	15.7	11.9	3.8	15	38	Miyagi	15.9	11.6	4.3	36						
9	Tokushima	16.3	13.6	2.7	9	19	Saitama	17.8	14.8	3.1	24	29	Niigata	18.1	14.2	3.9	45	39	Akita	17.7	13.2	4.5	8						
10	Kyoto	17.8	15.1	2.7	50	20	Nagasaki	17.3	14.2	3.1	61	30	Mie	17.9	13.9	3.9	14	40	Saga	18.3	13.4	4.9	20						
																								41	Hokkaido	20.0	15.0	5.1	15

Six prefectures (Aomori, Tochigi, Wakayama, Shimane, Miyazaki, and Okinawa) were not included because of the small sample size (n≤5).

Fig. 6. Vertical temperature difference between 1 m and 0 m in the living room for each prefecture.

Living room temperature at 1 m in the evening and morning

Temporal difference



No	Pref.	Eve.	Mor.	Dif.	n	No	Pref.	Eve.	Mor.	Dif.	n	No	Pref.	Eve.	Mor.	Dif.	n	No	Pref.	Eve.	Mor.	Dif.	n							
1	Hokkaido	21.1	19.9	1.2	15	11	Okayama	18.0	15.3	2.7	12	21	Nagasaki	18.8	15.7	3.1	61	31	Saga	19.4	16.0	3.4	20							
2	Tokushima	16.5	15.0	1.5	9	12	Akita	18.4	15.7	2.8	8	22	Yamanashi	19.1	15.9	3.3	18	32	Gunma	16.1	12.6	3.5	6							
3	Tottori	17.4	15.8	1.6	6	13	Nagano	17.3	14.5	2.8	9	23	Saitama	19.4	16.1	3.3	24	33	Niigata	20.2	16.7	3.5	45							
4	Ishikawa	17.2	15.1	2.1	24	14	Kochi	16.9	14.1	2.8	39	24	Mie	20.0	16.7	3.3	14	34	Oita	17.4	13.8	3.6	6							
5	Kanagawa	19.1	16.8	2.3	98	15	Shizuoka	19.2	16.4	2.9	80	25	Kagawa	14.5	11.3	3.3	8	35	Toyama	18.2	14.6	3.6	15							
6	Shiga	17.4	15.0	2.4	108	16	Fukui	16.8	13.9	2.9	23	26	Ehime	19.7	16.4	3.3	9	36	Aichi	18.0	14.3	3.6	66							
7	Tokyo	18.7	16.2	2.5	51	17	Chiba	19.5	16.6	2.9	27	27	Kumamoto	17.9	14.6	3.3	72	37	Gifu	16.1	12.3	3.7	28							
8	Osaka	18.4	15.9	2.5	82	18	Kyoto	19.5	16.6	2.9	50	28	Kagoshima	17.5	14.1	3.3	26	38	Hiroshima	17.5	13.7	3.8	15							
9	Yamaguchi	17.4	14.8	2.6	49	19	Hyogo	18.3	15.3	3.0	81	29	Fukuoka	19.3	15.9	3.4	95	39	Miyagi	18.2	13.8	4.4	36							
10	Nara	17.7	15.0	2.6	69	20	Yamagata	17.8	14.7	3.1	67	30	Fukushima	16.3	12.9	3.4	31	40	Ibaraki	18.2	13.3	4.8	19							
																									41	Iwate	18.9	14.0	4.9	12

Six prefectures (Aomori, Tochigi, Wakayama, Shimane, Miyazaki, and Okinawa) were not included because of the small sample size (n≤5).

Fig. 7. Diel difference of the living room temperature in the morning and evening for each prefecture.

**Table 3**  
Characteristics of participants in the SWH survey.

Variable	Mean or Number	(SD) or (%)
Age, years	57.4	(13.5)
Duration of residence in house, years	25.4	(15.6)
Body mass index, kg/m <sup>2</sup>	22.8	(3.6)
Amount of clothes while awake, clo†	0.97	(0.20)
Amount of clothes during sleep, clo†	0.76	(0.16)
Sex		
Male	1,333	(47.7)
Female	1,460	(52.3)
Household income		
Low (<2 million JPY)	287	(11.0)
Middle (2–6 million JPY)	1,294	(49.4)
High (≥6 million JPY)	1,038	(39.6)
Meal quantity		
Eating the same or less than others	2,335	(84.0)
Eating more than others	444	(16.0)
Exercise		
Rarely	1,995	(71.8)
Regularly	785	(28.2)
Smoking		
None	2,219	(85.6)
Currently	373	(14.4)
Drinking		
None	1,266	(45.9)
Currently	1,493	(54.1)
Climate area‡		
Area 2	19	(0.7)
Area 3	50	(1.8)
Area 4	277	(9.9)
Area 5	781	(28.0)
Area 6	1,513	(54.2)
Area 7	153	(5.5)

† clo is a unit that represents the thermal resistance of clothes. 1 clo = 0.155 (m<sup>2</sup>K)/W.

‡ Detailed classification of climate area is shown in Fig. 2.

**4. Strengths and limitations**

This study has three main strengths. Firstly, it is one of the largest surveys to measure indoor temperatures inside the house in several rooms and heights, involving over 1,500 households in Japan. Secondly, its nationwide participant recruitment from all 47 Japanese prefectures minimizes regional bias, enhancing the generalizability of the findings. Lastly, the study features two weeks of real-world, field-based indoor temperature measurements, providing objective data that likely reduces observational bias.

This study has the following limitations. First, we were unable to survey participants' bedclothes in detail, which might largely affect perceived coldness in the bedroom. This might result in the paradox where, despite the bedroom temperatures being lower compared to the living room, fewer people felt coldness. Secondly, because the results of

this paper were based on a cross-sectional analysis, we could not determine any causal relationships. For example, in the results of multivariate logistic regression analyses, residents wearing more clothing reported perceived coldness more frequently, which could be attributed to them wearing extra layers because they felt cold. Similarly, the observation that individuals who eat more tended to feel colder might be explained by these individuals increasing their food intake in response to feeling cold. While these causal relationships are plausible, they cannot be definitively concluded without further investigation. Therefore, a combination of experimental or intervention studies is necessary for a more detailed examination of these potential causes. Thirdly, due to variations in sample sizes across different prefectures, further discussion is necessary regarding the representativeness of the sample. Fourthly, owing to the constraints of the field measurements, it was not possible to strictly adhere to the ASHRAE and ISO guidelines for the installation height of the sensors, which require positioning at 1.1 m and 0.1 m above the floor. Finally, indoor temperatures for the living room, changing room, and bedroom were extracted based on the at-home and sleep times recorded in the diary. However, since the time spent in each specific room was not recorded, there is a possibility that the actual exposure temperatures may differ. Future studies should include human-detecting sensors, utilizing both direct methods (e.g., infrared sensors and motion sensors) and indirect methods (e.g., CO<sub>2</sub> sensors) to accurately determine the time spent in each specific room.

**5. Conclusions**

This study, based on real-world measurements in Japan, explored spatial and temporal indoor temperature differences inside houses during winter, and their relationship with perceived coldness, drawing on data from nearly 2,800 participants. The primary conclusions are as follows:

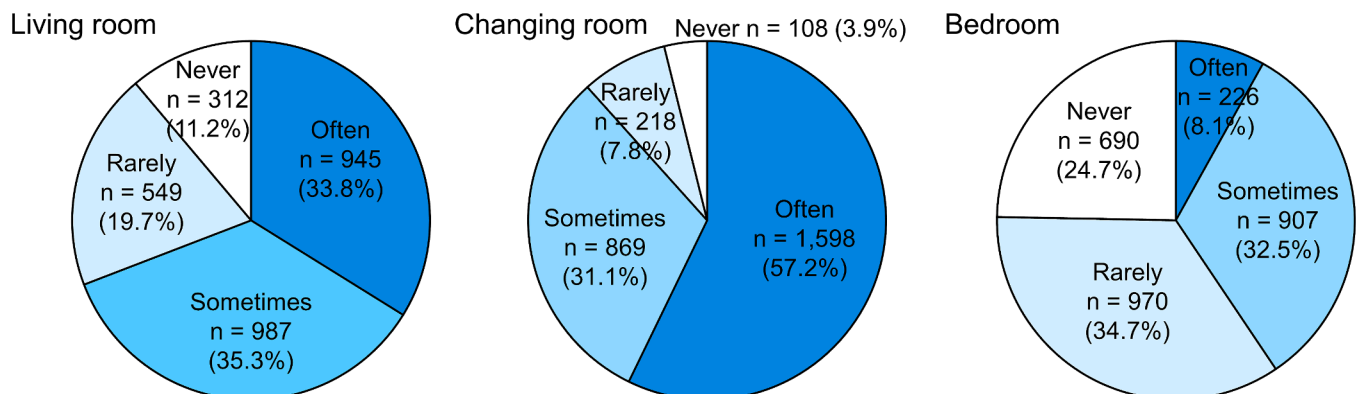
(1) Average spatial and temporal indoor temperature differences in Japan.

Significant temperature differences were observed in homes: horizontally, the changing room and bedroom were about 4 °C colder compared to the living room temperature. Vertically, temperatures at floor level were 3.1 °C colder than those at 1 m above the floor in the living room. Additionally, morning temperatures were 3.0 °C colder than evening temperatures in the living room.

(2) Regional variations in spatial-temporal indoor temperature differences.

In Japan, the spatial and temporal differences vary greatly by region. In a comparison of average values by prefecture, the horizontal temperature difference between the living room and changing room ranged widely from 1.2 °C to 9.2 °C, the vertical temperature difference in the living room ranged from 1.6 °C to 5.1 °C, and the diel difference in the living room varied from 1.2 °C to 4.9 °C.

(3) Mismatch of perceived coldness and indoor temperatures.



**Fig. 8.** Frequency of feeling coldness in the living room, changing room, and bedroom.

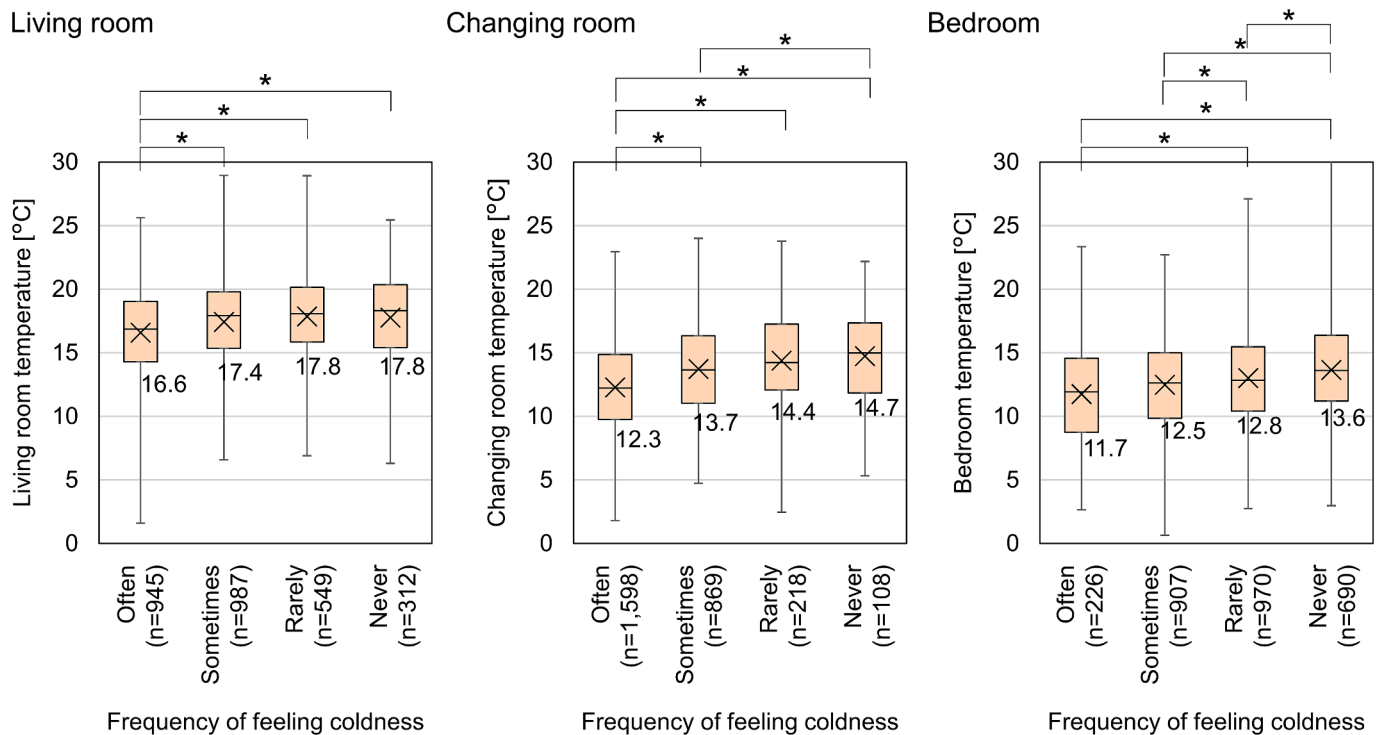


Fig. 9. Average indoor temperatures in the living room, changing room, and bedroom in each category of feeling coldness. \* indicates  $p < 0.05$ .

**Table 4**  
Factors associated with perceived coldness in the living room, changing room, and bedroom.

Variable	Living room			Changing room			Bedroom		
	OR*	(95 %CI)	P	OR*	(95 %CI)	P	OR*	(95 %CI)	P
Average indoor temperature, °C	0.89	(0.86, 0.92)	<0.001	0.83	(0.79, 0.88)	<0.001	0.92	(0.89, 0.95)	<0.001
Horizontal temperature difference, °C	1.02	(0.98, 1.05)	0.382	0.97	(0.92, 1.02)	0.238	1.01	(0.98, 1.04)	0.431
Vertical temperature difference, °C	1.11	(1.06, 1.17)	<0.001	1.20	(1.08, 1.34)	<0.001	1.12	(1.06, 1.19)	<0.001
Diel variation in temperature, °C	1.02	(0.98, 1.05)	0.350	1.08	(0.99, 1.18)	0.091	1.00	(0.96, 1.03)	0.799
Age, years	0.98	(0.98, 0.99)	<0.001	0.97	(0.96, 0.98)	<0.001	0.98	(0.97, 0.99)	<0.001
Duration of residence, years	1.00	(1.00, 1.01)	0.425	1.01	(1.00, 1.03)	0.059	1.00	(1.00, 1.01)	0.265
Amount of clothes†, clo	1.15	(0.70, 1.89)	0.574	2.97	(1.46, 6.05)	0.003	2.52	(1.49, 4.27)	<0.001
BMI, kg/m <sup>2</sup>	0.98	(0.95, 1.01)	0.280	0.99	(0.95, 1.04)	0.750	1.00	(1.00, 1.01)	0.265
Sex									
Male	Ref.	–	–	Ref.	–	–	Ref.	–	–
Female	0.87	(0.70, 1.08)	0.197	1.68	(1.21, 2.35)	0.002	1.27	(1.04, 1.55)	0.018
Household income									
Low (<2 million JPY)	Ref.	–	–	Ref.	–	–	Ref.	–	–
Middle (2–6 million JPY)	0.88	(0.64, 1.22)	0.456	1.29	(0.80, 2.09)	0.293	0.89	(0.66, 1.19)	0.415
High (≥6 million JPY)	0.99	(0.71, 1.39)	0.949	1.24	(0.75, 2.06)	0.410	0.83	(0.61, 1.12)	0.219
Meal quantity									
Eating the same or less than others	Ref.	–	–	Ref.	–	–	Ref.	–	–
Eating more than others	1.71	(1.29, 2.27)	<0.001	1.24	(0.82, 1.87)	0.319	1.37	(1.08, 1.74)	0.010
Exercise									
Rarely	Ref.	–	–	Ref.	–	–	Ref.	–	–
Regularly	0.78	(0.63, 0.96)	0.017	0.62	(0.46, 0.85)	0.003	0.79	(0.64, 0.96)	0.018
Smoking									
None	Ref.	–	–	Ref.	–	–	Ref.	–	–
Currently	1.17	(0.88, 1.57)	0.285	1.17	(0.75, 1.84)	0.490	1.02	(0.79, 1.32)	0.887
Drinking									
None	Ref.	–	–	Ref.	–	–	Ref.	–	–
Currently	1.10	(0.91, 1.34)	0.330	1.43	(1.05, 1.95)	0.023	0.91	(0.76, 1.10)	0.333

\*The odds ratio (OR) was calculated by inputting all the above independent variables along with climate areas. †For the living room and changing room, the amount of clothes worn while awake was input into the model. For the bedroom, the model included the amount of clothes worn during sleep. CI, confidence interval.

Even residents who did not feel cold inside their homes were actually living under poor thermal conditions. In other words, there was a significant gap between what was subjectively perceived as an adequate temperature and what is objectively considered adequate to protect health.

(4) Indoor temperature indices associated with perceived coldness. Both average indoor temperatures and vertical temperature differences were associated with perceived coldness, while horizontal temperature differences and diel differences did not show significant associations.

### (5) Special consideration for vulnerable populations.

Older adults were less likely to perceive coldness despite being more vulnerable to the health impacts of low temperatures. This highlights the necessity of not solely relying on human perception for indoor temperature management.

The implications of our findings are as follows:

(1) Importance of considering temperature measurement heights in the WHO guidelines.

The current guidelines recommend a minimum indoor temperature of 18 °C but do not specify the height at which temperature should be measured. Our study revealed that floor-level temperatures were approximately 3 °C lower, indicating the importance of considering vertical temperature differences and specifying measurement heights.

(2) Support for older residents against cold exposure.

The WHO guidelines note that “A higher minimum indoor temperature than 18 °C may be necessary for vulnerable groups including older people,” while our study revealed that older people were less sensitive to cold. Therefore, to protect the elderly from health hazards of cold homes, automated temperature control using objective values of sensors could be essential.

(3) Necessity of future studies on temperature variability, perceived coldness, and health impacts.

At present, epidemiological evidence regarding the health effects of spatial-temporal temperature variability is limited. Nevertheless, an early experimental study (Hashiguchi et al., 2002) has demonstrated that temperature differences between rooms can lead to fluctuations in BP, indicating the need for further evidence on this topic. Additionally, future studies are necessary to explore the relationship between perceived coldness and health, such as whether subjective cold stress can influence BP independently of objective cold stress such as low indoor temperatures.

### CRedit authorship contribution statement

**Wataru Umishio:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Toshiharu Ikaga:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Yoshihisa Fujino:** Writing – review & editing, Methodology, Conceptualization. **Shintaro Ando:** Writing – review & editing, Methodology, Conceptualization. **Tatsuhiko Kubo:** Writing – review & editing, Methodology, Conceptualization. **Yukie Nakajima:** Formal analysis, Writing – review & editing. **Naoki Kagi:** Writing – review & editing. **Tanji Hoshi:** Writing – review & editing. **Masaru Suzuki:** Writing – review & editing. **Kazuomi Kario:** Supervision, Writing – review & editing. **Takesumi Yoshimura:** Writing – review & editing, Supervision. **Hiroshi Yoshino:** Writing – review & editing, Supervision. **Shuzo Murakami:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

### Declaration of competing interest

Toshiharu Ikaga has received research grants from Asahi Kasei Homes Corp., Fuyo Home Co. Ltd., Japan Gas Association, Japan Sustainable Building Consortium, LIXIL Corp., Nomura Real Estate Development Co., Ltd., Osaka Gas Co., Ltd., Panasonic Homes Co. Ltd., Sekisui House, Ltd., Tokyo Gas Co., Ltd., and Toyota Housing Co., Ltd. Yukie Nakajima works for Nikken Sekkei Research Institute. Tanji Hoshi has received an honorarium from LIXIL Corp. The other authors have no competing interests.

### Data availability

The data that has been used is confidential.

### Acknowledgement

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2024.108630>.

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