



# A warmer indoor environment in the evening and shorter sleep onset latency in winter: The HEIJO-KYO study



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## HIGHLIGHTS

- We measured indoor temperature and sleep onset latency at home among 861 elderly.
- Warmer evening indoor temperature was associated with shorter sleep onset latency.
- The findings were consistent in subjective and actigraphic sleep onset latency.
- Bed temperature was also associated with sleep onset latency and sleep efficiency.

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## ABSTRACT

Difficulty in initiating sleep is an important problem because it is associated with an increased incidence of depression, diabetes, myocardial infarction, and higher all-cause mortality. Although experimental studies in controlled settings have shown that warm skin temperature of the extremities (feet and hands) before bedtime is associated with shorter sleep onset latency (SOL), evidence from real life situations is limited. We assessed the relationship between indoor temperatures in the evening (2 h before bedtime) and SOL among 861 home-dwelling elderly participants. Subjective SOL was determined according to a self-administered sleep diary. Actigraphic (objective) SOL, indoor temperature, and bed temperature were simultaneously measured at participants' homes for 48 h during the colder seasons (October–April). The association between evening indoor temperature and SOL was assessed using a multilevel linear regression model with random intercept for individual participants. Evening indoor temperature showed a significant inverse association with log-transformed subjective SOL ( $\beta = -0.021$ ,  $P < 0.01$ ) and actigraphic SOL ( $\beta = -0.019$ ,  $P < 0.01$ ), independent of potential confounders including gender, insomnia medication, evening physical activity, and bedtime. Higher bed temperature during the 2 h after bedtime was significantly associated with shorter log-transformed actigraphic SOL ( $\beta = -0.028$ ,  $P < 0.01$ ). These significant associations were maintained even after adjustment for evening outdoor temperature. The clinically important findings of the present study indicate that SOL may be shortened by modification of evening indoor temperature and bed temperature for 2 h after bedtime.

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## 1. Introduction

Sleep disturbance is common among the elderly population. In one study, approximately half of the elderly participants reported chronic complaints associated with sleep, and 10%–20% reported difficulty in initiating sleep [1]. Difficulty in initiating sleep is clinically important because it is associated with an increased incidence of diabetes [2], myocardial infarction [3], and higher all-cause mortality [4,5]. Furthermore, there is a stronger association between depression and delayed sleep initiation than that between other complaints of sleep disturbance such as early morning awakening or difficulty maintaining sleep [6,7].

In a sleep study of 18 healthy young participants in a fixed environmental temperature of 22 °C and in a supine position without physical activity, a higher distal–proximal gradient (DPG) resulting from increased skin temperature of the extremities (feet and hands) before bedtime showed a stronger correlation with shorter sleep onset latency (SOL) than core body temperature, onset of melatonin release, and subjective sleepiness [8,9]. Interventions to warm the extremities around bedtime decreased the SOL among healthy young ( $N = 8$ ) and elderly ( $N = 8$ ) participants [10,11]. These experimental studies conducted under controlled conditions in terms of posture, physical activity, clothing, and temperature suggest an association between the thermal environment and SOL. However, the impact of evening indoor temperature on SOL in real life situations remains unclear because there are many

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factors that could modify the association, such as habitual bedtime, physical activity, time spent outdoors, posture, and clothing.

Quantification of the association between indoor temperature and SOL in a large-scale epidemiologic study would provide useful information to determine an optimal environment to shorten the SOL and to expand the generalizability of physiological experiments. To quantify the association between indoor temperature in the evening and SOL, we simultaneously measured indoor temperature and actigraphic SOL during the colder seasons among home-dwelling elderly participants.

## 2. Methods

### 2.1. Participants

The present analysis was conducted at the baseline of a community based cohort study: the Housing Environments and Health Investigation among Japanese Older People in Nara, Kansai Region (HEIJO-KYO) study. Inclusion criteria for the HEIJO-KYO study were aged 60 years or older and home dwelling males and females. From September to March in 2010, 2011, 2012, and 2013, we voluntarily recruited 880 according to the inclusion criteria. Exclusion criteria for the present analysis were failure to complete indoor temperature measurements for a 48 h period during the colder seasons (October–April) and/or failure to complete measurements of actigraphy for a 48 h period during the colder seasons. After exclusion of 19 participants, data for 861 participants remained for the analysis. All participants provided written informed consent, and the study protocol was approved by the Nara Medical University Ethics Review Board.

#### 2.1.1. Study protocol

Participants' characteristics, including age, gender, smoking and drinking habits, and medication use (insomnia medication, antidepressants), were recorded during an interview using a standardized questionnaire. Height, weight, and body mass index (BMI) were measured before the 48-h recording session. The indoor temperature of the participants' living rooms and bedrooms was measured simultaneously with physical activity measured using actigraphy. All participants were instructed to maintain a standardized diary to log the amount of time spent in the bedroom, and time spent out of home during the recording session. We revisited each participant at home to retrieve instruments and to collect their diaries.

#### 2.1.2. Indoor, outdoor, and microclimate bed temperatures

Temperatures were measured at 10-min intervals in the living room and bedroom, 60 cm above the floor. Microclimate bed temperatures ( $Temp_{bed}$ ) were measured at 10-min intervals at the center of the bed, 50 cm from the headboard, beneath the top sheet. These temperatures were measured using Thermochron iButtons (DS1922L; Maxim Integrated, Dallas, TX, USA) with an accuracy of  $\pm 0.5$  °C from  $-10$  °C to  $+65$  °C and a  $0.0624$  °C resolution. The validity of using iButtons to measure skin temperature has been reported in previous studies [12, 13].

For indoor temperature ( $Temp_{in}$ ), we selected from living room temperature or bedroom temperature recorded every 10 min based on the participants' location at each time according to their diary. The local meteorological office in Nara (34°N) provided outdoor temperature data ( $Temp_{out}$ ) recorded at 10-min intervals. We calculated mean values of  $Temp_{in}$ ,  $Temp_{out}$ , and  $Temp_{bed}$  during the morning (2 h after rising), evening (2 h before bedtime), and initial nighttime (2 h after bedtime).

#### 2.1.3. Bedtime, subjective, and objective sleep onset latency

Participants were instructed to record the time that they got into bed as bedtime. After waking up, the time taken to fall sleep the previous night was also recorded. The subjective SOL was determined according to the sleep diary. Physical activity was measured at 1-min time epochs

using an actigraph (Actiwatch 2; Respironics Inc., Murrysville, PA, USA) that was worn on the non-dominant arm for 48 h.

The sleep/awake status at each epoch, and sleep onset and offset were automatically determined by the Actiware version 5.5 software using the default algorithm. Epochs with activity counts higher than the moderate threshold (40 counts/min) were regarded as awake periods. Sleep onset was considered as initial minutes that were followed by a 10-min period of immobility that contained no more than one epoch with any motion count. Actigraphic SOL was determined based on the actigraphic sleep onset and bedtime. Sleep efficiency (SE) was the percentage of sleep epochs between bedtime and rising time.

### 2.2. Statistical analysis

For continuous variables with a normal distribution, mean  $\pm$  standard deviation (SD) was reported. For variables with a skewed distribution, medians and interquartile ranges were reported. Mean and median values were compared using the t-test and the Mann–Whitney test, respectively. Proportions of both groups were compared using the chi-squared test. The reproducibility of temperature was assessed using the intraclass correlation coefficient (ICC). Because subjective and objective (actigraphic) SOL revealed a skewed distribution, they were log-transformed and included in the linear regression analysis.

The parameters  $Temp_{in}$  and  $Temp_{out}$ ,  $Temp_{bed}$ , SOL, and SE were calculated and mean values for the two study days were used for analysis (Table 1). Mean values of  $Temp_{in}$ ,  $Temp_{out}$ ,  $Temp_{bed}$ , SOL, and SE were used to compare the gender difference. Mean values for the first and second days were used to create a scatter plot of the correlation between indoor and outdoor temperatures in the evening (Fig. 1).

**Table 1**

Basic characteristics of 861 participants, sleep parameters, and temperature by gender.

	Male (n = 423)	Female (n = 438)	P-value
Basic characteristics			
Age, mean (SD)	72.3 (7.1)	71.9 (7.1)	0.45
BMI ( $\geq 25$ ), n (%)	115 (27.2)	95 (21.7)	0.07
Habitual drinker, n (%)	266 (62.9)	51 (11.6)	<0.01
Current smoker, n (%)	41 (9.7)	3 (0.7)	<0.01
Medication			
Antidepressant, n (%)	4 (0.95)	10 (2.3)	0.18
Insomnia medication, n (%)	30 (7.1)	53 (12.1)	0.02
Habitual behavior			
Late bed time, n (%) <sup>a</sup>	188 (44.4)	242 (55.3)	<0.01
Physical activity in evening (counts/min), mean (SD)	223.8 (133.4)	291.8 (154.9)	<0.01
Socioeconomic status			
Household income ( $\geq 4$ million JPY per year), n (%)	182 (43.0)	165 (37.7)	0.40
Sleep parameters <sup>b</sup>			
Subjective SOL, min, median, [IQR]	23.0 [12.0, 47.0]	27.0 [12.0, 55.0]	0.10
Actigraphic SOL, min, median, [IQR]	21.0 [10.5, 40.8]	17.5 [8.0, 34.5]	0.01
Actigraphic SE, %, mean (SD)	83.9 (8.2)	85.4 (8.4)	<0.01
Outdoor temperature <sup>b</sup> , °C, mean (SD)			
Morning	5.9 (5.2)	5.8 (5.2)	0.72
Evening	6.8 (5.1)	6.6 (5.1)	0.53
Initial nighttime	5.9 (5.0)	5.8 (5.1)	0.79
Indoor temperature <sup>b</sup> , °C, mean (SD)			
Morning	14.6 (4.4)	14.4 (4.4)	0.44
Evening	17.4 (3.9)	16.9 (4.1)	0.07
Initial nighttime	15.4 (3.9)	15.0 (4.1)	0.14
Bed temperature <sup>b</sup>			
Initial nighttime	28.3 (5.0)	27.6 (5.0)	0.03

SD, standard deviation; IQR, interquartile range; BMI, body mass index; SOL, sleep onset latency; SE, sleep efficiency; morning, 2 h after rising; evening, 2 h before bedtime; and initial nighttime, 2 h after bedtime.

<sup>a</sup> Later bed time than median (22:33).

<sup>b</sup> After calculating parameters of indoor and outdoor temperatures, bed temperatures, SOL and SE in each day, and mean values of two days were demonstrated.

The longitudinal associations between the objective SOL and subjective SOL and study variables were assessed using a multilevel linear regression model consisting of participant-level variables with only one data point for each participant, and measurement-day level variables, such as Temp<sub>in</sub>, Temp<sub>out</sub>, Temp<sub>bed</sub>, physical activity in the evening, bedtime, time spent outdoors in the evening, and actigraphic SOL, with two data points for each participant. Regression coefficients for associations between SOL and independent variables with random intercept for individual participants were estimated using the maximum likelihood method. All *P*-values were two-sided, and those <0.05 were considered statistically significant. All statistical analyses were performed using the SPSS 21.0 software (SPSS Inc., Chicago, IL, USA).

### 3. Results

Of the 861 participants (mean age  $\pm$  SD,  $72.1 \pm 7.1$  years), 423 (49.1%) were male. Medians (interquartile range) of the subjective SOL and actigraphic SOL were 25.0 (12.0, 51.3) min and 16.0 (6.0, 34.6) min, respectively. The evening Temp<sub>in</sub> and initial nighttime Temp<sub>bed</sub> were  $17.1 \pm 4.1$  °C and  $28.0 \pm 5.1$  °C, respectively. The total number of participants who spent more than 30 min outdoors during the evening on the first and second measurement days was 33 (3.8%) and 25 (2.9%), respectively. The reproducibility of the evening Temp<sub>in</sub> and initial nighttime Temp<sub>bed</sub> assessed by ICC was 0.89 and 0.84, respectively. After log-transformation to normalize distribution, actigraphic SOL and subjective SOL for the two nights showed a weak but significant correlation ( $r = 0.27$ ,  $P < 0.01$ ). Significantly more male than female participants were habitual drinkers or current smokers. More females than males used insomnia medication, and compared with males, females had a later bedtime and higher levels of physical activity in the evening. The actigraphic SOL was significantly shorter among females

( $P = 0.01$ ), but the subjective SOL was shorter among males ( $P = 0.10$ ) (Table 1).

Evening Temp<sub>out</sub> and Temp<sub>in</sub> showed a lower correlation below the median Temp<sub>out</sub> ( $r = 0.14$ ) than above the median Temp<sub>out</sub> ( $r = 0.53$ ) (Fig. 1). Subjective SOL was significantly associated with older age, sleep medication use, and later bedtime in the univariate model. Evening Temp<sub>in</sub> showed a significant association with log-transformed SOL in the univariate model ( $\beta = -0.022$ ,  $P < 0.01$ ) and the multivariate model that simultaneously included all potential confounders ( $\beta = -0.021$ ,  $P < 0.01$ ; Table 2).

Further adjustment for evening Temp<sub>out</sub> did not attenuate the significant association between evening Temp<sub>in</sub> and subjective SOL ( $\beta = -0.019$ ,  $P < 0.02$ ).

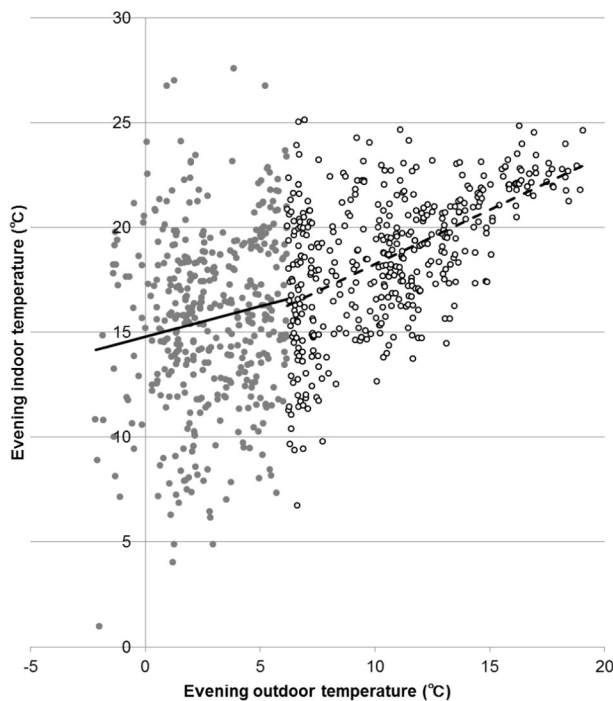
In terms of association with actigraphic SOL, evening Temp<sub>in</sub> and initial nighttime Temp<sub>bed</sub> showed a significant association in the univariate model (evening Temp<sub>in</sub>,  $\beta = -0.020$ ,  $P = 0.01$ ; initial nighttime Temp<sub>bed</sub>,  $\beta = -0.029$ ,  $P < 0.01$ ), and in the multivariate model, independent of all potential confounders (evening Temp<sub>in</sub>,  $\beta = -0.019$ ,  $P = 0.02$ ; initial nighttime Temp<sub>bed</sub>,  $\beta = -0.028$ ,  $P < 0.01$ ; Table 3). According to this model, an increase in evening Temp<sub>in</sub> from 10 °C to 25 °C was associated with shorter actigraphic SOL, with a decrease from 16.7 min to 12.4 min (Fig. 2). After further adjustment for evening Temp<sub>out</sub>, actigraphic SOL showed a significant association with evening Temp<sub>in</sub> ( $\beta = -0.022$ ,  $P = 0.02$ ), and initial nighttime Temp<sub>bed</sub> ( $\beta = -0.028$ ,  $P < 0.01$ ).

Furthermore, initial nighttime Temp<sub>bed</sub> was significantly associated with higher actigraphic SE in the univariate model [ $\beta = 0.127$ , 95% confidence interval (CI): 0.042–0.213,  $P = 0.003$ ] and the multivariate model simultaneously including age, gender, BMI > 25, habitual drinking, current smoking, antidepressant use, insomnia medication use, late bedtime, and household income ( $\beta = 0.139$ , 95% CI: 0.054 to 0.223,  $P = 0.001$ ).

### 4. Discussion

We identified an inverse association between evening indoor temperatures and both subjectively measured SOL and objectively measured SOL among elderly participants. Evening indoor temperatures were significantly and independently associated with subjective SOL. Moreover, indoor temperature in the evening and bed temperature 2 h after bedtime were significantly associated with objectively measured actigraphic SOL, independent of potential confounders such as age, gender, BMI, habitual drinking, current smoking, household income, use of antidepressant and insomnia medications, physical activity in the evening, bedtime, and time spent outdoors. To the best of our knowledge, this is the first study to evaluate the association between indoor temperatures and sleep quality in a real life situation. Our findings from this population-based epidemiologic study in a real life situation expand the generalizability of experimental evidence regarding thermoregulation and sleep in controlled settings.

Arteriovenous anastomoses (AVAs), exclusively found in the skin of the extremities, play an important role in thermoregulation to control heat loss [14]. In cold ambient temperatures, the vasoconstriction of AVAs decreases heat loss, and skin temperatures in the extremities decrease more than that in proximal regions such as the trunk. At neutral evening temperatures, the vasodilation of AVAs increases blood flow in the dermal venous plexus to promote heat loss and to increase the DPG of skin temperature. Kräuchi et al. reported an inverse association of DPG with SOL; a low DPG during the 1.5 h before lights off was the best predictor for long SOL compared with core body temperature and its change rate, heart rate, onset of melatonin release, and subjective sleepiness ratings [8,9]. Furthermore, the fact that interventions to increase proximal skin temperature [10] and passive foot warming can shorten SOL [11] suggests that the relationship between thermoregulation and sleep is not only a simple correlation but also a causal link. Although these findings in controlled settings suggest the influence of



**Fig. 1.** Scatter plot of the correlation between indoor and outdoor temperatures in the evening ( $n = 861$ ). For indoor and outdoor temperatures, the mean values for the first and second evenings were used. Filled circles show data in the lower half of the evening outdoor temperature range ( $-2.75$  °C– $6.16$  °C) and evening indoor temperature range. The solid line shows the linear regression line ( $y = 0.29x + 14.80$ ,  $r = 0.14$ ). Open circles show data in the higher half of the evening outdoor temperature range ( $6.17$  °C– $19.04$  °C) and evening indoor temperature range. The dashed line shows the linear regression line ( $y = 0.52x + 13.04$ ,  $r = 0.53$ ).

**Table 2**

Associations between subjective sleep onset latency and evening indoor temperature using linear mixed regression analysis with random intercept at individual participants.

Independent variables	$\beta^a$	95% CI	P value	Adjusted $\beta^b$	95% CI	P value
Basic characteristics						
Age	0.008	−0.001, 0.02	0.08	0.001	−0.008, 0.010	0.79
Male	−0.074	−0.196, 0.048	0.24	−0.134	−0.289, 0.011	0.07
BMI $\geq 25$	0.023	−0.119, 0.166	0.75	0.042	−0.098, 0.182	0.55
Habitual drinker	0.006	−0.121, 0.133	0.93	0.036	−0.109, 0.181	0.63
Current smoker	0.292	0.013, 0.571	0.04	0.339	0.060, 0.619	0.02
Medication						
Antidepressant	0.175	−0.308, 0.658	0.48	0.132	−0.358, 0.612	0.60
Insomnia medication	0.342	0.138, 0.547	<0.01	0.314	0.109, 0.520	<0.01
Habitual behavior						
Late bedtime <sup>c</sup>	−0.360	−0.461, −0.259	<0.01	−0.353	−0.456, −0.249	<0.01
Physical activity in evening (per 100 counts/min)	−0.003	−0.036, 0.031	0.88	0.007	−0.028, 0.041	0.71
Time spent outdoors in the evening ( $\geq 30$ min)	0.047	−0.204, 0.298	0.71	0.026	−0.222, 0.275	0.83
Socioeconomic status						
Household income ( $\geq 4$ million JPY per year)	−0.083	−0.212, 0.046	0.21	−0.045	−0.173, 0.082	0.49
Outdoor temperature						
Morning	−0.004	−0.014, 0.006	0.47			
Evening	−0.008	−0.020, 0.005	0.23			
Initial nighttime	−0.007	−0.017, 0.003	0.16			
Indoor temperature						
Morning	−0.006	−0.016, 0.004	0.26			
Evening	−0.022	−0.036, −0.008	<0.01	−0.021	−0.034, −0.070	<0.01
Initial nighttime	−0.004	−0.016, 0.008	0.54			
Bed temperature						
Initial nighttime	0.002	−0.008, 0.013	0.65			

Morning, 2 h after rising; evening, 2 h before bedtime; and initial nighttime, 2 h after bedtime.

<sup>a</sup>  $\beta$  coefficient represents the difference of log-transformed subjective sleep onset latency associated with 1 unit change of independent variables.<sup>b</sup>  $\beta$  coefficients were estimated from the multivariate model which simultaneously contains basic characteristics, medication, habitual behavior, socioeconomic status, and the evening indoor temperature as independent variables.<sup>c</sup> Bed time before median value: 22:33.

indoor temperature on sleep onset, the association between indoor temperature and SOL had not previously been quantified. One review pointed out the need for further study of thermoregulation and sleep in the typical home environment [15]. We identified a significant inverse association of evening indoor temperatures with subjectively and objectively measured

SOL in a large elderly population in a setting with no control in terms of posture, physical activity, time spent outdoors, and clothing.

According to an intervention study manipulating skin temperature during nighttime, warmer skin temperature not only shortens the SOL but also enhances sleep depth [16]. We also found that bed temperature

**Table 3**

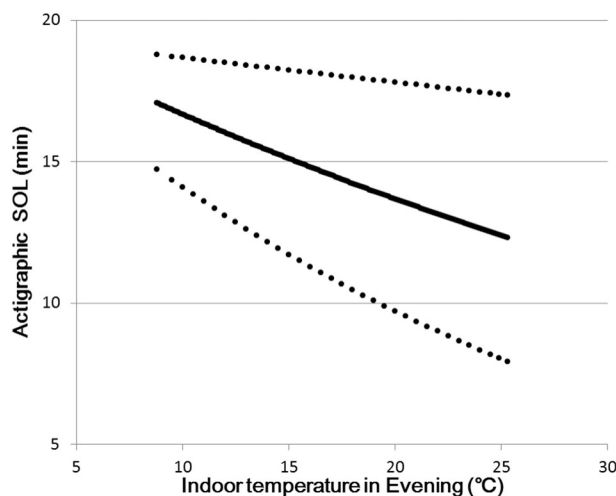
Associations between actigraphic sleep onset latency and evening indoor temperature using linear mixed regression analysis with random intercept at individual participants.

Independent variables	$\beta^a$	95% CI	P-value	Adjusted $\beta^b$	95% CI	P-value
Basic characteristics						
Age	0.010	0.001, 0.019	0.04	0.007	−0.002, 0.017	0.14
Male	0.194	0.061, 0.327	<0.01	0.292	0.131, 0.453	<0.01
BMI $\geq 25$	0.025	−0.130, 0.180	0.75	0.021	−0.134, 0.176	0.79
Habitual drinker	0.105	−0.033, 0.244	0.14	−0.018	−0.178, 0.142	0.83
Current smoker	0.087	−0.218, 0.391	0.58	0.047	−0.262, 0.356	0.77
Medication						
Antidepressant	0.351	−0.199, 0.902	0.21	0.379	−0.186, 0.945	0.19
Insomnia medication	0.250	0.024, 0.476	0.03	0.242	0.012, 0.472	0.04
Habitual behavior						
Late bedtime <sup>c</sup>	−0.257	−0.382, −0.132	<0.01	−0.246	−0.374, −0.119	<0.01
Physical activity in evening (per 100 counts/min)	0.063	0.019, 0.106	<0.01	0.096	0.050, 0.142	<0.01
Time spent outdoors in evening ( $\geq 30$ min)	0.117	−0.209, 0.444	0.482	−0.041	−0.365, 0.284	0.81
Socioeconomic status						
Household income ( $\geq 4$ million JPY per year)	0.016	−0.125, 0.157	0.82	0.043	−0.098, 0.184	0.55
Outdoor temperature						
Morning	−0.001	−0.013, 0.011	0.83			
Evening	−0.005	−0.017, 0.008	0.46			
Initial nighttime	−0.006	−0.019, 0.006	0.32			
Indoor temperature						
Morning	−0.007	−0.023, 0.007	0.28			
Evening	−0.020	−0.036, −0.005	0.01	−0.019	−0.034, −0.003	0.02
Initial night-time	−0.001	−0.015, 0.013	0.87			
Bed temperature						
Initial nighttime	−0.029	−0.041, −0.016	<0.01	−0.028	−0.040, −0.015	<0.01

Morning, 2 h after rising; evening, 2 h before bedtime; and initial nighttime, 2 h after bedtime.

<sup>a</sup>  $\beta$  coefficient represents the difference of log-transformed actigraphic SOL associated with 1 unit change of independent variables.<sup>b</sup>  $\beta$  coefficients were estimated from the multivariate model which simultaneously contains basic characteristics, medication, habitual behavior, socioeconomic status, the evening indoor temperature, and bed temperature in initial nighttime as independent variables.<sup>c</sup> Later bedtime than median value: 22:33.





**Fig. 2.** Association between indoor temperature (2 h before bedtime) and actigraphic sleep onset latency (SOL). The figure shows estimated actigraphic SOL and 95% CI in the range of mean  $\pm$  2 SD of evening indoor temperature. To estimate actigraphic SOL, mean values were substituted for the multivariate model in Table 3.

2 h after bedtime was significantly associated with higher actigraphic SE, independent of potential confounders.

Although the exact mechanism of this relationship is not clear, Raymann et al. discussed the hypothesis that skin temperature may modulate thermosensitive neurons in the preoptic anterior hypothalamus (POAH), which is a thermointegrative center of the mammalian brain that plays a key role in arousal-state regulation [10]. The fact that proximal skin warming decreased the response speed on a vigilance task also supports that mechanism [17].

Gender differences in subjective and objectively measured actigraphic SOL, and longer SOL among participants with sleep medications in the present study were consistent with the findings of previous population-based studies that measured actigraphic sleep parameters. Lauderdale et al. reported longer actigraphic SOL values among males than females in a cohort of 669 middle-aged participants from the Coronary Artery Risk Development in Young Adults (CARDIA) study. Actigraphic SOL among males in the present study ( $31.5 \pm 41.8$  min) was longer than that of white males ( $18.5 \pm 23.2$  min) and shorter than that of black males ( $35.9 \pm 47.0$  min) from the CARDIA cohort. Moreover, SOL among female participants in the present study was longer than that among white females ( $13.3 \pm 15.7$  min) and shorter than that among black females ( $28.3 \pm 32.6$  min) from the same analysis [18]. In a study of 956 elderly participants from the Rotterdam study cohort (age:  $68.4 \pm 6.8$  years), van den Berg et al. reported a longer subjective SOL value among females than males, whereas female participants showed significantly longer actigraphic total sleep time and higher SE [19]. A meta-analysis of 65 studies that measured the objective sleep latency revealed significantly worse sleep quality among participants who used sleep medications in terms of total sleep time, SE, and SOL [20].

Strengths of the present study include the measurement of indoor temperatures, and assessment of SOL using both objective and subjective methods. Although outdoor temperatures are usually easy to obtain, a decreased correlation between indoor and outdoor temperatures in cold climates (Fig. 1), and limited time spent outdoors in the evening among the participants highlighted the need to assess indoor temperature. In fact, there was no significant association between outdoor temperature and SOL. Furthermore, we observed significant associations between evening indoor temperature and both subjective SOL and objective SOL. Objectively measured SOL has been scientifically important for the quantification of sleep quality. Compared with the self-reported SOL, the actigraphic SOL is closer in value to the results of polysomnography [21]. However, the night-to-night variability of an

objectively measured sleep profile is not negligible [22]. Therefore, similarity between the results for the subjective SOL and objective SOL in the present study strengthens the evidence from the objective SOL.

The present study also has some limitations. First, the participants were volunteers recruited using nonrandom sampling. Therefore, the generalizability of the study may be limited. However, the proportion of participants using antihypertensive and antihyperglycemic medications was similar to that in a large-scale, random sampling national survey among 3499 elderly ( $\geq 60$  years) individuals conducted in 2010 (antihypertensive medication use: 40.3%; antihyperglycemic treatment: 12.0%) [23].

Second, actigraphy is not the gold standard to distinguish sleep from periods of wakefulness. However, an epoch-by-epoch comparison between polysomnography and actigraphy as used in the present study revealed high sensitivity (0.93) and moderate specificity (0.69) [24]. Another previous study comparing polysomnography and actigraphy reported that SOL measured by the two methods showed strong agreement with a  $\beta$  coefficient of 0.668 ( $P < 0.001$ ) [25]. Third, the duration of actigraphic measurements (two nights) is relatively short compared with that of previous population-based studies such as the CARDIA study (three nights), the Rotterdam study (at least five nights), a study of osteoporotic fractures (at least three nights) [26], and the MeOS sleep study (at least four nights) [27]. To estimate reliable representative sleep parameters by aggregating data, more than seven nights of data collection are needed to account for night-to-night variability [28]. Taking into account the day-to-day variability in temperature and actigraphic SOL using multilevel analysis in the present study may have addressed this problem. Fourth, the significant longitudinal association between evening indoor temperature and subsequent SOL must be interpreted with care in terms of causality because there was a relatively short period between temperature measurement (2 h before bedtime) and sleep onset. Finally, the finding that higher evening indoor temperature was associated with shorter SOL was for cold seasons only. However, a study comparing sleep quality among the four seasons found that the worst sleep quality was in summer [29]. Further study including all seasons is necessary to determine the optimal indoor temperature for sleep.

In conclusion, the present study identified a significant association between low indoor temperatures and prolonged subjective and objective SOL in a large cohort of home-dwelling elderly participants. In terms of clinical implications, the findings suggest that the effect of increased indoor temperature may be too small to use as treatment for patients with sleep initiation difficulties. However, the information from the present study is potentially useful to reduce the population distribution of risk factors associated with insomnia by controlling indoor temperature and bed temperature [30].

### Author contributions

K.S. and K.O. designed the study and conducted data collection. N.T. contributed to methods of measurement. N.K. contributed to the interpretation of data. K.S. analyzed the data and prepared the draft of this study and all authors reviewed it.

### Conflict of interest

The authors have no conflicts of interest to declare.

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