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Electrophysiological effects of Japanese cedarwood on sleep quality in humans

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Abstract

Sleep plays an important role in human health. Changes in the sleeping environment can affect sleep quality. The present study investigated the effects of natural wood on sleep quality. The interior material was a fully used *Cryptomeria japonica* wood board (Japanese cedar room), while the particleboard and medium-density fiberboard (MDF) were covered by a vinyl cloth with a woodgrain (resin room). In order to assess sleep quality, the sleep–depth index (SDI) is calculated based on the lengths of sleep stage 3 and the rapid eye movement (REM) stage using electroencephalography (EEG). Before the sleep experiments, the Pittsburgh Sleep Quality Inventory (PSQI) and Morningness–Eveningness Questionnaire (MEQ) were administered to confirm the participants' usual sleep habits. Thirteen participants were invited to sleep in two different environments. The MEQ before sleep experiments confirmed that eight participants were of the intermediate type and five participants were of the moderate evening type. According to the PSQI, three participants were poor sleepers and ten were good sleepers. The sleep EEG demonstrated that 12 of 13 participants had higher SDI in the Japanese cedarwood room than in the resin room. A Wilcoxon signed-rank test revealed that SDI was significantly prolonged in the Japanese cedarwood room than in the resin room, regardless of the small sample size ($n = 13$, $z = 2.48$, $p = 0.014$, effect size $= 0.78$). The present study demonstrated that the indoor environment with *C. japonica* induced a significantly higher SDI compared to that with wood-grain vinyl cloth. This indicates that the interior materials of *C. Japonica* wood can positively influence the sleep environment.

Keywords Wooden environment, Japanese cedarwood, Electroencephalography, EEG, Sleep–depth index, SDI

Introduction

Sleep is vital to human life, and the quality of individuals' sleep can affect their health and mental well-being. Sleep duration and consistency are highly correlated with cognitive activities such as academic performance [1]. Rotenberg and other have reported that not only sleep duration but also the sleep stage itself becomes an important factor in determining sleep quality [2, 3]. Several additional factors can affect sleep quality, including the sleep environment's temperature, humidity level, and odor [4–7], and these factors are affected by seasonal changes, especially in four-season countries such as Japan [8]. It is therefore necessary to consider the living environment materials that support or maintain sleep quality.

In Japan, based on data from the Japan Forestry Agency, the high demand for natural wood has been dominated

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by the following tree species: 59.1% for *Cryptomeria japonica* (i.e., Japanese cedarwood), 14.1% for cypress, 9.1% for larch, and 8.1% for hardwood [9]. Shimizu et al. reported that compared to a room without *C. japonica*, a room containing a high amount of *C. japonica* contained high levels of volatile sesquiterpenes such as δ-cadinene and α-muurolene [8]. Several research groups have explored the effects of *C. japonica* on human physiology and psychological activity. For example, Sun et al. demonstrated that their participants' blood pressure decreased in accord with the participants' preference for a wood smell in a room with *C. japonica* interior wood, suggesting physiological relaxation effects of Japanese cedarwood [10]. Nakashima et al. reported that a room with interior materials made of *C. japonica* can increased participants' perceptual change detection during visual processing [11]. Matsubara and Kawai observed that volatile compounds emitted from *C. japonica* could induce a relaxing effect in individuals who inhaled this aroma [12]. Each of these studies investigated participants' daytime cognitive activity, however; the effects of sesquiterpenes from Japanese cedarwood on sleep quality as part of human electrophysiological activity have not yet been revealed.

We conducted the present study to (i) clarify the effects of Japanese cedarwood (*C. japonica*) on sleep quality, and (ii) test our hypothesis that changes in the sleep stage induced by Japanese cedarwood would characterize the changes in brain activity for sleep quality induced by cedarwood. We thus investigated the effects of *C. japonica* on sleep quality using a combination of electroencephalography (EEG) and psychological questionnaires. To evaluate the sleep quality associated with *C. japonica* wood material, two experimental huts were built at Kyushu University. One was made of *C. japonica* (the Japanese cedarwood room), and the other was made of particleboard and medium-density fiberboard (MDF) covered by a vinyl cloth with a woodgrain pattern (the resin room).

Before assessing our participants' sleep quality by EEG, we conducted behavioral evaluations to determine each participant's usual sleep habits on the Pittsburgh Sleep Quality Inventory (PSQI) and Morningness–Eveningness Questionnaire (MEQ). The participants' sleep stages were monitored via EEG during one night of sleep.

The PSQI is a standard questionnaire used for behavioral evaluations in sleep studies [13, 14]. Because of its consistency, this sleep questionnaire is used to both quantify sleep quality and validate methods of measuring sleep quality [15]. Some researchers have paired the PSQI with the MEQ [16, 17], which is a self-administered questionnaire that evaluates the respondent's tendency toward a personal sleep type [18]. The combination of these two questionnaires can help determine usual sleep type and quality.

Some studies have indicated that the N3 stage is a significant factor in determining sleep quality [19, 20]. In the present study we calculated the difference between the durations of the N3 state and rapid eye movement (REM) sleep and compared the difference with the total sleep duration as the sleep–depth index (SDI). To our knowledge, this is the first study to use electrophysiology to investigate sleep effects in a natural wood environment in which *C. japonica* was used as the interior material.

Methods

Participants

Thirteen healthy males (aged 21.0 ± 1.2 years) participated in this study after providing written informed consent. The participants were recruited from the general population and were required to meet the following criteria: absence of any psychiatric or neurological disorders that significantly affect sleep. During the course of their participation in the experiment, the participants were instructed to avoid strenuous exercise and the consumption of stimulants, including alcohol, caffeine, and spicy foods. Each participant was required to sleep for 8 h in each of the two experimental rooms, on separate days. The Ethics Committee of the Faculty of Agriculture of Kyushu University approved this study (application no. 13-009; approval no. 30). All study methods were performed in accord with the approved guidelines of the Ethics Committee and the Declaration of Helsinki.

Experimental environments

The experiment was performed in two experimental rooms of the same size with the same design but different materials. One had Japanese cedar (*C. japonica*) wood boards (the Japanese cedarwood room) as the room's interior material, and the other was built with particleboard and MDF covered by a vinyl cloth with a woodgrain (the resin room). Figure 1 shows a picture and schematic layout of the room. The size of each room was 2×5 m^2, with two areas; one for the participant and the other for a researcher. The details of the material of the experimental room are the same as those in our previous studies [10, 11].

Procedure

This study was conducted during the two periods April to June 2013 and May to July 2014. For all of the participants, the second one-night measurement was performed 1 week after the first one-night measurement. The order of exposure (rooms) was counterbalanced. Each participant came to the designated room at approx. 10:00 pm, where a well-trained technician set up the

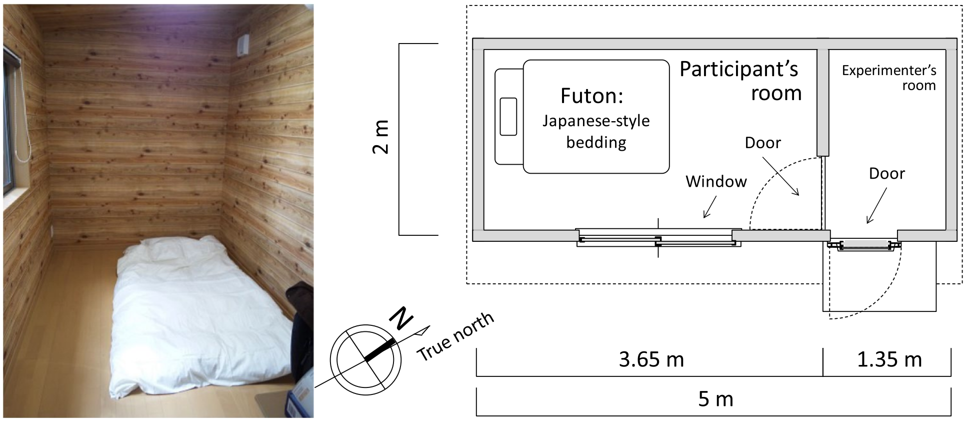

Fig. 1 Inside and schematic layout of each experimental room. The photograph depicts the interior of the room with wood-grain vinyl cloth. The two experimental huts were constructed in close proximity to one another, approximately 2.5 m apart, at the same location on the Hakozaki campus of Kyushu University. This configuration ensured that the daylight and noise environments were nearly identical. For further details regarding the interior and exterior photographs, please refer to Sun et al. [10] and Nakashima et al. [11]

EEG electrodes and recording system for the participant. The interior lights were switched off at 11:00 pm, and the participant stayed in bed until 7:00 am; then, the technician woke up the participant and removed the electrodes (Fig. 2). Each participant wore the same type of sweatshirt and slept in Japanese-style bedding (a futon) placed at the corner opposite the room's entrance door. The futon was dried using a drying machine (FD-F06A6, Panasonic), and the futon sheets and pillow cover were changed every night. For security reasons, the experimental rooms were locked. The technicians also remained near the experimental rooms.

Both experimental rooms were maintained at a temperature of 20.0 ± 1.0 ℃ and < 70% humidity with an air conditioner and humidifier before the experiment started. To control the sleep environment and avoid external influences, the air conditioner and humidifier were left off overnight. The indoor and outdoor temperatures and humidity were measured using a data logger (TR-72Ui: T&D Corp., Matsumoto, Japan).

All 13 participants completed the questionnaires on their circadian preferences (MEQ) and sleep quality (PSQI) before the electrophysiological recordings.

Electroencephalogram data acquisition

EEG recordings were performed across six channels (Fz, Cz, Pz, Oz, C4, and C3) according to the international 10–20 system (Fig. 3) using a Polymate II system

Night	22:00	Participant arrives	Light: ON	Air conditioning: ON
		Change of clothes		
		Electrode attachment		Temperature: 20.0 ± 1.0 °C Humidity: < 70%
	22:30	Participant goes to bed (futon)		
		Participant lies down		
	23:00	EEG recording start	Light: OFF	Air conditioning: OFF
		:		
Morning	7:00	EEG recording end		
		Participant sits up in bed (futon)	Light: ON	
	7:20	Participant gets out of bed (futon)		
		Electrode detachment		Air conditioning: ON
		Change of clothes		
	8:00	Participant departs		

Fig. 2 Experimental schedule

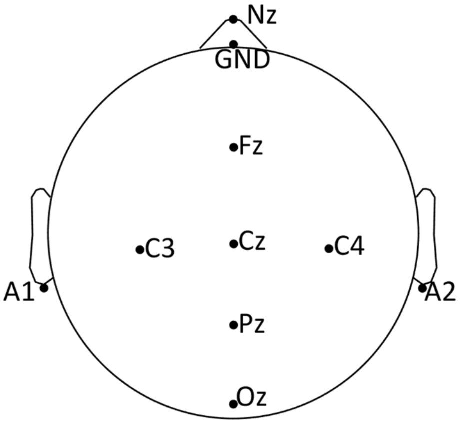

Fig. 3 Locations of the EEG electrodes

(AP-216, Digitex Lab, Tokyo). The reference electrode was placed on the tip of the participant's nose, and the ground electrode was placed on Fpz. Two additional electrodes were placed on A1 and A2 for re-reference. The impedance was maintained below 20 kΩ through the use of active gold-plated electrodes with internal amplifiers. This configuration enables the device to record EEGs even when the impedance is high, exceeding 5 kΩ. The sampling frequency for the data acquisition was 1000 Hz.

Sleep stages detection

The participants' sleep stages were monitored by the EEG setup described above. EEG is frequently used in sleep research [21–24]. Common features extracted from EEG data are frequency bands such as δ (0.5–3 Hz), θ (4–7 Hz), α (8–13 Hz), σ (12–16 Hz), β (18–30 Hz), and the muscle (EMG) band (40–128 Hz). We categorized these frequency bands into a power ratio index between sigma and beta (SBI), delta and beta (DBI), beta and EMG (BEI), and the ratio of average delta after and before the removal of the artifact (EMI).

The number of sleep spindles in one epoch (NSP), the number of cortical arousals (NAR), and the total length of all arousals in the epoch (LAR) were measured. We also determined the W (wakeful state), and other sleep stages such as REM, NREM stage N1 (N1), NREM stage 2 (N2), and NREM stage 3 (N3 or slow-wave sleep) [25, 26].

Automatic scoring was used to determine the sleep stages. The algorithms operate on an EEG channel and involve the following three steps: a spectral analysis of raw data, a dimensionality reduction of the features used for the sleep-stage decision, and sleep staging with a decision tree.

Spectral analysis: The algorithm divides and determines the signal power in the six-frequency band used to divide sleep EEG: δ (0.5–3 Hz), θ (4–7 Hz), α (8–13 Hz), σ (12–16 Hz), β (18–30 Hz), and the EMG band (40–128 Hz).

Feature extraction: Extracting the SBI, DBI, BEI, and EMI; detecting the NSP, NAR, and LAR; and determining the W, REM stage, N1, N2, and N3.

Sleep staging: The algorithm for determining sleep staging is described in Table 1. The algorithm referred to previous research [22, 23] and was applied to both the cedarwood and resin conditions. The algorithm was also used to compare physiological activities between the conditions.

Sleep quality analysis based on psychological questionnaire

The Japanese version of the PSQI was used to measure sleep qualities and current sleep habits. It differentiates 'poor sleep' from 'good sleep' by measuring seven domains: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction over the last month. We used the MEQ to categorize the participants' sleep types. The MEQ involves questions framed in a preferential manner, where the respondent is asked to indicate his/her preference for their sleeping time. The Japanese version of the MEQ consists of 19 items, each scored from 0 to 4 points. The sum of the 19 scores gives a total score ranging from 16 to 86. The MEQ scores and types are explained in Table 2.

Table 1 Algorithm for the classification of sleep stages

Rule	IF	Classified as	ELSE as
R1	$(\mathrm{SBI} \geq 1.5)$ OR $(\mathrm{NSP} \geq 1)$ OR $((\mathrm{EMI} \geq 0.015)$ AND $(\mathrm{NSP} = 0))$	N1/N2/N3	W/REM
R2	$\mathrm{DBI} \geq 35$ AND $\mathrm{BETA} < 0.12$	N3	N2/N1
R3	$\mathrm{SBI} < 1.45$ AND $\mathrm{BEI} > 2.5$ or $1.45 < \mathrm{SBI} < 1.5$ AND $\mathrm{BEI} > 2.25$ AND $\mathrm{EMI} < 0.014$	REM/N1	W/N2/N3
R4	NAR (with EMG) ≥ 1 AND $\mathrm{LAR} > 20\%$	N1	REM
R5	$\mathrm{NAR} \geq 1$ AND $(\mathrm{NSP} = 0$ OR $\mathrm{NSP} = 1$ AND $\mathrm{LAR} > 10\%)$	N1	N2
R6	$\mathrm{SBI} < 1.5$ AND $\mathrm{BEI} < 2$	WAKE	Same as for the previous epoch

Table 2 Scores and types on the Morningness–Eveningness Questionnaire (MEQ)

Score, points	Type
16–30	Definite evening
31–41	Moderate evening
42–58	Intermediate
59–69	Moderate morning
70–86	Definite morning

Time–frequency analysis

After the raw EEG data were obtained, we conducted offline time–frequency analyses using signal processing techniques on MATLAB (The MathWorks, Inc., Natick, MA, USA). This approach applies spectral analyses using a discrete Fourier transform to demonstrate the frequencies present in the signal based on the time domain and spectrograms and to verify the distribution of the power peaks along a time course. The values of power spectra were calculated as follows.

$$I = 10\log_{10}\left(V^2\right), \tag{1}$$

where I is the decibel (dB), which is representative of the spectral power intensity, and V is the signal voltage amplitude.

Sleep–depth index

SDI was calculated using the following formula:

$$\mathrm{SDI} = (D_{\mathrm{N3}} - D_{\mathrm{REM}})/D_{\mathrm{TS}}, \tag{2}$$

where D_{N3}, D_{REM}, and D_{TS} are the duration of N3, REM, and total sleep, respectively.

Statistical analyses

We compared the SDI values between the room conditions by using Wilcoxon's signed-rank test because the Shapiro–Wilk test for the normality assumption test results in significance ($W = 0.823$, $p = 0.013$). All statistical tests were conducted using JASP ver. 0.18.3, and a p value less than 0.05 was considered significant.

Results

Table 3 summarizes the participants' answers on the MEQ and PSQI, which they completed before the sleep experiments. Eight of the 13 participants were defined as intermediate types, and the other five were categorized as moderate evening types. The PSQI results showed that three participants were poor sleepers and ten were good sleepers.

Table 3 Individual scores and types on the MEQ and PSQI questionnaires before the sleep experiment

Participant	MEQ		PSQI	
	Score	Type	Score	Type
A	54	Intermediate	4	Good sleeper
B	45	Intermediate	5	Good sleeper
C	38	Moderate evening	2	Good sleeper
D	43	Intermediate	7	Poor sleeper
E	36	Moderate evening	5	Good sleeper
F	49	Intermediate	3	Good sleeper
G	38	Moderate evening	8	Poor sleeper
H	48	Intermediate	4	Good sleeper
I	50	Intermediate	4	Good sleeper
J	46	Intermediate	6	Poor sleeper
K	43	Intermediate	3	Good sleeper
L	36	Moderate evening	4	Good sleeper
M	40	Moderate evening	4	Good sleeper

The electrophysiological activity demonstrated that 12 of the 13 participants had higher SDIs in the Japanese cedarwood room than in the resin room (Fig. 4). Figure 2 depicts a time-course comparison for 8 h. The hourly comparisons showed a higher SDI in the Japanese cedarwood room for all of the time windows. Compared to the resin room, the Japanese cedarwood room induced a significantly higher SDI for total sleep ($z = 2.48$, $p = 0.014$, effect size = 0.78) (bottom panel in Fig. 5).

Discussion

We investigated the psychophysiological sleep quality induced by *C. japonica* because the demand in Japan for this type of wood in living environments is the highest [27]. The MEQ results demonstrated that the usual sleep pattern of the 13 participants was intermediate or moderate evening. The PSQI results defined 10 participants as good sleepers and three as poor sleepers. Regardless of the MEQ and PSQI scores and usual sleep types, 12 of the 13 participants' SDI values were higher in the Japanese cedar room than in the resin room. The SDI results were also significantly elevated in the Japanese cedar room. These results suggest that sleeping in a Japanese cedar room can prolong the duration of deep sleep, regardless of the sleeper's usual sleep type.

Matsubara and Kawai reported that the volatile compounds of *C. japonica* consisted of δ-cadinene and α-muurolene [12], and they noted that *C. japonica* induced relaxation. In an investigation of the impact of sleeping in a natural forest, Hassan et al. mentioned

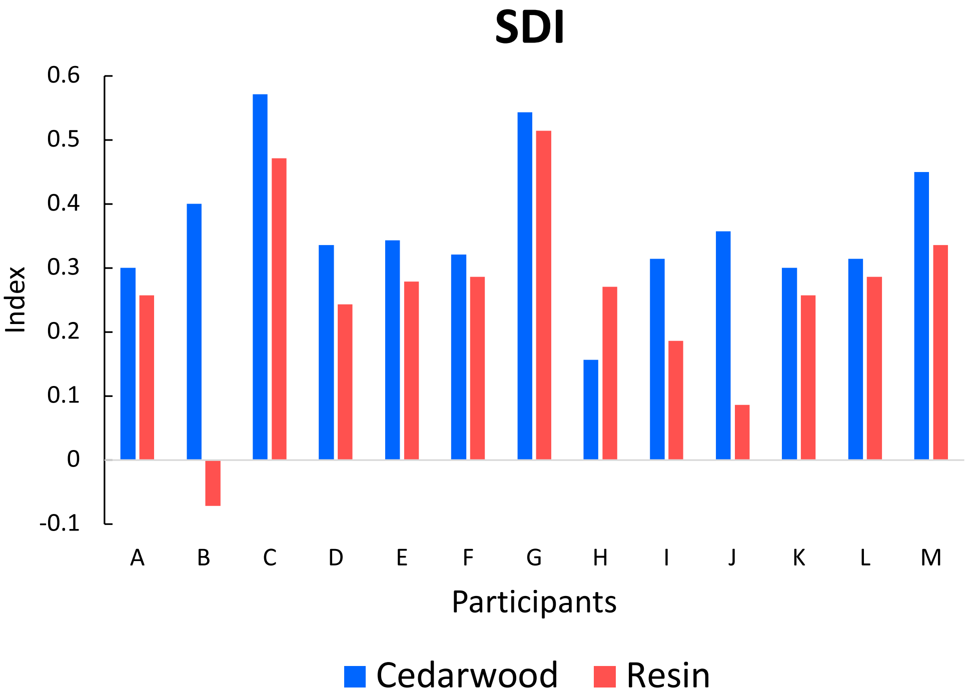

Fig. 4 SDI score of each of the 13 participants. With the exception of participant H, all of the participants showed higher sleep-depth index (SDI) values in the Japanese cedarwood room compared to the resin room. A positive SDI indicates that the duration of sleep stage 3 is longer than that of REM sleep. Conversely, a negative SDI indicates that the duration of REM sleep is longer than that of sleep stage 3

that anxiety scores decreased when their participants slept for 12 min in a forest environment [28]. Anxiety can cause a short duration of deep sleep and induce a lower sleep–depth index. Consistent with this, our present findings demonstrated that sleep quality based on the SDI was higher in the Japanese cedarwood room than in the resin room. Shimizu et al. clarified that Japanese cedarwood affects moisture absorption and the temperature control of indoor air. According to their study [8], the total amounts of sesquiterpenes (α-cubebene, α-copaene, β-elemene, β-caryophyllene, *cis*-thujopsene, *cis*-muurola-3, 5-diene, α-humulene, γ-cadinene, γ-muurolene, *trans*-muurola-4(14), 5-diene, α-muurolene, δ-cadinene, and calamenene) emitted from Japanese cedarwood, the use of which was the same in the present experimental environment and during the same season, were approx. 946–2000 μg/m^3 (mean, 1370 μg/m^3; SEM ± 230 μg/m^3) for the Japanese cedar room and approx. 685–918 μg/m^3 (mean, 824 μg/m; SEM ± 50 μg/m^3) for the resin room. Moreover, Shimizu et al. [29] reported temperature and humidity changes while participants were sleeping for 8 h at night during the same season in the same experimental hut as in this study. The researchers observed no difference in temperature changes between the cedar (22.1–23.5 ℃) and resin rooms (22.1–23.8 ℃) but did note a significant moisture absorption effect in the cedar room, which suppressed the increase in humidity by 73–78% compared to the resin room, which exhibited an increase of 85–90%. Consequently, it can be posited that a higher concentration of sesquiterpene, i.e., approx. > 1000 μg/m^3, and/or the cedar wood's moisture-absorbing properties can enhance sleep quality. Future research should investigate whether sesquiterpenes concentration or moisture-absorbing effects contribute more to improving sleep quality.

The MEQ results showed that the present participants were categorized into two groups (intermediate and moderate evening types), and the PSQI categorized the participants into two groups (good sleepers and poor sleepers [participants D, G, and J]). No clear relationship was observed between the participants' prior sleep habits and the interior cedarwood's effect of prolonging deep sleep. However, all three of the poor sleepers had a higher SDI in the Japanese cedarwood room than in the resin room, suggesting the effectiveness of *C. japonica* in inducing longer deep sleep. Notably, one participant (H) had a different SDI pattern compared to the other 12 participants, although his PSQI result categorized him as a good sleeper. It is possible that participant H had different preferences or anxiety characteristics toward wood scents than the other participants. Future research should include sleep experiments that take into account each individual's preference and anxiety characteristics toward

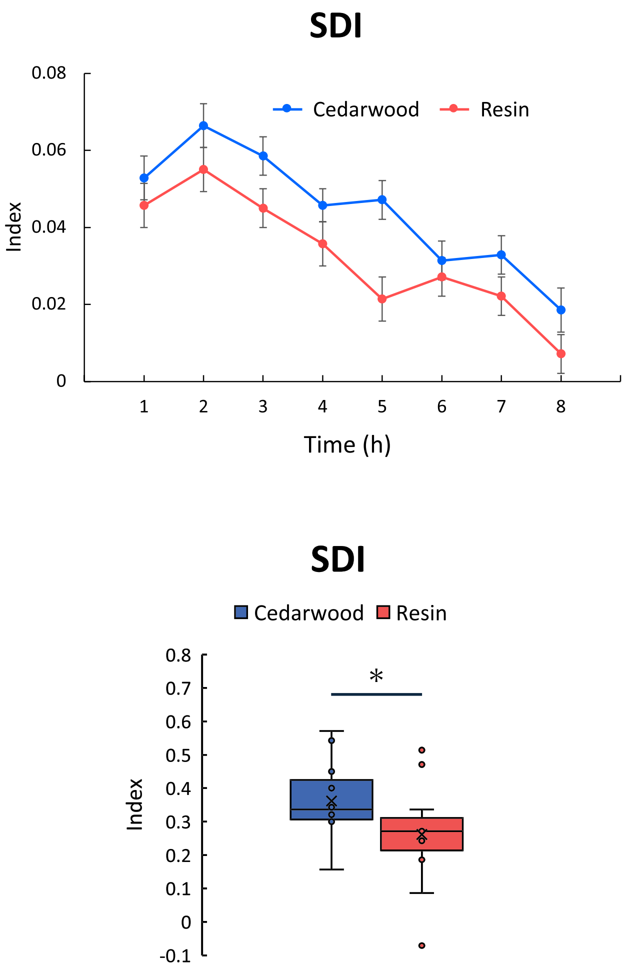

Fig. 5 Time course changes in the SDI scores (± SD) throughout the time (upper column) and comparison of the SDIs under each condition for total sleep (lower column). The participants' SDI values in the Japanese cedar room were significantly higher than those in the resin room throughout the one-night sleep period, suggesting that the participants could generate a longer duration of deep sleep than the REM-stage duration in the Japanese cedar room (Wilcoxon's signed-rank test, $n = 13$, $z = 2.48$, $p = 0.014$, effect size = 0.78)

wood scents and examine the changes in sleep quality. Otherwise, the different SDI pattern of participant H suggest that not only the length of deep sleep but also REM sleep and other sleep stages can be a factor for good psychological sleep. It has been reported that the REM stage is an important feature for distinguishing sleep quality [30]. In the future, the effects of interior cedarwood on sleep quality should be examined using an index that considers not only the length of deep sleep but also the function of REM sleep.

Conclusions

A comparison was conducted between the effects of natural wood interior materials on sleep quality. Two rooms were utilized: a room with *Cryptomeria japonica* (Japanese cedar room) and a room with particleboard and medium-density fiberboard (MDF) covered by a vinyl cloth with a woodgrain (resin room). The SDI index using sleep EEG demonstrated that the Japanese cedarwood room significantly induced a higher SDI than the resin room. These results suggest that the interior materials of *C. japonica* wood can prolong deep sleep durations. This superior effect on sleep quality can be attributed to the higher concentration of sesquiterpene and/or the moisture-absorbing properties of cedar wood. Further studies should investigate the extent to which a higher concentration of sesquiterpenes or moisture-absorbing effects contribute to improving sleep quality.

Abbreviations

D_{N3}	Duration of N3
D_{REM}	Duration of REM
D_{TS}	Duration of total sleep
EEG	Electroencephalogram
EMG	Electromyogram
LAR	Length of arousals
MDF	Medium-density fiberboard
MEQ	Morningness–Eveningness Questionnaire
N1	Non REM stage 1
N2	Non REM stage 2
N3	Non REM stage 3
NAR	Number of arousals
NSP	Number of sleep spindles
PSQI	Pittsburgh Sleep Quality Inventory
REM	Rapid eye movement
BEI	Ratio of beta and EMG power
DBI	Ratio of delta and beta power
SBI	Ratio of sigma and beta power
EMI	Ratio of the delta power before and after median filtering
SDI	Sleep–depth index
SEM	Standard error of the mean

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Author contributions

T.O. conceived the experiments, wrote the script for the EEG analysis, supervised the EEG recordings and analyses, and contributed to the manuscript's writing. T.N. summarized the results and supervised the preparation of the manuscript. K.E.P. analyzed the data and prepared the manuscript's first draft. Z.F. organized the data and contributed to the manuscript's writing. Y.W. prepared the natural cedarwood for the hut construction. S.Y. built the experimental huts. J.N. provided emergency responses for the participants' medical conditions and contributed to the manuscript's writing. N.F. gave advice about the wood materials. K.S. managed this project. All authors reviewed and approved the final manuscript.

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Availability of data and materials

The data sets used and/or analyzed in this study are available from the first author or the corresponding author upon reasonable request.

Declarations

Competing interests

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

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