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The effects of ventilation and temperature on sleep quality and next-day work performance: pilot measurements in a climate chamber

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ABSTRACT

Ten healthy young adults slept one by one in a specially designed and constructed sleep capsule located in a climate chamber at two temperatures (24 °C and 28 °C) and two ventilation rates that ensured that the resulting CO_2 concentrations were 800 and 1700 ppm. Subjectively rated sleep quality was reduced at 28 °C and reduced ventilation, while sleep onset latency was longer under these conditions. Sleep efficiency was lower at 28 °C. Subjectively rated fatigue and sleepiness decreased after sleeping under all conditions but less so after sleeping at 28 °C. The subjects indicated that their work performance improved after sleeping at 24 °C but not when ventilation was reduced and the temperature increased. Both objectively measured and subjectively rated work performance was worse after sleeping in the condition with increased temperature. The subjects felt warmer at 28 °C although the thermal environment was still rated as acceptable but the air in the capsule was rated stuffier, the acceptability of the air quality decreased and the rated odour intensity increased at this condition. The wrist skin temperature was always higher at 28 °C with reduced ventilation but only during the sleep onset latency period. The subjects felt slightly warm and rated the air stuffier when ventilation was reduced. The present results, albeit from a small exploratory pilot study, show that increased temperature and reduced ventilation both have negative effects on sleep quality, which may have consequences for next-day work performance. These pilot experiment results require validation due to the low number of subjects.

1. Introduction

Sleep is fundamental to well-being as it allows the body to recover by promoting various physiological and cognitive processes. Poor sleep quality has been linked to human health including cardiovascular problems [1], a weakened immune system [2], a higher risk of obesity [1,3] and type II diabetes [4], and also reduced next-day work performance (NDWP) [5]. However, these are associations and do not prove the direction of causality – poor sleep might indeed lead to these conditions, but it is also possible that these conditions, or the physiological malfunctions causing them, might be the reason for poor sleep quality. Recently, four reviews have concluded that the bedroom environment significantly affects sleep quality, through its thermal environment (temperature) [6,7] and indoor air quality (IAQ, ventilation) [8,9]. Many field measurements have examined the relationships between the parameters characterizing the quality of bedroom environment and sleep quality [10–15]. However, field investigations which passively monitor conditions have an inherent weakness in that the effects of potential confounders cannot be fully controlled [11]. This makes it hard to prove causality. Intervention studies can do this in both field and laboratory studies, but there have been only a few intervention experiments examining the impact of temperature [16–22] and IAQ [5,23,24] on sleep quality.

Haskell et al. (1981) investigated the effects of high and low temperature on sleep quality for six subjects who slept in a sleep laboratory wearing only shorts [21]. They found that the thermally neutral temperature was 29 °C and that sleep quality was worse when the

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The list of acronyms

IAQ	Indoor Air Quality
PAQ	Perceived Air Quality
TVOC	Total Volatile Organic Compounds
PM	Particulate Matter
HVAC	Heating, Ventilation, and Air-Conditioning
SPL	Sound Pressure Level
PSPL,	Peak Sound Pressure Level
BMI	Body Mass Index
BSA	Body Surface Area
ST	Skin Temperatur
MST	Mean Skin Temperature
CBT	Core Body Temperature
HR	Heart Rate
HRV	Heart rate variability
ES	Effect Size
SOL,	Sleep Onset Latency
DS	Deep Sleep
WASO	Wake After Sleep Onset
SE	Sleep Efficiency
TST	Total Sleep Time
TIB	Time In Bed
LS	Light Sleep
REM	Rapid Eye Movement
PSQI	Pittsburgh Sleep Quality Index
GSQS	Groningen Sleep Quality Scale
SSQ	Subjective Sleep Quality
SEPX	Self-reported Work Performance
NDWP	Next-day Work Performance
SI	Supplementary Information

temperature departed from 29 °C in the range from 21 °C to 37 °C. This was later confirmed by three studies conducted in a climate chamber [16,19,20]. Pan et al. (2012) explored the effects on sleep quality of exposure to cold and found that sleep quality became worse when the temperature decreased from 23 °C to 17 °C [20]. Cao et al. (2021) [16] found that sleep quality was better at 20 °C than at 23 °C or 17 °C, probably because different thermally neutral temperatures were created by systematically adapting the thermal insulation of the bedding system to bedroom air temperature. Lan et al. (2014) examined the effects of both cool and warm exposure on sleep quality and found longer Sleep Onset Latency (SOL), shorter Deep Sleep (DS) and reduced Subjective Sleep Quality (SSQ) when the temperature was 30 °C (warm condition) or 23 °C (cool condition) compared with 26 °C (the thermally neutral condition in their exposures) [19]. Two more studies examined the effects of dynamic changes in temperature on sleep quality; the temperature was changed and cycled between 25 °C, 26 °C, 27 °C and 28 °C in a number of specified orders [17,18]. No significant effects on sleep quality were observed [18], but a comfortably cool or warm environment during the initial phase of the sleeping period extended SOL, a significant difference being observed only in a cool environment (25 °C) [17]. In these studies [19,20], skin temperature (ST) was commonly measured during sleep and it increased as the temperature increased. Other studies also monitored core body temperature (CBT) [22] and heart rate (HR) and heart rate variability (HRV) [25] during sleep at different temperatures but they did not provide information that makes it possible to identify the physiological mechanism behind the effects of temperature on sleep.

Two very recent studies were conducted in a climate chamber to examine the effects of IAQ on sleep quality [23,24]; CO_2 concentration was used as an indicator of IAQ [8] as the ventilation was changed with subjects present. Other studies summarized by Akimoto et al. (2021) [9] were performed in the field. Lan et al. (2021) examined the effects of changes in ventilation resulting in CO_2 levels of ca. 1400 ppm and below 1000 ppm. They found that Wake After Sleep Onset (WASO, total time awake after sleep onset) decreased and Sleep Efficiency (SE) increased when ventilation was increased so as to decrease the CO_2 concentration [24]. Xu et al. (2020) also examined the effects of different ventilation rates; the resulting CO_2 concentrations were 800, 1900 and 3000 ppm [23]. They observed shorter DS, longer SOL, and reduced SSQ when the CO_2 concentration increased from 800 ppm to 3000 ppm. Xu et al. (2020) were not able to attain a sufficiently high CO_2 concentration by restricting ventilation only so they recruited volunteers to be present in the sleep chamber before the subjects entered to build up the intended CO_2 level [23]. As the pre-sleep environment also affects sleep quality [11], this procedure could affect the findings.

Sleep quality has been shown to affect NDWP [26,27]. However, only one laboratory study investigated how sleep quality at different temperatures affected NDWP [18] and found no effect. Similar results were observed in a field experiment [28]. One field experiment found on the other hand that the NDWP decreased after sleep at reduced IAQ[5]. In this study, the task was performed in bedrooms after waking up so task performance could have been affected by the actual conditions in bedrooms, since IAQ has been shown to have direct effects on cognitive performance [29]. In this experiment, any direct effects on NDWP will have been confounded with those of poor sleep quality.

Table 1
Anthropometric data of the 10 subjects (Mean ± SD).

Sex	No.	Age (y)	Height (m)	Weight (kg)	BMI (kg/m^2)	BSA (m^2)	PSQI
Male	4	27 ± 1	1.77 ± 0.04	64.0 ± 4.3	20.5 ± 1.5	1.78 ± 0.07	5 ± 2
Female	6	29 ± 5	1.62 ± 0.05	58.6 ± 5.3	22.3 ± 0.9	1.62 ± 0.10	6 ± 1

BMI=Body Mass Index; BSA=Body Surface Area; PSQI=Pittsburgh Sleep Quality Index.

We thus conducted a small pilot laboratory study to examine the effects of ventilation and temperature on sleep quality and NDWP while monitoring multiple physiological responses. The purpose was to advance our knowledge of the effects of temperature and ventilation on sleep quality as well as to improve and extend measuring protocols. The study was a part of an experiment whose main purpose was to measure emission rates from humans during sleep, for both CO_2 [30] and other bioeffluents. Those findings will be reported separately.

2. Methods

2.1. Subjects

Eleven healthy subjects without sleep disorders [30] were recruited and slept a night under each of the experimental conditions. The data from one subject were excluded as she perceived the air in the capsule to be extremely dry (which was not the case as illustrated in Table 2) and her TST deviated significantly from the other subjects. The main demographic data of the ten remaining subjects are summarized in Table 1; other information about the subjects was published elsewhere [30].

The subjects participating in the experiments were told not to engage in very strenuous exercise, to avoid caffeine, alcohol and the use of personal care products (i.e., deodorants and perfumes, etc.) containing fragrances during the experimental period. Furthermore they were told

Table 2
Planned and measured parameters in the capsule during sleep.

Planned conditions		Condition initials	Measured conditions		Sound pressure level (SPL) (dB(A))	Peak SPL (dB(A))	Relative humidity (RH) (%)	Absolute humidity (g/m^3)
Temperature (°C)	CO_2 concentration (ppm)		Temperature (°C)	CO_2 concentration (ppm)				
24	800	T24P800[a]	23.7 ± 0.2	765 ± 30	51.3 ± 5.0	68.4 ± 7.0	48 ± 2	10.2 ± 0.5
	1700	T24P1700	24.1 ± 0.2	1679 ± 123	47.4 ± 2.0	66.3 ± 5.8	56 ± 3	12.3 ± 0.6
28	800	T28P800	28.0 ± 0.2	794 ± 78	50.7 ± 5.2	70.1 ± 2.7	39 ± 2	10.6 ± 0.6

[a] The first adaption night condition.

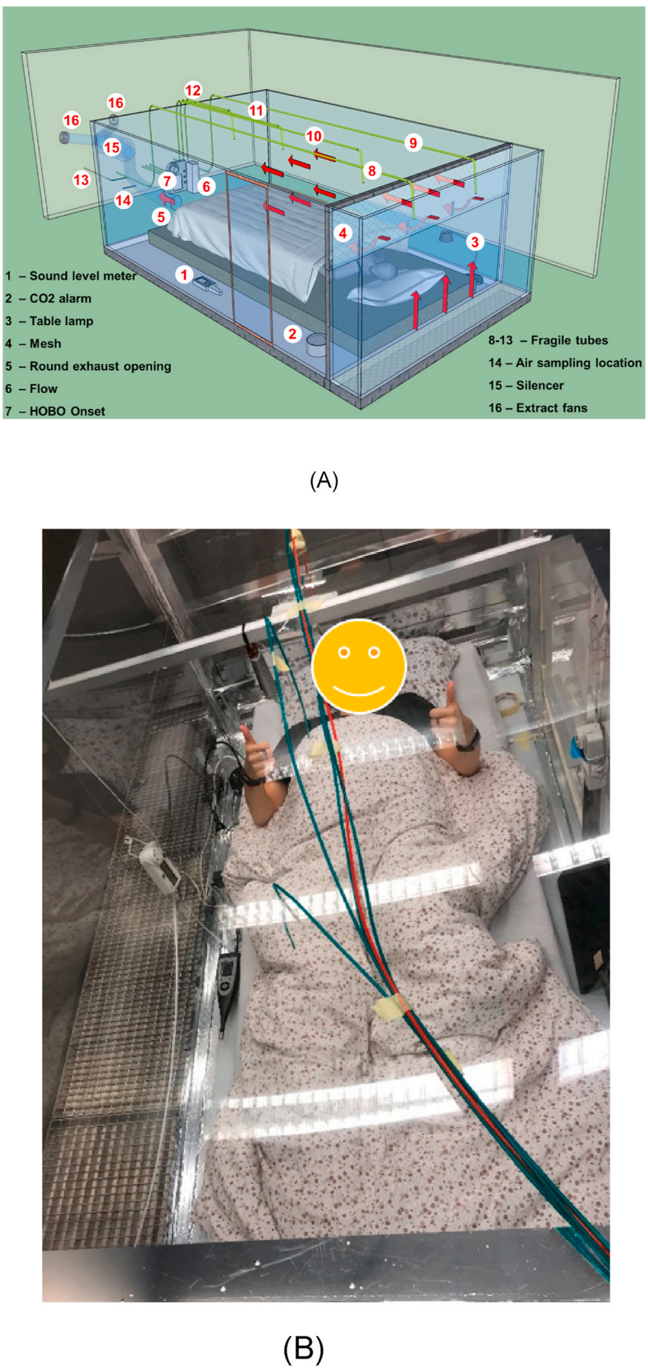

Fig. 1. (A) The model of the capsule layout; (B) The capsule with subjects slept in.

to maintain their usual diet, avoid spicy foods, and travel to the laboratory each day by the same means of transportation. These measures were intended to eliminate any external effects on sleep quality and to avoid any undue influence on the chemical measurements.

The subjects went to bed and woke up each day according to their usual circadian rhythm to avoid any changes in their normal sleeping habits.

2.2. Facilities

We designed and constructed a unique sleep capsule made of transparent reinforced acryl plates attached to aluminium rails, as shown in Fig. 1. The gap between each plate and the framework was sealed both inside and outside with aluminium tape. A door that could be closed and opened from the inside and the outside was installed in one sidewall.

Fig. 1A shows a schematic diagram of the sleep capsule (length (L) of 2.4 x width (W) of 1.1 x height (H) of 0.9 m). The capsule was divided into two parts by a partition consisting of an open mesh in the upper part and an acrylic plate in the lower part. The larger part with a volume of 2.2 m^3 and the dimensions of L x W x H of 2.2 x 1.1 × 0.9 m was the sleep zone, and the smaller, with a volume of 0.20 m^3 and the dimensions of L x W x H of 0.2 x 1.1 × 0.9 m was used as a plenum for the air supplied to the sleep zone. The exhaust opening was in the lower part of the end wall opposite the plenum. With a net volume of 1.9 m^3 (excluding the volume occupied by the bedding, which was approximately 0.3 m^3), the intended conditions in the capsule can be attained by reducing the ventilation during the adaption period that was scheduled before sleep (Fig. S1 in the Supplementary Information (SI)).

This ventilation design was intended to simulate ventilation resulting in almost complete mixing without having to operate mixing fans inside the capsule [30]. The climate chamber air was delivered through the plenum in the smaller volume and mixed with the air within the volume occupied by the subject. Two extract fans that ensured the airflow through the capsule were installed at the end of a Y-piece connection outside the chamber where the capsule was located. A flexible duct connected the exhaust and the Y-piece. To reduce the noise from the extract fans, a silencer was mounted upstream of the fans.

The capsule was installed in one of the twin stainless-steel chambers located at the Technical University of Denmark (DTU) [31] with the dimensions of 3.6 x 2.5 × 2.5 m. The chamber was ventilated with 100% outdoor air through a perforated floor, and the air was exhausted through four outlets in the ceiling. The chamber was equipped with its own Heating, Ventilation, and Air-Conditioning (HVAC) system for supplying and conditioning the outdoor supply airflow to the chamber.

A bedding system, including a mattress, a cotton quilt, a pillow, and bedclothes, was set up in the sleep zone of the capsule (Fig. 1B). The thermal insulation of the bedding system was estimated to be 0.98 clo without the quilt cover and 4.03 clo with 94.1% coverage of body surface area (with head outside), excluding the thermal insulation of the sleepwear [32]. A table lamp was located beside the bed.

An alarm with a built-in CO_2 sensor was installed in the capsule to wake the subjects while they were sleeping in case the CO_2 concentration unexpectedly reached the occupational exposure limit of 5000 ppm, indicating that the ventilation system was not working properly.

Two workstations were set up in the adjacent twin stainless-steel chamber, one for the subject and another for the experimenter. Each consisted of a table and a chair. One PC and one table lamp were provided for the subject. The tasks measuring cognitive performance were performed in this chamber. This chamber was equipped with a separate HVAC system to supply and condition its outdoor supply airflow [31].

The chambers were thoroughly cleaned and 'baked' immediately before the experiments with each new subject. Together with the instruments involved, the capsule was sanitized in the morning after the experiment for that day had been completed to conform to the COVID-19 pandemic guidelines in force when conducting the study from June to August 2020 in Denmark. The bedclothes, pyjamas, and towels used by the subjects were laundered every day using fragrance-free washing powder.

2.3. Experimental conditions

Three conditions were established as listed in Table 2 with two temperatures (24 °C and 28 °C) and two ventilation rates resulting in a concentration of metabolically generated CO_2 by the subjects sleeping in the capsule of 800 ppm and 1700 ppm. The other conditions were not controlled which resulted in small but negligible differences in the sound pressure level as a result of changing ventilation rate, as well as differences in the relative and absolute humidity, especially at the lower ventilation rate when the moisture generated by the sleeping subjects could not be removed to the same extent as at the higher ventilation rate. It should be noticed that these changes were probably not caused by the changes in the humidity of the outdoor air supplied to the chamber as the absolute humidity at two temperature levels was very similar.

The temperatures of 24 °C and 28 °C were selected as they are within the range of temperatures typically measured in bedrooms, as found in recently published review papers [8,33]. The temperature of 24 °C is within the range recommended by the relevant standards [34,35], while 28 °C is outside this range and was selected for the purpose of generating a condition producing warm discomfort. The temperature condition in the capsule was maintained by controlling the temperature of the air drawn into the capsule from the stainless-steel chamber in which it was located.

Two different levels of IAQ were established by changing the ventilation rate in the capsule. They were indicated by two levels of CO_2 emitted by the subjects when present in the capsule and corresponded to CO_2 concentrations of 800 ppm and 1700 ppm. These two levels of IAQ represent the highest and the lowest category of the bedroom environment and office/living room respectively as defined in EN16798-1 [34]. That these conditions were common in actual bedrooms in the field had been documented by two contemporary reviews [8,33].

The CO_2 level of 800 ppm corresponded to a ventilation rate of 11.4 L/s per person and 1700 ppm to 2.5 L/s per person, assuming that the CO_2 emission rate produced while sleeping is 11.0 L/h per person [30].

The chamber in which the performance tasks were performed was maintained at 23 °C to create a thermally neutral environment, with a ventilation rate of 27.8 L/s. The conditions measured in this chamber are shown in Table S1 in the SI.

2.4. Measurements

The air temperature, RH, CO_2 concentration, SPL and peak SPL, and certain air pollutants in the capsule (NO_2, Total Volatile Organic Compound (TVOC), $PM_{2.5}$ and PM_{10} (Particulate Matter)) were continuously measured. Grab samples on Tenax tubes for the subsequent GC-MS analysis were made twice: in the empty capsule before the subject entered it and towards the end of the night when the subject was still sleeping in the capsule; these analytical results will be reported separately. Physiological parameters, including ST, CBT, and HR, were also monitored during sleep using wearable devices. Mean skin temperature (MST) was calculated by the four-point method (Equation (1)) used in a previous study [36]. The time-domain measure of HRV was determined using the percentage of adjacent inter-beat intervals differing by > 50 ms (pNN_{50}). Detailed descriptions of these measurements and the instruments with their accuracy and measurement range can be found in Fan et al. (2021) [30]; they are also listed in Table S2 in SI.

$$MST = 0.2*T_1 + 0.2*T_2 + 0.3*T_3 + *0.3*T_4 \tag{1}$$

- where $T_{1\text{-}4}$ are the ST measured at the anterior calf, anterior thigh, chest, and upper arm, respectively.

The air temperature, RH, and CO_2 concentration in the chamber where the cognitive tasks were performed were continuously monitored by sensors that were an integral part of the chamber system (Table S1 in SI).

Sleep quality was monitored using a wrist-worn sleep tracker (Fitbit Charge 3) as it was in many previous studies [5,11,13]. Five other sleep-trackers currently available on the market were also used to measure sleep quality. This was done to compare their performance and will be reported separately. Fitbit, based on whose measurements the present analysis was made, registered TST, Time In Bed (TIB), and the number of awakenings, as well as WASO, DL, Light Sleep (LS), rapid eye movement (REM). No restrictions on subjects' sleep duration were imposed in the present study, resulting in apparent between-subject differences in TST and time spent in different sleep stages, so we used relative metrics (%) to measure any changes in sleep quality. TST data recorded by the Fitbit were verified by the times of sleep onset and wake up indicated by the subjects.

Two sleep diaries were used, one completed in the evening just before the subjects fell asleep and one in the morning as soon as they woke up. They both recorded subjective ratings of the sleeping environment and other information relevant for assessing sleep quality. They were presented on paper and completed by the subjects while they were in the sleep capsule. The evening diary consisted of questions on activities (exercise and use of electronic devices before sleep), naps taken and diet (drinking and food intake) during the day prior to experiments and any measures taken to improve sleep, current sleepiness and the quality of the environment in the capsule. The morning diary consisted of questions on the time the subject fell asleep and woke up, the number of awakenings during the night and the reasons for them, whether they left the capsule during the night, the retrospectively assessed quality of the capsule environment during sleep and after waking up, current sleepiness and finally sleep quality using the Groningen Sleep Quality Scale (GSQS).

Sleepiness was assessed on the four-point Likert scale as follows: wide awake (1), somewhat awake (2), somewhat sleepy (3), and very sleepy (4). Ratings of the capsule environment included: thermal sensation on a continuous 7-point scale ((-3-cold, -2-cool, -1-slightly cool, 0-neutral, +1-slightly warm, +2-warm, +3-hot), odour intensity on a continuous 6-point scale (0-no, 1-slight, 2-moderate, 3-strong, 4-very strong, 5-overwhelming odour), air freshness, air dryness, noise and light intensity on the visual analogue scales (VAS) – an ungraduated horizontal line with end labels marking the minimum and maximum ratings and acceptability of the sleeping environment on a modified DTU scale of acceptability with a break in the middle between the acceptable and unacceptable coded as follows: clearly unacceptable (−2), just unacceptable (−0.01), just acceptable (+0.01), clearly acceptable (+2)) with the mid-point of each half-scale also labeled (unacceptable (−1), acceptable (+1)). Some of these methods were used in previous studies examining the effects of sleep environment on sleep quality [11]. The subjects assessed fatigue using Yoshitake's method [37]. Their self-reported work performance (SEPX) was also collected by using VAS. Cognitive performance was objectively measured using the N-back test in which a random sequence of letters appears on a screen, with four different working memory loads [38] and the Baddeley test of grammatical reasoning [39] presented both in the evening and in the morning; the tests were designed and generated by E-Studio and E-Prime 2.0 [40]. Detailed descriptions of the tests can be found in the SI.

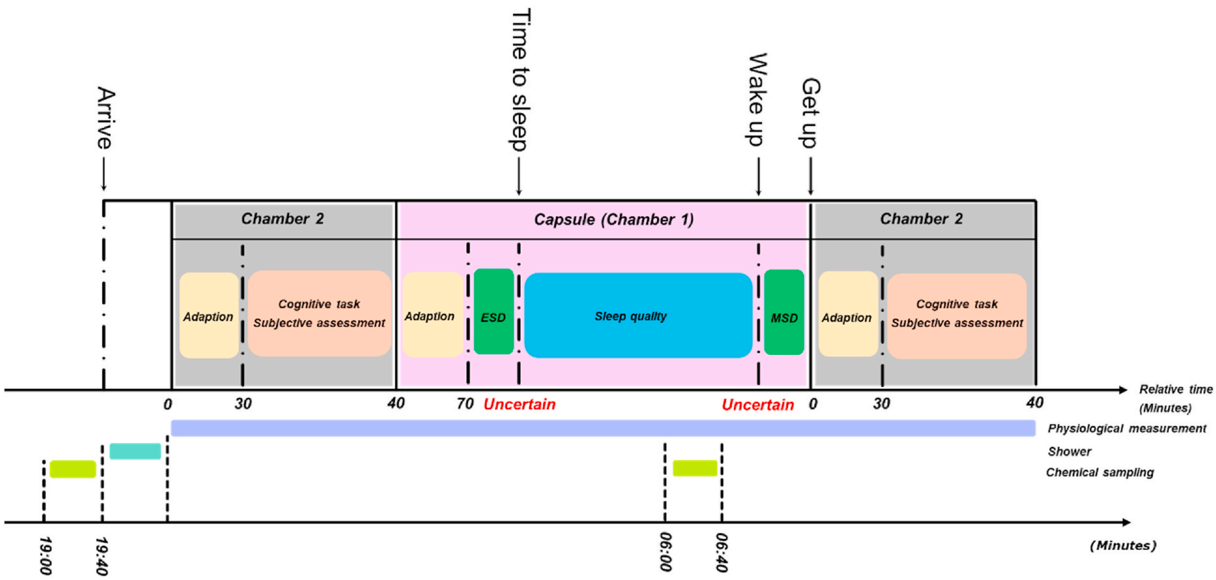

Fig. 2. Experimental procedure. ESD: evening sleep diary; MSD: morning sleep diary.

2.5. Experimental procedures

Each subject slept in the capsule for four consecutive nights, including weekends, in a design balanced for order of presentation of conditions to eliminate bias due to carry-over effects. The first night was for adaption under the reference condition with an air temperature of 24 °C and a ventilation rate resulting in a CO_2 concentration of 800 ppm (Table 2).

Immediately prior to the first night, a practice-and-instruction session was held during which the subjects were informed about the experiment and acquainted themselves with the questionnaires, cognitive performance tasks, and the devices to be used; the cognitive tests were practiced six times. Physiological and sleep quality measurements were not performed then but the instruments were introduced to the subjects. The subjects also adjusted their pyjamas to feel thermally comfortable. The adjustment took place at a temperature of 23 °C, i.e., one degree lower than the lower temperature level planned as one of the experimental conditions. This was to compensate for the fact that the neutral temperature is lower while awake than during sleep [19]. The measurements made during the experiments showed that subjects felt thermally neutral at 24 °C (Fig. 4A). The same pyjamas ensemble was worn in all of the experimental conditions.

The experimental procedure adopted every day is shown in Fig. 2.

Evening: The grab samples of the air in the capsule on Tenax tubes were taken between 19:00 and 19:40, before the subjects arrived at the laboratory. The subjects arrived 2 h before their usual bedtime. They then took a shower with the shower gel and shampoo that were provided and spent 30 min in the chamber where the cognitive tests were performed. During this time they put on their pyjamas and the physiological sensors were attached to their body. They completed the cognitive tasks and rated their fatigue and work performance and could use the toilet and drink water if required before moving to the capsule. After entering the capsule, they sealed the door from the inside and the chamber's lights were then turned off, although they could still use the small table lamp in the capsule. In the next 30 min they remained awake in the capsule and completed the evening diary before going to sleep.

Morning: The grab samples on Tenax tubes of the air in the capsule were taken again towards the end of the sleep period. Upon waking up, the subjects completed the morning diary, left the capsule and moved to the adjacent chamber where they stayed for 30 min before performing the cognitive tasks and answering some final questions on fatigue and SEPX. We did not wake the subjects at any particular time but allowed them to wake up on their own.

The subjects could end their participation in the study if they felt uncomfortable or if they found that it was stressful to sleep in the capsule. They could also leave the capsule at any time during the sleep period, if necessary; only one subject went to the toilet during the entire experimental period, and only during one night. The alarm would have been activated if the CO_2 level had reached 5000 ppm but this did not occur. An experimenter could be contacted at any time throughout the entire night, but no subject used this opportunity.

The protocol of this study was approved under the general permission of the Ethics Review Board of the DTU issued for studies conducted by the International Centre for Indoor Environment and Energy (KA04741). Verbal and written informed consent were obtained from each subject before they took part in the study.

2.6. Statistical analysis

The data were screened for consistency and then subjected to analysis of variance with a repeated-measures design where increased temperature and reduced ventilation were independent variables; the Greenhouse-Geisser method was used to adjust the violation of sphericity. Post hoc analysis was performed using the Bonferroni test. All the statistical analyses were performed using IBM SPSS Statistics 22 (SPSS Inc, Chicago, IL, USA) except for the statistical power analysis, which was tested with G*Power 3.1.9.7. The significance level was set at $P = 0.05$ (2-tail). The effect size (ES) was calculated [41]. It measures the differences between the observed value and the value expected under the null hypothesis and its size indicates whether the difference is of practical importance. Cohen's f was a measure of ES for outcomes that were examined based on their variance; Cohen's f of 0.1, 0.25, and 0.4 define the small, medium, and large ES [42]. Cohen's d was used as a measure of ES for outcomes that were examined by comparing the mean values; Cohen's d of 0.2, 0.5 and 0.8 define a small, medium, and large ES. Small, medium and large ES indicate that 58%, 69% and 79% of the results were higher than the mean value, respectively [42]. As this was an exploratory pilot experiment with a reduced number of subjects, we reported post-hoc analyses not only when the statistical analysis indicated significant differences but also when the ES for the main effect or its interaction with time was large [24].

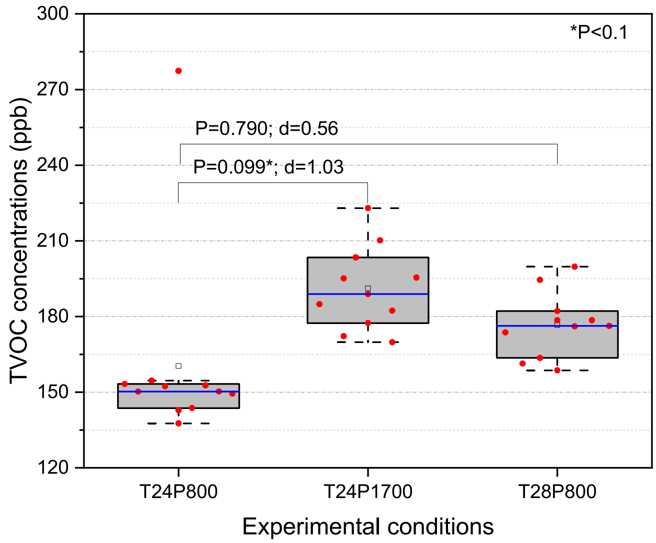

Fig. 3. Measured TVOC concentrations at different conditions in the capsule during sleep. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

3. Results

The air temperature and CO_2 concentration did not deviate from their intended levels (Table 2); the RH was lower at increased temperature and increased ventilation, as expected. The measured SPLs were higher than the levels of 25–35 dB(A) prescribed by EN16798-1 [34] even though a silencer was installed. The measured $PM_{2.5}$, PM_{10} and NO_2 during sleep did not differ between the experimental conditions established in the present experiments (Figs. S2–3 in SI). The TVOC concentrations tended to be higher at reduced ventilation and raised temperature ($d > 0.5$), but the difference approached statistical significance ($P < 0.10$) only when the ventilation rate was reduced (Fig. 3). The conditions in the chamber where the cognitive tasks were performed did not vary between the different experimental conditions examined in the present study (Table S1 in SI).

Table 3 summarizes the subjective assessments of the sleeping environment in the capsule. The thermal sensation, the acceptability of the thermal environment, air freshness and perceived air quality (PAQ) differed significantly between conditions. The differences in odour intensity approached significance ($P < 0.1$; $f = 0.68$). There were no statistically significant differences between conditions in the acceptability of the acoustic and visual comfort, or air dryness, or the noise and light intensity, and Cohen's f ES was not large. Figs. 4 and 5 show the ratings for which a statistically significant difference or at least a medium Cohen's d ES was observed.

The subjects were just below thermal neutrality at T24P800 and slightly above at T24P1700 (Fig. 4A), both conditions being rated as highly acceptable (Fig. 4B). The subjects felt thermally warmer at T28P800, but they still rated this thermal environment as acceptable (Fig. 4). They also felt slightly warmer when the ventilation rate was reduced ($P < 0.1$; $d > 0.5$) (Fig. 4A).

Fig. 5A shows that the subjects assessed the air to be significantly stuffier when the temperature increased from 24 °C to 28 °C. The air was also rated slightly stuffier when the ventilation was reduced but the difference did not reach statistical significance ($P < 0.1$; $d > 0.5$). The acceptability of the air quality decreased when the temperature increased from 24 °C to 28 °C (Fig. 5B). The odour intensity tended to be stronger at T28P800 ($P > 0.1$; $d > 0.5$) (Fig. 5C).

Table 4 shows different measures of subjective sleep quality obtained under the three conditions examined in the present experiment. The subjective sleep quality as rated on the GSQS differed significantly between the three conditions. The self-reported sleepiness and complaint rates of fatigue tended to be affected by the conditions ($P < 0.1$; $f > 0.4$). The significant differences and at least a medium Cohen's d ES are further illustrated in Figs. 6 and 7.

The general complaint rates of fatigue were higher before sleep under all three conditions (Fig. 6A), as expected. Sleepiness was also higher before sleep (Fig. 6B). The complaint rates of fatigue and sleepiness were lower after sleep but the difference was significant only under T24P800 and T24P1700, i.e., not when sleeping at 28 °C. The complaint rate of fatigue tended to be higher at 28 °C than at 24 °C after sleep ($P > 0.1$; $d > 0.5$).

Fig. 7 shows the GSQS results. GSQS increased significantly when the temperature increased from 24 °C to 28 °C and reducing ventilation also tended to increase GSQS ($P > 0.1$; $d > 0.5$), indicating reduced sleep quality. According to Meijman et al. (1990) [43] and Leppämäki et al. (2003) [44] a GSQS in the range 0–2 indicates undisturbed and unrestricted sleep.

The objectively measured sleep quality derived using Fitbit is shown in Table 5. The subjects in the present study slept on average 7.1 ± 0.5 h which is in the range of 7–9 h that is regarded as adequate for normal sleep [45]. Sleep Efficiency (SE) and Sleep Onset Latency (SOL) tended to be significantly affected ($P > 0.1$; $f \geq 0.4$ and $P < 0.1$; $f > 0.4$); there were either no significant effects or large Cohen's f ES for the other

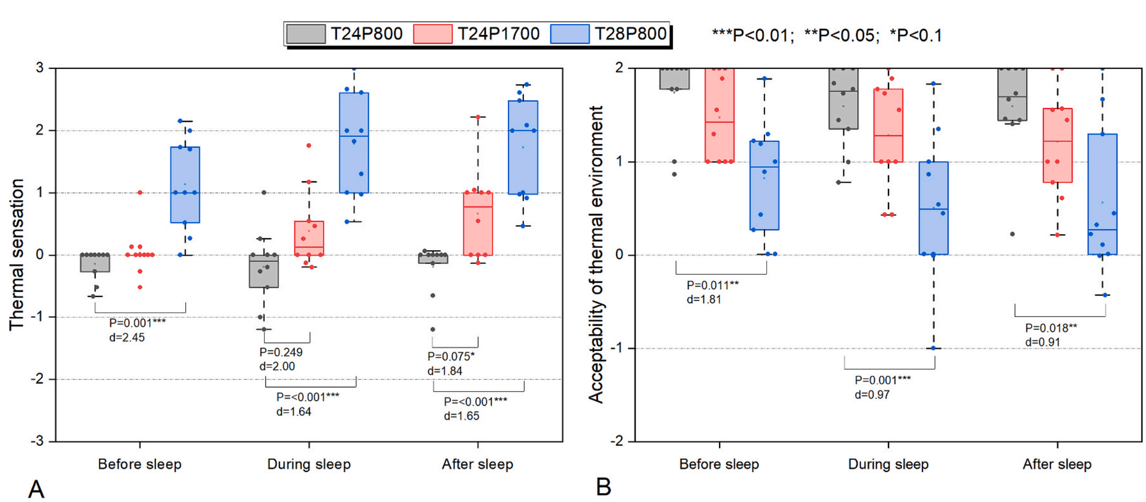

Fig. 4. (A) Thermal sensation; and (B) acceptability of thermal environment before, during (recalled), and after sleep under the different conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

Table 3
Perceived sleep environmental quality in the capsule before, during (recalled) and after sleep (Mean ± SD) under different conditions. Cohen's f ES is shown. ***P < 0.01; **P < 0.05; *p < 0.1

Outcomes		T24P800	T24P1700	T28P800	Condition effects[a]			Time effects[b]			Condition x time effects[c]		
					F	P-value	f[d]	F	P-value	f[d]	F	P-value	f[d]
Cold (−3) – Hot (+3)	Before sleep	−0.1 ± 0.3	0.0 ± 0.4	1.1 ± 0.7	26.66	**<0.001*****	**1.72**	9.76	**0.001 *****	**1.04**	2.35	**0.073 ***	**0.51**
	During sleep	−0.2 ± 0.6	0.4 ± 0.6	1.8 ± 0.8									
	After sleep	−0.2 ± 0.4	0.7 ± 0.7	1.7 ± 0.8									
Clearly unacceptable (−2) – acceptable (+2) thermal environment	Before sleep	1.7 ± 0.4	1.5 ± 0.5	0.8 ± 0.6	13.59	**<0.001*****	**1.23**	3.28	**0.061 ***	**0.60**	0.17	0.952	0.14
	During sleep	1.6 ± 0.4	1.3 ± 0.6	0.5 ± 0.8									
	After sleep	1.6 ± 0.5	1.2 ± 0.6	0.6 ± 0.8									
No odour (0) – Overwhelming (+5) odour	Before sleep	0.2 ± 0.3	0.2 ± 0.3	0.4 ± 0.4	4.17	**0.059 ***	**0.68**	0.91	0.387	0.32	0.03	0.998	0.05
	During sleep	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.3									
	After sleep	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.4									
Fresh (0) – Stuffy (100)	Before sleep	8.8 ± 12.4	22.7 ± 20.6	23.8 ± 19.6	12.68	**<0.001*****	**1.19**	1.44	0.264	**0.40**	1.08	0.383	0.35
	During sleep	7.6 ± 9.5	22.5 ± 23.3	30.3 ± 18.8									
	After sleep	8.2 ± 9.7	27.5 ± 23.7	33.3 ± 19.3									
Dark (0) – Bright (100)	Before sleep	44.8 ± 5.3	43.8 ± 4.3	44.3 ± 7.6	0.08	0.926	0.09	0.06	0.854	0.08	0.62	0.557	0.26
	During sleep	44.5 ± 9.8	42.0 ± 9.2	44.4 ± 11.0									
	After sleep	42.6 ± 7.7	44.4 ± 10.1	43.3 ± 15.0									
Dry (0) – Humid (100)	Before sleep	38.4 ± 8.8	35.9 ± 15.0	38.1 ± 13.1	0.02	0.977	0.05	3.44	**0.088 ***	**0.62**	1.30	0.289	0.38
	During sleep	31.9 ± 13.4	32.9 ± 14.0	27.8 ± 13.5									
	After sleep	30.3 ± 14.9	31.4 ± 12.2	32.7 ± 12.8									
Quiet (0) – Noisy (100)	Before sleep	61.5 ± 13.1	60.1 ± 12.3	60.7 ± 11.0	0.65	0.535	0.27	3.34	**0.058 ***	**0.61**	1.36	0.267	0.39
	During sleep	56.2 ± 11.2	61.3 ± 10.6	56.8 ± 7.6									
	After sleep	58.5 ± 9.0	59.3 ± 11.4	54.4 ± 8.0									
Clearly unacceptable (−2) – acceptable (+2) air quality	Before sleep	1.7 ± 0.4	1.4 ± 0.5	1.3 ± 0.6	6.23	**0.009 *****	**0.83**	4.70	**0.023 ****	**0.88**	0.39	0.686	0.21
	During sleep	1.4 ± 0.7	1.3 ± 0.6	1.1 ± 0.5									
	After sleep	1.5 ± 0.6	1.2 ± 0.5	0.9 ± 0.6									
Clearly unacceptable (−2) – acceptable (+2) acoustic comfort	Before sleep	0.5 ± 0.8	0.4 ± 0.8	0.4 ± 0.8	0.17	0.844	0.14	1.85	0.187	**0.45**	0.59	0.671	0.26
	During sleep	0.7 ± 0.4	0.6 ± 0.7	0.6 ± 0.5									
	After sleep	0.6 ± 0.6	0.6 ± 0.7	0.7 ± 0.6									
Clearly unacceptable (−2) – acceptable (+2) visual comfort	Before sleep	1.3 ± 0.5	1.4 ± 0.4	1.5 ± 0.5	0.22	0.803	0.16	2.06	0.156	**0.48**	0.32	0.864	0.19
	During sleep	1.3 ± 0.5	1.3 ± 0.4	1.3 ± 0.7									
	After sleep	1.2 ± 0.7	1.2 ± 0.5	1.2 ± 0.7									

[a] Main effects of the three conditions.
[b] Main effects of time.
[c] Interaction between condition and time.
[d] Cohen's f with values of 0.1, 0.25, 0.4 indicate the small, medium, and large ES.

objectively measured sleep quality parameters. Detailed results for the parameters for which significant differences or at least a medium Cohen's d ES were obtained are shown in Fig. 8.

A significantly longer SOL was observed when the ventilation was reduced (Fig. 8A). The SOL tended to be longer when the temperature increased from 24 °C to 28 °C (P > 0.1; d >= 0.5) (Fig. 8A). SE tended to be lower at 28 °C even though no significant differences were observed (P > 0.1; d > 0.5) (Fig. 8B).

No significant differences between conditions in the self-reported work performance were observed (Table 6) but the Cohen's f ES for

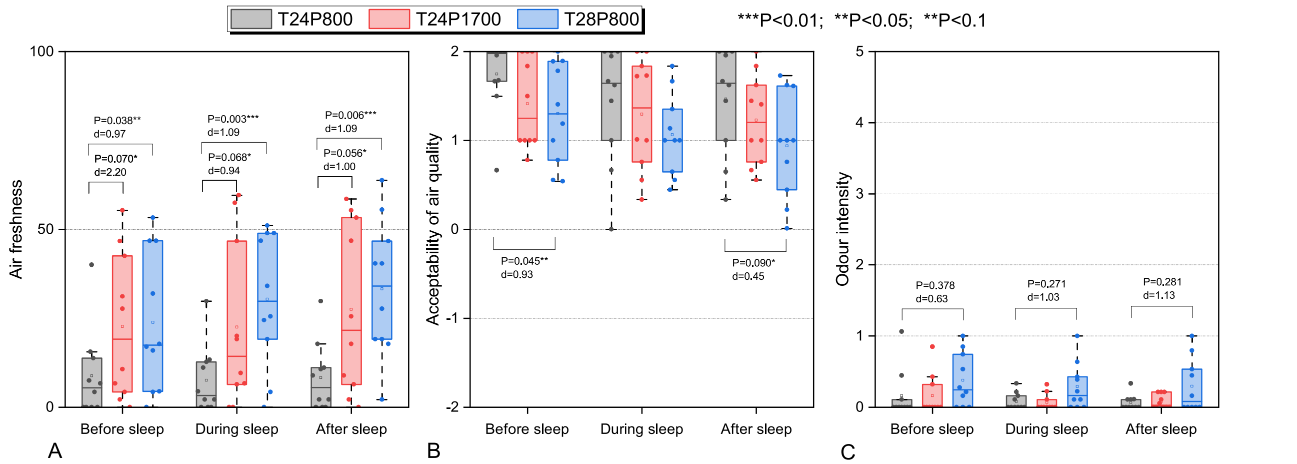

Fig. 5. Ratings of (A) air freshness; (B) acceptability of air quality; and (C) odour intensity before, during (recalled), and after sleep under the different conditions. Cohen's d is indicated; its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

Table 4
Subjectively rated measures of sleep quality before and after sleep at three conditions examined in the present experiments (Mean ± SD). Cohen's f ES is shown. ***P < 0.01; **P < 0.05; *p < 0.1

Sleep quality		T24P800	T24P1700	T28P800	Condition effects[a]			Time effects[b]			Condition x time effects[c]		
					F	P-value	f[d]	F	P-value	f[d]	F	P-value	f[d]
GSQS scores		0.9 ± 1.1	2.0 ± 1.9	3.9 ± 3.4	4.79	__0.042**__	**0.73**						
Awakening times		1.1 ± 0.9	1.4 ± 0.8	1.7 ± 0.8	1.09	0.358	0.35						
Complaint rate of fatigue (%)	Before sleep	18.3 ± 17.0	17.3 ± 16.5	15.0 ± 14.1	0.38	0.690	0.20	9.00	__0.015**__	**1.00**	3.28	__0.093*__	**0.60**
	After sleep	5.0 ± 4.8	6.0 ± 4.9	11.3 ± 15.2									
Sleepiness	Daytime	2.0 ± 0.7	2.3 ± 0.8	1.9 ± 0.6	2.12	0.149	**0.49**	15.00	__<0.001***__	**1.29**	0.77	0.55	0.29
	Before sleep	3.2 ± 0.8	3.5 ± 0.5	3.0 ± 0.8									
	After sleep	1.9 ± 0.9	1.9 ± 0.7	1.9 ± 0.6									

[a] Main effects of the three conditions.
[b] Main effects of time.
[c] Interaction between condition and time.
[d] Cohen's f with values of 0.1, 0.25, 0.4 indicate the small, medium, and large ES.

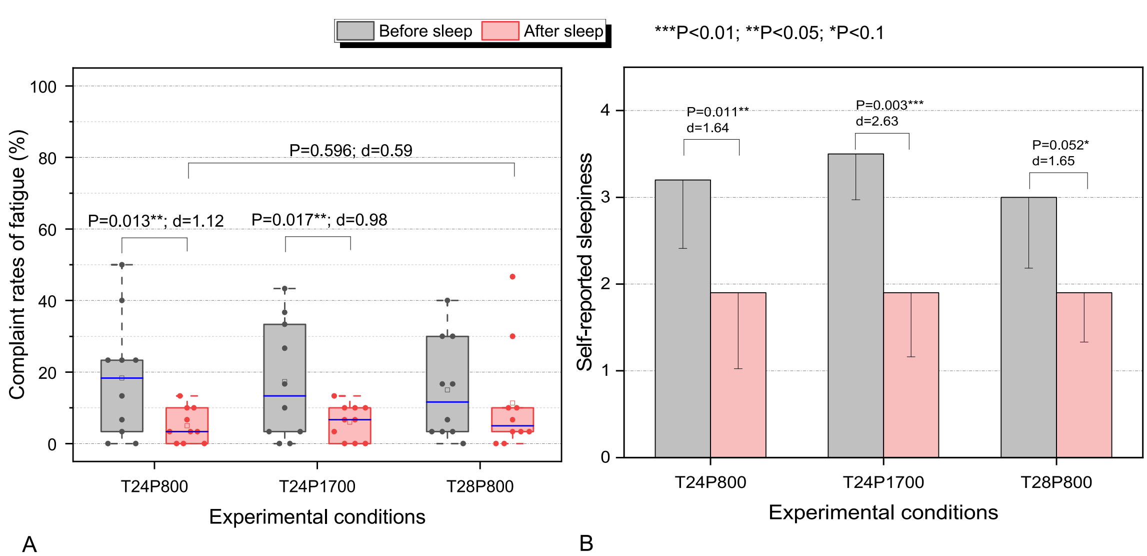

Fig. 6. (A) The complaint rates of fatigue; and (B) sleepiness before and after sleep under the three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

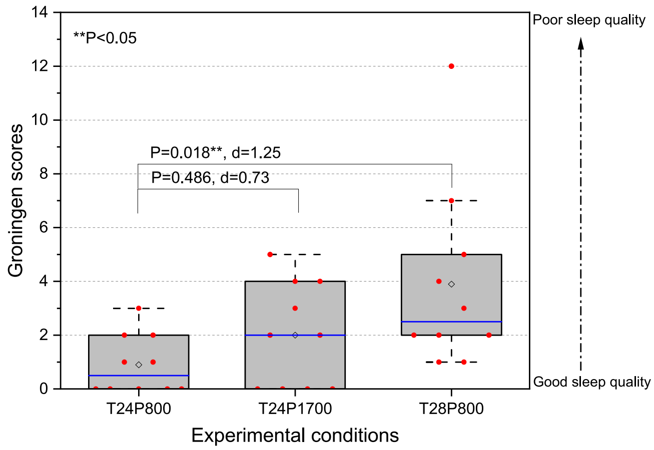

Fig. 7. Subjective measurements of sleep quality in the three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

Table 5
Objectively measured sleep quality parameters under the three conditions (Mean ± SD). Cohen's f ES is shown. *p < 0.1

Sleep quality	T24P800	T24P1700	T28P800	Conditions effects[a]		
				F	P-value	f[b]
Deep sleep, DS (%)	17.3 ± 2.8	17.2 ± 4.0	17.1 ± 2.3	0.02	0.985	0.04
Light sleep, LS (%)	49.0 ± 4.7	50.7 ± 6.7	51.7 ± 6.4	0.74	0.493	0.29
Rapid eye movement sleep, REM (%)	23.6 ± 5.5	22.6 ± 4.4	21.4 ± 5.4	0.59	0.565	0.26
Wake time after sleep onset, WASO (%)	10.0 ± 3.7	9.5 ± 3.6	9.8 ± 1.3	0.11	0.894	0.11
Sleep efficiency, SE (%)	88.7 ± 4.1	87.2 ± 5.5	86.7 ± 4.4	1.46	0.258	**0.40**
Sleep onset latency, SOL (min)	7.1 ± 8.4	18.8 ± 16.3	19.6 ± 21.9	2.90	**0.081***	**0.57**
Total sleep time, TST (min)	434.3 ± 34.7	413.9 ± 29.3	425.9 ± 33.1	1.30	0.298	0.38
Time in bed, TIB (min)	490.3 ± 43.5	476.7 ± 47.6	492.2 ± 40.1	0.61	0.554	0.26

[a] Main effects of the three conditions.
[b] Cohen's f with values of 0.1, 0.25, 0.4 indicate the small, medium, and large ES.

self-reported work performance, exerted effort, time pressure and used capacity to do the tasks were all large (f > 0.4).

Paired comparisons show that self-estimated work performance was significantly improved after sleeping at T24P800 but not for the other two conditions (Fig. 9A). The subjects reported that they exerted significantly more effort to complete the tasks after sleeping at 28 °C (Fig. 9B).

The objectively measured work performance is shown in Table 7. The response time of 1-Back was significantly affected by the three conditions. The response time of 2-back and the results of the grammatical reasoning test tended to be affected by the three conditions (P > 0.1; f ≥ 0.4). Detailed results of paired comparisons are shown in Fig. 10.

The response time in the Grammatical Reasoning test tended to be longer after sleeping at 28 °C in comparison with 24 °C (P > 0.1; d > 0.5; it also increased in the morning after sleeping at 28 °C compared with the evening before sleeping at this condition (P > 0.1; d > 0.5).

The physiological parameters measured during sleep are shown in Table 8. The wrist skin temperature was significantly different during the SOL period. Some differences in the core body temperature during the SOL period, pNN_{50} and wrist skin temperature while asleep were also observed but they did not reach statistical significance (P > 0.1; f > 0.4).

Fig. 11 confirms that the sleep onset latency was longer at 28 °C with reduced ventilation. The temperature trends were similar under all three conditions although the wrist skin temperature was systematically higher at 28 °C.

4. Discussion

The SOL and SE of subjects participating in the present experiment were within the ranges recommended by the National Sleep Foundation Guidelines [46]. This suggests that their quality of sleep was not adversely affected by the experimental conditions or by sleeping in the capsule. However, we still observed that some parameters describing sleep quality changed when ventilation was reduced or temperature increased.

Increasing temperature to 28 °C reduced SSQ measured with the GSQS: average GSQS changed from approx. 1 at 24 °C to approx. 4 at 28 °C, which according to Meijman et al. (1990) [43] and Leppämäki et al. (2003) [44] could be considered as disturbed sleep quality, GSQS ≤ 2 indicating no disturbed and unrestricted sleep. The subjects indicated that their fatigue and sleepiness were alleviated less after sleeping in the condition with increased temperature, which may indirectly suggest that their sleep quality was reduced. SOL was higher and SE was lower at 28 °C (d > 0.5) but the difference did not reach formal statistical significance compared with 24 °C. These results imply that increased temperature exerted some negative effects on sleep quality; these effects are similar to what has been reported by Lan et al. (2016, 2017) [6,7]. Lan et al. (2016) did not observe changes in the objectively and subjectively measured sleep quality when air temperatures changed between 26 °C and 28 °C [18] although a recent study found increased SOL, increased DS, and poorer SSQ when bedroom temperature increased from 26 °C to 30 °C [19].

It would be useful to identify the reasons behind the negative effect of increased temperature on sleep. In the present experiment, changing temperature from 24 °C to 28 °C caused subjects to feel warmer and caused them to rate the air quality in the capsule as stuffier, as expected, as the higher temperature has been shown to reduce PAQ [36]. At 28 °C, TVOC concentration increased (d > 0.5) which could be caused by the increased emission of bioeffluents, as suggested by Tsushima et al. (2018) [47]. Both increased warmth and reduced IAQ could disturb sleep quality and both were reported as the major factors disturbing sleep in a large survey in Danish bedrooms performed by Liao et al. (2021) [48]. In the present experiment, we additionally observed that the CBT did not drop before sleep at 28 °C while it did so both at 24 °C and in the reduced ventilation condition (Fig. 12). A decrease in CBT is a normal physiological reaction when the body is preparing to sleep [49]. This mechanism could impact SOL but further studies are needed to study this in detail. Other published studies have observed that during sleep the MST (temperature change from 23 to 30 °C) [19], CBT (temperature change from 13 to 23 °C) [22] and HR and LF/HF (temperature change from 3 to 17 °C)[25] all increased at higher temperatures in the range of temperature studied. In the present experiment, we did not observe statistically significant differences between conditions in any of the physiological parameters during sleep; they differed significantly only during the SOL period and approaching the time that the subjects woke up. We observed that CBT decreased in the first part of the night and then remained fairly constant until the subjects woke up, as would be expected; these changes would be expected to be accompanied by changes in ST [49].

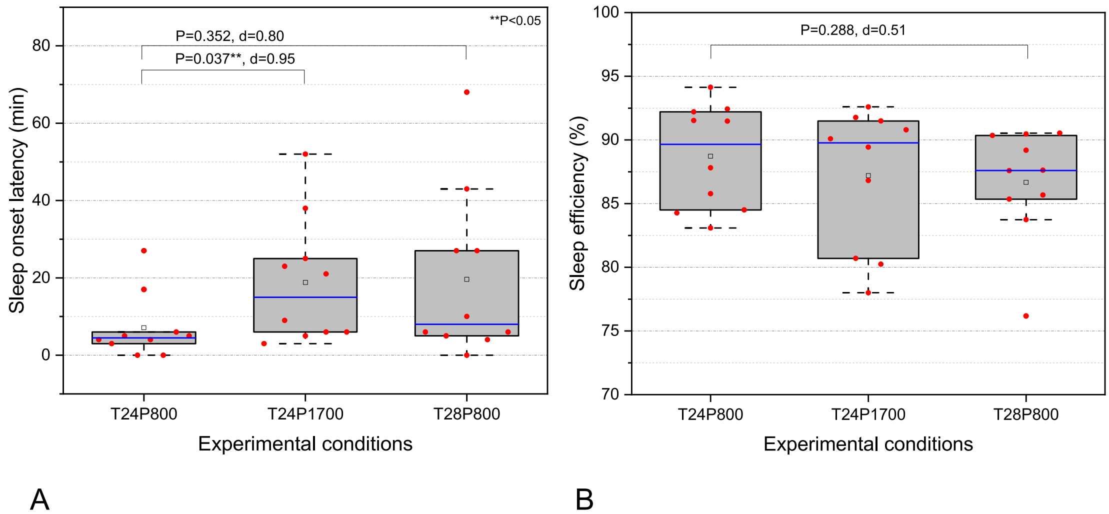

Fig. 8. (A) Sleep onset latency and (B) sleep efficiency under three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

Table 6
Self-reported work performance before and after sleep at three conditions (Mean ± SD). Cohen's f ES is shown. **P < 0.05.

Outcomes		T24P800	T24P1700	T28P800	Condition effects[a]			Time effects[b]			Condition x time[c]		
					F	P-value	f[d]	F	P-value	f[d]	F	P-value	f[d]
The tasks were easy (0) – hard (100)	Before sleep	33.9 ± 18.9	32.525.2	36.0 ± 23.4	0.12	0.885	0.11	2.33	0.161	**0.51**	0.31	0.737	0.18
	After sleep	27.9 ± 17.0	30.9 ± 18.2	30.3 ± 13.6									
The level of effort was low (0) – high (100)	Before sleep	59.6 ± 24.6	60.1 ± 26.7	59.2 ± 31.6	0.754	0.485	0.29	0.04	0.841	0.07	1.48	0.253	**0.41**
	After sleep	57.2 ± 25.8	59.4 ± 26.5	63.9 ± 25.3									
Time pressure was low (0) – high (100)	Before sleep	27.4 ± 19.8	25.8 ± 26.7	30.0 ± 28.3	1.50	0.251	**0.41**	0.14	0.718	0.12	1.26	0.309	0.37
	After sleep	19.2 ± 13.0	28.1 ± 19.9	30.3 ± 20.6									
Full capacity was used at 0–100%	Before sleep	67.0 ± 16.7	70.1 ± 18.6	71.2 ± 18.9	2.34	0.125	**0.51**	0.57	0.469	0.25	0.07	0.844	0.08
	After sleep	62.9 ± 17.4	68.3 ± 13.6	69.7 ± 16.4									
Performance was poor (0) – excellent (100)	Before sleep	60.5 ± 16.1	66.6 ± 13.8	61.6 ± 19.4	0.05	0.953	0.07	1.43	0.262	**0.40**	4.37	**0.028****	**0.70**
	After sleep	71.0 ± 15.8	62.8 ± 16.8	69.7 ± 14.6									

[a] Main effects of the three conditions.
[b] Main effects of time.
[c] Interaction between condition and time.
[d] Cohen's f with values of 0.1, 0.25, 0.4 indicate the small, medium, and large ES.

We are not able to define the temperature that is optimal for sleep from the present results, although a temperature of 28 °C appears to be the upper threshold temperature for establishing a comfortably warm environment for sleep [17] as increasing the temperature from 26 °C to 30 °C has been reported, as mentioned earlier, to result in poorer sleep quality [19]. The optimal temperature for sleep seems likely to depend on the thermal insulation of the bedding and the pyjamas [32,50]. For example, the thermally neutral temperature in the sleeping environment at a relative humidity of 50% was found to be dependent on the total insulation of the bedding [32]: it decreased from 30.1 °C to 8.9 °C in China when the total insulation increased from 0.90 clo to 4.89 clo. In the study of Haskell et al. (1981), their western subjects slept naked and remained thermally neutral at 29 °C [21]. Rohles Jr and Munson (1981) concluded that their subjects could maintain their body temperature at its normal comfort level by adjusting their bedding insulation over the air temperature range of 21.1–32.2 °C [51]. In the present study, the subjects were able to adjust the thermal insulation provided by the quilt and their pyjamas during sleep so they were able to maintain thermal comfort by adjusting the thermal insulation over the range from about 4 to 1 clo.

Reduced ventilation caused SOL to increase significantly. GSQS increased to about 2 but this change was not significant (d > 0.5). In the study of Strøm-Tejsen et al. (2016) [5] there was a significant reduction in GSQS from about 3.5 to 2 when the ventilation in bedrooms was improved from the baseline so as to result in average CO_2 concentrations of 660 ppm, compared with a CO_2 concentration of 2585 ppm. The change in ventilation in the present experiment may have been too small to cause any significant effects on GSQS. Reducing ventilation increased the level of TVOC and this is probably why subjects rated the air quality to be slightly poorer under this condition. As mentioned earlier, poor PAQ may disturb sleep. In the reduced ventilation condition, the CO_2 concentration increased to 1700 ppm. This would be expected to affect

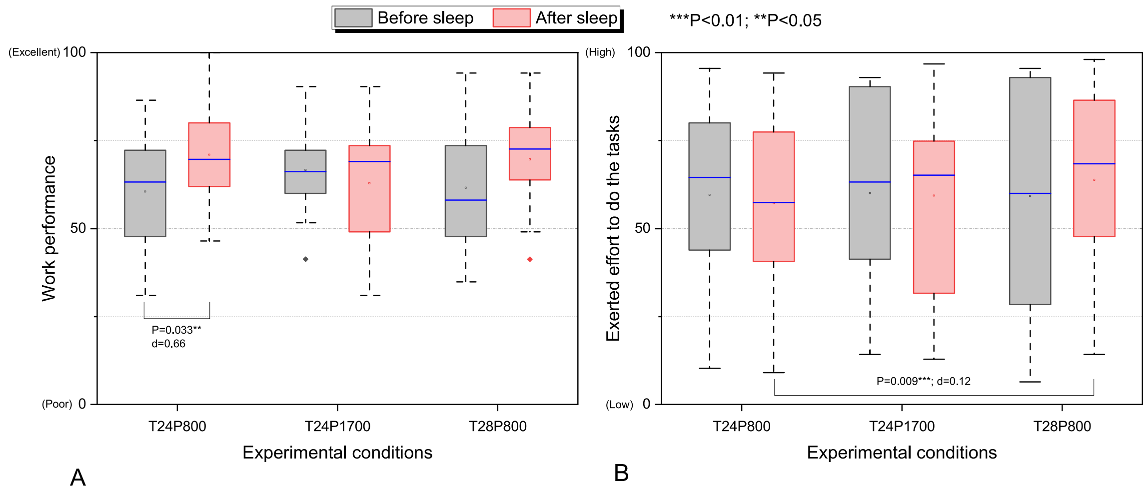

Fig. 9. Self-reported (A) work performance; and (B) exerted effort to do the tasks before and after sleep under the three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

Table 7
Performance of tasks typical of office work before and after sleep under the three conditions (Mean ± SD). Cohen's f ES is shown. **P < 0.05.

Outcomes			T24P800	T24P1700	T28P800	Condition effects[a]			Time effects[b]			Condition x time[c]		
						F	P-value	f[d]	F	P-value	f[d]	F	P-value	f[d]
0-Back	Performance index (units/s)	Before sleep	8.2 ± 3.1	7.9 ± 3.6	14.4 ± 23.7	1.04	0.336	0.34	0.19	0.676	0.14	0.30	0.608	0.18
		After sleep	7.7 ± 2.5	9.9 ± 6.1	10.7 ± 9.0									
	Response time (s/stimulus)	Before sleep	0.15 ± 0.05	0.15 ± 0.07	0.15 ± 0.06	0.37	0.695	0.20	2.16	0.176	**0.49**	0.39	0.680	0.21
		After sleep	0.15 ± 0.04	0.12 ± 0.06	0.13 ± 0.06									
1-Back	Performance index (units/s)	Before sleep	5.9 ± 2.3	6.4 ± 2.9	6.1 ± 2.2	0.71	0.507	0.28	0.67	0.436	0.27	0.95	0.406	0.32
		After sleep	5.5 ± 1.8	6.7 ± 4.7	8.7 ± 8.0									
	Response time (s/stimulus)	Before sleep	0.33 ± 0.24	0.26 ± 0.18	0.27 ± 0.19	4.05	**0.035****	**0.67**	0.90	0.367	0.32	0.81	0.411	0.30
		After sleep	0.47 ± 0.45	0.23 ± 0.11	0.30 ± 0.23									
2-back	Performance index (units/s)	Before sleep	1.7 ± 0.9	1.8 ± 0.8	1.8 ± 1.0	0.28	0.762	0.18	0.70	0.425	0.28	0.22	0.806	0.16
		After sleep	1.5 ± 0.5	1.8 ± 0.8	1.6 ± 0.6									
	Response time (s/stimulus)	Before sleep	2.95 ± 0.42	2.67 ± 0.72	3.05 ± 0.38	1.90	0.179	**0.46**	2.10	0.181	**0.48**	0.09	0.918	0.10
		After sleep	2.71 ± 0.99	2.45 ± 0.69	2.67 ± 0.81									
3-back	Performance index (units/s)	Before sleep	2.0 ± 0.9	2.1 ± 0.9	2.3 ± 1.1	0.01	0.988	0.03	1.76	0.218	**0.44**	0.74	0.494	0.28
		After sleep	2.0 ± 1.0	1.9 ± 0.9	1.7 ± 0.6									
	Response time (s/stimulus)	Before sleep	2.89 ± 0.72	2.90 ± 0.70	2.71 ± 0.86	0.40	0.678	0.21	0.22	0.653	0.16	1.14	0.341	0.36
		After sleep	2.58 ± 0.70	3.16 ± 0.60	2.99 ± 0.97									
Grammatical Reasoning	Performance index (units/s)	Before sleep	0.24 ± 0.07	0.24 ± 0.07	0.24 ± 0.07	0.35	0.707	0.20	0.46	0.514	0.23	1.76	0.201	**0.44**
		After sleep	0.25 ± 0.08	0.26 ± 0.08	0.23 ± 0.08									
	Response time (s/stimulus)	Before sleep	0.13 ± 0.07	0.12 ± 0.05	0.12 ± 0.04	0.54	0.591	0.25	0.38	0.554	0.20	1.44	0.263	**0.40**
		After sleep	0.11 ± 0.03	0.12 ± 0.05	0.15 ± 0.07									

[a] Main effects of the three conditions.
[b] Main effects of time.
[c] Interaction between condition and time.
[d] Cohen's f with values of 0.1, 0.25, 0.4 indicate the small, medium, and large ES.

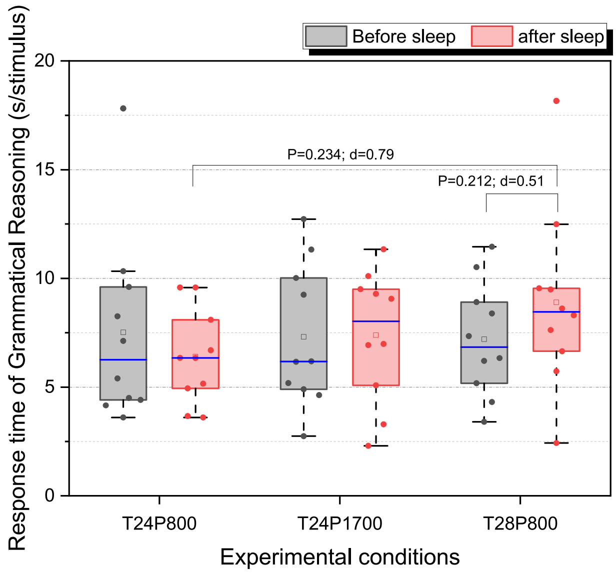

Fig. 10. The response time in the Grammatical Reasoning test before and after sleep under three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

sleep quality according to Akimoto et al. (2021) [9] and Sekhar et al. (2020) [8] who presented a tentative relationship between bedroom ventilation and sleep quality. These results also agree with two recent laboratory studies: Xu et al. (2020) [23] found that SSQ and DS decreased and SOL increased when the ventilation was reduced so that the CO_2 concentration increased from 800 ppm to 3000 ppm, while Lan et al. (2021) [24] observed shorter WASO and increased SE when ventilation was increased so that the CO_2 concentration decreased from about 1400 ppm to below 1000 ppm.

Self-reported work performance was significantly improved after sleeping at T24P800, but no significant differences were observed at either increased temperature or reduced ventilation. This may suggest that the NDWP could be affected by increased temperature and reduced ventilation. The subjects reported that they exerted significantly more effort to do the tasks at 28 °C, and the objectively measured NDWP tended to be worse ($d > 0.5$). These results support the expectation that NDWP was negatively affected by sleeping under warm conditions even though no effects on NDWP were observed in a study performed in a dormitory when the air temperature was either increased or decreased by 2 °C from the preferred bedroom temperature [28]. Lan et al. (2016) [18] also found no effects of warmth. One explanation could be that the change in temperature in these two previous experiments was too small. There were no effects of reduced ventilation on NDWP in the present experiment. Strøm-Tejsen et al. [5] reported that reduced ventilation during sleep had negative effects on the grammatical reasoning test that was used in the present experiment. In their studies, the reduced ventilation was about 60% lower than the one examined in the present experiments (the resulting CO_2 concentration was around 2600 ppm). This could be the reason why no effects were seen in the present study. Their study was also carried out in normal bedrooms where other sources of pollution were certainly present, while the present study was carried out in a climate chamber with very few pollution sources. Future experiments should examine the importance of different sources of pollution but it is worth noting that in a survey Liao et al. (2021) found that the more sources of pollution in a bedroom the higher the risk that subjectively rated sleep quality would be reduced [48].

The effects of increased temperature and reduced ventilation on NDWP should be investigated in future studies but it is important to emphasize that any sleep disturbance substantially increases the likelihood of adverse work outcomes, including occupational accidents, absenteeism, and presenteeism [27]. One reason that few effects on NDWP were found may be that the number of subjects may have been too small. We performed a Power Analysis and found that in order to have medium sized and significant effects at least 15 subjects would be needed (assuming Cohen's f of 0.5 [42] and a non-major sphericity correction of 0.5 [41]). In the study of Strøm-Tejsen et al. (2016) [5], no effects of changed bedroom ventilation on the NDWP could be shown in the pilot and main study with either 14 or 16 subjects, while combining the data from all 30 subjects yielded significant differences. No effects on NDWP were found by Lan et al. (2016) [18] in a study in which only 12 subjects participated.

4.1. Limitations and experimental design

A major limitation of the present study is that only data from ten subjects were available and that they were all young and healthy individuals with normal BMI. We did not investigate gender differences, which had been found in a previous study [52], as only data from four males and six females were available.

We did not perform an a priori Power Analysis to determine the minimum sample size. Instead, we relied on a recent publication that examined the effects of ventilation on sleep quality, in which significant results were obtained using only nine subjects [24].

Another limitation was that the subjects did not sleep in their normal sleeping environment. We used the first night to allow subjects to adapt to the sleeping arrangements according to recommendations by other studies [53]. We did not use the data from the first night which was used for adaptation and could bias the results. As the SOL and SE of the subjects were within the ranges recommended by the National Sleep Foundation [46], we do not think that sleeping in a capsule had any effects on our results.

Table 8
Measured physiological parameters under the three conditions (Mean ± SD). Cohen's f ES is shown. ***P < 0.01.

Outcomes	Sleep period	T24P800	T24P1700	T28P800	Condition effects[a]		
					F	P-value	f[b]
pNN_{50} (%)	SOL[c]	30.4 ± 16.1	30.0 ± 18.5	31.3 ± 24.5	0.01	0.988	0.04
	Asleep	30.4 ± 21.9	26.6 ± 15.7	37.3 ± 20.7	1.62	0.233	**0.48**
Heart rate (bpm)	SOL[c]	63 ± 7	64 ± 9	65 ± 8	0.36	0.707	0.22
	Asleep	60 ± 7	60 ± 7	60 ± 7	0.03	0.967	0.07
Wrist skin temperature (°C)	SOL[c]	32.4 ± 0.9	32.9 ± 0.9	33.6 ± 0.5	9.41	**0.002*****	**1.02**
	Asleep	33.4 ± 0.7	33.3 ± 0.8	33.8 ± 0.4	2.49	0.111	**0.53**
Mean skin temperature (°C)	SOL[c]	33.6 ± 0.6	33.5 ± 0.6	33.7 ± 0.4	1.04	0.373	0.34
	Asleep	33.7 ± 0.5	33.8 ± 0.4	33.7 ± 0.4	0.21	0.814	0.15
Core body temperature (°C)	SOL[c]	36.9 ± 0.3	36.9 ± 0.2	36.8 ± 0.2	1.94	0.173	**0.46**
	Asleep	36.7 ± 0.2	36.7 ± 0.1	36.7 ± 0.2	0.06	0.946	0.08

[a] Main effects of the three conditions.
[b] Cohen's f with values of 0.1, 0.25, 0.4 indicate the small, medium, and large ES.
[c] Sleep Onset Latency.

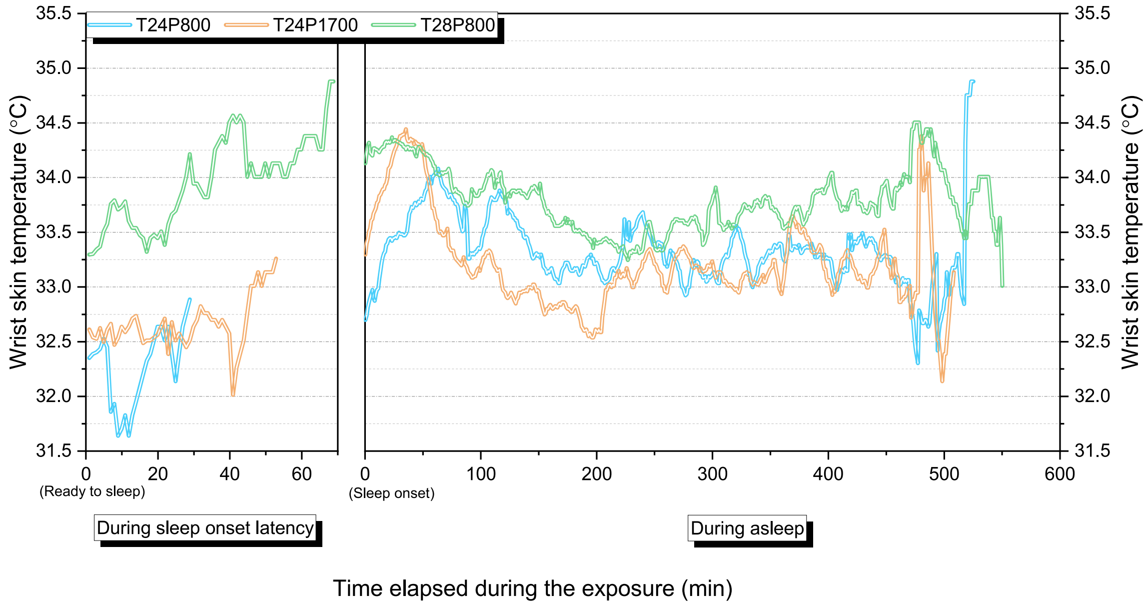

Fig. 11. Wrist skin temperature in each condition during sleep.

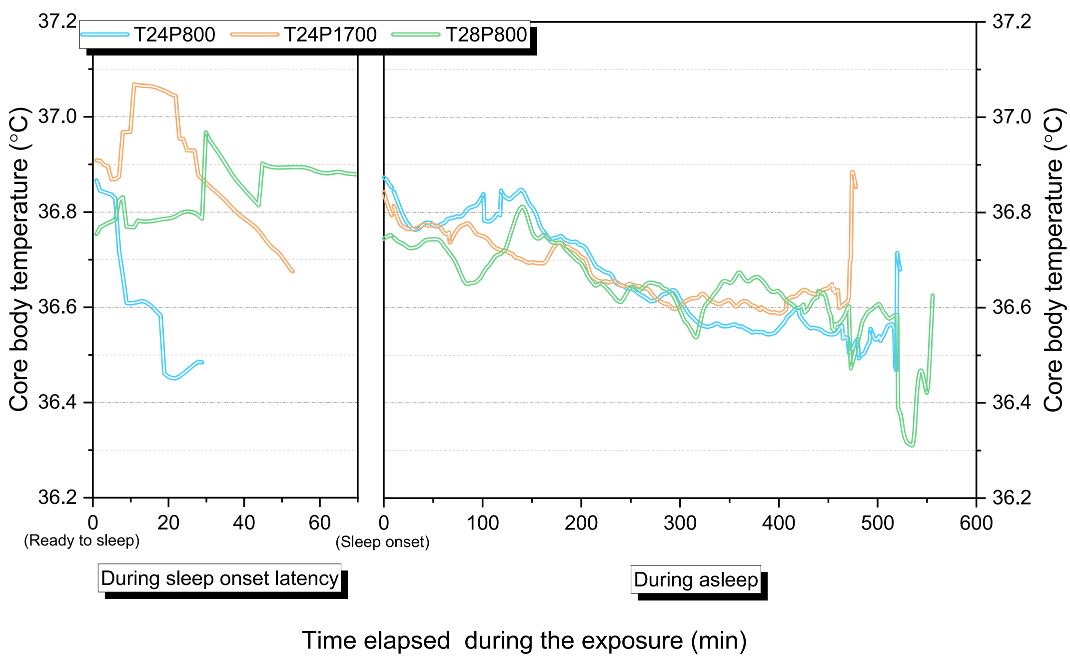

Fig. 12. Core body temperature in each condition during sleep (Temperature effects: $P > 0.1$; $d < 0.5$; ventilation effects: $P > 0.1$; $d < 0.5$).

We did not examine a full 2x2 design for two reasons. The combination of high temperature (28 °C) and low ventilation (resulting in a CO_2 concentration of 1700 ppm) occurs seldom in actual bedrooms according to our recent survey of bedroom conditions [8]. Furthermore, adding one condition would extend the study by one night which would further reduce the number of subjects willing to take part.

We did not control the relative humidity in the capsule, but it differed only slightly between conditions as a result of changes in the outdoor air supply rate, moisture generated by subjects during sleep, capsule temperature and ambient humidity level. We calculated the enthalpy and examined the relationships between the subjective assessments and enthalpy under each condition (Table S3). Only thermal sensation and the acceptability of the thermal environment were linearly correlated with enthalpy. No effects on perceived air quality were observed.

Some of the results may have been affected by elevated noise levels (Table 2). A recent study [24] has reported that increasing the ventilation noise level from 34.7 dB(A) to 50.8 dB(A) or from 48 dB(C) to 54.9 dB(C) significantly decreased DS and REM and the duration of LS. We did not see these effects in the present experiment.

The capsule had a small volume so the conditions could be quickly established (Fig. S1 in SI). In the study of Xu et al. (2020), the high CO_2 condition could not be established by restricting the ventilation so the CO_2 concentration had to be increased by having volunteers present in the climate chamber before the subjects arrived [23]. We introduced a 30 min adaptation period in the capsule before sleep to reduce or even eliminate any bias caused either by the environment experienced outside the capsule or a period of lower CO_2 concentration in the capsule during the initial phase of sleep.

A new aspect of the present work was that subjects performed the cognitive tasks and made some assessments in a thermally neutral condition with good IAQ after having slept at reduced ventilation and increased temperature. This was done to remove any direct effects of the conditions on test performance, as any direct effects must have been confounded with the effects of disturbed sleep in the study reported by Strøm-Tejsen et al. (2016) [5].

5. Conclusions

➢ Subjectively rated sleep quality decreased significantly when the air temperature increased from 24 °C to 28 °C. Sleep onset latency was longer and sleep efficiency was lower at 28 °C ($d > 0.5$). Next-day work performance as measured objectively ($d > 0.5$) and subjectively was poorer after sleeping at 28 °C. The TVOC concentration increased at higher temperature ($d > 0.5$). The subjects felt warmer but they still rated the thermal environment in which the subjects were sleeping acceptable. The odour intensity was stronger ($d > 0.5$), the air was rated as stuffier and the acceptability of the air quality decreased significantly when the temperature was increased to 28 °C. The decrease in subjectively rated fatigue and sleepiness was significantly less after sleeping at 28 °C compared with 24 °C. Measured wrist skin temperature was systematically higher at 28 °C.

➢ Sleep onset latency increased significantly when the ventilation was reduced so that the CO_2 concentration increased from 800 ppm to 1700 ppm. The subjectively rated sleep quality was worse when the ventilation had been decreased ($d > 0.5$). The self-reported or objectively measured work performance were not improved as self-reported work performance was at T24P800 after sleeping at reduced ventilation. Measured TVOC increased when ventilation was reduced, the perceived air freshness decreased and the subjects felt slightly warmer under this condition. Measured wrist skin temperature was higher during the sleep onset latency period ($d > 0.5$) when the ventilation had been reduced.

➢ The present results require validation with a larger group of subjects, for different age groups and for a greater range of health status. They should be performed in actual bedrooms so they can be generalized to other populations and conditions. However, the present results provide evidence consistent with previously published studies showing that increased temperature and reduced ventilation in bedrooms should be avoided because they can negatively affect sleep quality and next-day work performance.

CRediT authorship contribution statement

Xiaojun Fan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Huiqi Shao:** Methodology, Investigation, Conceptualization. **Mitsuharu Sakamoto:** Conceptualization, Methodology, Writing – review & editing. **Kazuki Kuga:** Writing – review & editing, Methodology, Conceptualization. **Li Lan:** Writing – review & editing. **David P. Wyon:** Writing – review & editing. **Kazuhide Ito:** Writing – review & editing. **Mariya P. Bivolarova:** Writing – review & editing, Resources. **Chenxi Liao:** Writing – review & editing. **Pawel Wargocki:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108666.

References

[1] M. Miller, F. Cappuccio, Inflammation, sleep, obesity and cardiovascular disease, Curr. Vasc. Pharmacol. 5 (2007) 93–102, https://doi.org/10.2174/157016107780368280.
[2] L. Besedovsky, T. Lange, M. Haack, The sleep-immune crosstalk in health and disease, Physiol. Rev. 99 (2019) 1325–1380, https://doi.org/10.1152/physrev.00010.2018.
[3] B. Morrissey, E. Taveras, S. Allender, C. Strugnell, Sleep and obesity among children: a systematic review of multiple sleep dimensions, Pediatr. Obes. 15 (2020) 1–21, https://doi.org/10.1111/ijpo.12619.
[4] M. Azharuddin, P. Kapur, M. Adil, P. Ghosh, M. Sharma, The impact of sleep duration and sleep quality on glycaemic control in Asian population with type 2 diabetes mellitus: a systematic literature review and meta-analysis of observational studies, Clin. Epidemiol. Glob. Heal. 8 (2020) 967–975, https://doi.org/10.1016/j.cegh.2020.03.006.
[5] P. Strøm-Tejsen, D. Zukowska, P. Wargocki, D.P. Wyon, The effects of bedroom air quality on sleep and next-day performance, Indoor Air 26 (2016) 679–686, https://doi.org/10.1111/ina.12254.
[6] L. Lan, Z. Lian, Ten questions concerning thermal environment and sleep quality, Build. Environ. 99 (2016) 252–259, https://doi.org/10.1016/j.buildenv.2016.01.017.
[7] L. Lan, K. Tsuzuki, Y.F. Liu, Z.W. Lian, Thermal environment and sleep quality: a review, Energy Build. 149 (2017) 101–113, https://doi.org/10.1016/j.enbuild.2017.05.043.
[8] C. Sekhar, M. Akimoto, X. Fan, M. Bivolarova, C. Liao, L. Lan, P. Wargocki, Bedroom ventilation: review of existing evidence and current standards, Build. Environ. 184 (2020) 107229, https://doi.org/10.1016/j.buildenv.2020.107229.
[9] M. Akimoto, C. Sekhar, M.P. Bivolarova, C. Liao, X. Fan, J. Laverge, L. Lan, P. Wargocki, Reviewing how bedroom ventilation affects IAQ and sleep quality, ASHRAE J. 63 (2021) 56–60.
[10] M. Kim, C. Chun, J. Han, A study on bedroom environment and sleep quality in Korea, Indoor Built Environ. 19 (2010) 123–128, https://doi.org/10.1177/1420326X09358031.
[11] X. Zhang, G. Luo, J. Xie, J. Liu, Associations of bedroom air temperature and CO2 concentration with subjective perceptions and sleep quality during transition seasons, Indoor Air 31 (2021) 1004–1017, https://doi.org/10.1111/ina.12809.
[12] N. Zhang, B. Cao, Y. Zhu, Indoor environment and sleep quality: a research based on online survey and field study, Build. Environ. 137 (2018) 198–207, https://doi.org/10.1016/j.buildenv.2018.04.007.
[13] J. Xiong, L. Lan, Z. Lian, R. De dear, Associations of bedroom temperature and ventilation with sleep quality, Sci. Technol. Built Environ. 26 (2020) 1274–1284, https://doi.org/10.1080/23744731.2020.1756664.
[14] X. Xu, Z. Lian, J. Shen, L. Lan, Y. Sun, Environmental factors affecting sleep quality in summer: a field study in Shanghai, China, J. Therm. Biol. 99 (2021), https://doi.org/10.1016/j.jtherbio.2021.102977, 102977.
[15] P. Yin, Y. Ji, J. Xie, J. Liu, Q. Hou, S. Zhao, Research on residential thermal environment differences in relation to transition and heating periods in Beijing, Build. Environ. 197 (2021) 107851, https://doi.org/10.1016/j.buildenv.2021.107851.
[16] T. Cao, Z. Lian, S. Ma, J. Bao, Thermal comfort and sleep quality under temperature, relative humidity and illuminance in sleep environment, J. Build. Eng. 43 (2021) 102575, https://doi.org/10.1016/j.jobe.2021.102575.
[17] L. Lan, Z.W. Lian, Y.B. Lin, Comfortably cool bedroom environment during the initial phase of the sleeping period delays the onset of sleep in summer, Build. Environ. 103 (2016) 36–43, https://doi.org/10.1016/j.buildenv.2016.03.030.
[18] L. Lan, Z.W. Lian, X.L. Qian, C.Z. Dai, The effects of programmed air temperature changes on sleep quality and energy saving in bedroom, Energy Build. 129 (2016) 207–214, https://doi.org/10.1016/j.enbuild.2016.08.001.
[19] L. Lan, L. Pan, Z. Lian, H. Huang, Y. Lin, Experimental study on thermal comfort of sleeping people at different air temperatures, Build. Environ. 73 (2014) 24–31, https://doi.org/10.1016/j.buildenv.2013.11.024.
[20] L. Pan, Z. Lian, L. Lan, Investigation of sleep quality under different temperatures based on subjective and physiological measurements, HVAC R Res. 18 (2012) 1030–1043, https://doi.org/10.1080/10789669.2012.667037.
[21] E.H. Haskell, J.W. Palca, J.M. Walker, R.J. Berger, H.C. Heller, The effects of high and low ambient temperatures on human sleep stages, Electroencephalogr. Clin. Neurophysiol. 51 (1981) 494–501, https://doi.org/10.1016/0013-4694(81)90226-1.

[22] A. Muzet, J.P. Libert, V. Candas, Ambient temperature and human sleep, Experientia 40 (1984) 425–429, https://doi.org/10.1007/BF01952376.
[23] X. Xu, Z. Lian, J. Shen, T. Cao, J. Zhu, X. Lin, K. Qing, W. Zhang, T. Zhang, Experimental study on sleep quality affected by carbon dioxide concentration, Indoor Air (2020) 1–14, https://doi.org/10.1111/ina.12748.
[24] L. Lan, Y. Sun, D.P. Wyon, P. Wargocki, Pilot study of the effects of ventilation and ventilation noise on sleep quality in the young and elderly, Indoor Air (2021) 1–13, https://doi.org/10.1111/ina.12861.
[25] K. Okamoto-Mizuno, K. Tsuzuki, K. Mizuno, Y. Ohshiro, Effects of low ambient temperature on heart rate variability during sleep in humans, Eur. J. Appl. Physiol. 105 (2009) 191–197, https://doi.org/10.1007/s00421-008-0889-1.
[26] K.M. Lawson, S. Lee, Better previous night sleep is associated with less next day work-to-family conflict mediated by higher work performance among female nursing home workers, Sleep Heal 4 (2018) 485–491, https://doi.org/10.1016/j.sleh.2018.07.005.
[27] L.M. Swanson, J.T. Arnedt, M.R. Rosekind, G. Belenky, T.J. Balkin, C. Drake, Sleep disorders and work performance: findings from the 2008 national sleep foundation sleep in America poll, J. Sleep Res. 20 (2011) 487–494, https://doi.org/10.1111/j.1365-2869.2010.00890.x.
[28] P. Strøm-Tejsen, S. Mathiasen, M. Bach, S. Petersen, The effects of increased bedroom air temperature on sleep and next-day mental performance, Proc. Indoor Air (2016) 3–8. Ghent, Belgium, 2016.
[29] X. Zhang, P. Wargocki, Z. Lian, C. Thyregod, Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance, Indoor Air 27 (2017) 47–64, https://doi.org/10.1111/ina.12284.
[30] X. Fan, M. Sakamoto, H. Shao, K. Kuga, K. Ito, L. Lan, P. Wargocki, Emission rate of carbon dioxide while sleeping, Indoor Air 31 (2021) 2142–2157, https://doi.org/10.1111/ina.12911.
[31] O. Albrechtsen, Twin Climatic Chambers to Study Sick and Healthy Buildings, Proc. Heal. Build., 1988, pp. 25–30.
[32] Z. Lin, S. Deng, A study on the thermal comfort in sleeping environments in the subtropics-Measuring the total insulation values for the bedding systems commonly used in the subtropics, Build. Environ. 43 (2008) 905–916, https://doi.org/10.1016/j.buildenv.2007.01.027.
[33] N. Canha, C. Teixeira, M. Figueira, C. Correia, How is indoor air quality during sleep? A Review of Field Studies, Atmosphere (Basel) 12 (2021) 110, https://doi.org/10.3390/atmos12010110.
[34] EN 16798–1:2019, Energy Performance of Buildings – Ventilation for Buildings – Part 1 : Indoor Environmental Input Parameters for Design and Assessment of Energy Performance, 2019.
[35] ISO 7730, Moderate Thermal Environments: Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort, 1994. Geneva, Switzerland.
[36] X. Fan, W. Liu, P. Wargocki, Physiological and psychological reactions of sub-tropically acclimatized subjects exposed to different indoor temperatures at a relative humidity of 70, Indoor Air 29 (2019) 215–230, https://doi.org/10.1111/ina.12523.
[37] H. Yoshitake, Occupational Fatigue - Approach from Subjective Symptoms, The institute for science of labor, Tokyo, Japan, 1973 (In Japanese).
[38] T.S. Braver, J.D. Cohen, L.E. Nystrom, J. Jonides, E.E. Smith, D.C. Noll, A parametric study of prefrontal cortex involvement in human working memory, Neuroimage 5 (1997) 49–62.
[39] A.D. Baddeley, A 3 min reasoning test based on grammatical transformation, Psychonomic Sci. 10 (1968) 341–342, https://doi.org/10.3758/BF03331551.
[40] S.C. Andrews, K.E. Hoy, P.G. Enticott, Z.J. Daskalakis, P.B. Fitzgerald, Improving working memory: the effect of combining cognitive activity and anodal transcranial direct current stimulation to the left dorsolateral prefrontal cortex, Brain Stimul 4 (2011) 84–89, https://doi.org/10.1016/j.brs.2010.06.004.
[41] L. Lan, Z. Lian, Application of statistical power analysis - how to determine the right sample size in human health, comfort and productivity research, Build. Environ. 45 (2010) 1202–1213, https://doi.org/10.1016/j.buildenv.2009.11.002.
[42] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, second ed., Lawrence Erlbaum Associates, Mahwah, New Jersey, 1988.
[43] T.F. Meijman, M.J. Thunnissen, A.G.H. De Vries-Griever, The after-effects of a prolonged period of day-sleep on subjective sleep quality, Work Stress An Int. J. Work. Heal. Organ. 4 (1990) 65–70, https://doi.org/10.1080/02678379008256965.
[44] S. Leppämäki, Y. Meesters, J. Haukka, J. Lönnqvist, T. Partonen, Effect of simulated dawn on quality of sleep - a community-based trial, BMC Psychiatr. 3 (2003) 1–5, https://doi.org/10.1186/1471-244X-3-14.
[45] M.M. Ohayon, J. Zulley, Correlates of global sleep dissatisfaction in the German population, Sleep 24 (2001) 780–787.
[46] M. Ohayon, E.M. Wickwire, M. Hirshkowitz, S.M. Albert, A. Avidan, F.J. Daly, Y. Dauvilliers, R. Ferri, C. Fung, D. Gozal, N. Hazen, A. Krystal, K. Lichstein, M. Mallampalli, G. Plazzi, R. Rawding, F.A. Scheer, V. Somers, M. V Vitiello, National Sleep Foundation's sleep quality recommendations: first report, Sleep Heal 3 (2017) 6–19, https://doi.org/10.1016/j.sleh.2016.11.006.
[47] S. Tsushima, P. Wargocki, S. Tanabe, Sensory evaluation and chemical analysis of exhaled and dermally emitted bioeffluents, Indoor Air 28 (2018) 146–163, https://doi.org/10.1111/ina.12424.
[48] C. Liao, M. Akimoto, M.P. Bivolarova, C. Sekhar, J. Laverge, X. Fan, L. Lan, P. Wargocki, A survey of bedroom ventilation types and the subjective sleep quality associated with them in Danish housing, Sci. Total Environ. 798 (2021) 149209, https://doi.org/10.1016/j.scitotenv.2021.149209.
[49] R. Szymusiak, Body temperature and sleep, in: Handb. Clin. Neurol., first ed., Elsevier B.V., 2018, pp. 341–351, https://doi.org/10.1016/B978-0-444-63912-7.00020-5.
[50] F. Nicol, Temperature and sleep, Energy Build. 204 (2019) 109516, https://doi.org/10.1016/j.enbuild.2019.109516.
[51] F.H. Rohles, D.M. Munson, Sleep and the sleep environment temperature, J. Environ. Psychol. 1 (1981) 207–214, https://doi.org/10.1016/S0272-4944(81)80039-4.
[52] J.F. Van Den Berg, H.M.E. Miedema, J.H.M. Tulen, A. Hofman, A.K. Neven, H. Tiemeier, Sex differences in subjective and actigraphic sleep measures: a population-based study of elderly persons, Sleep 32 (2009) 1367–1375, https://doi.org/10.1093/sleep/32.10.1367.
[53] I. Fietze, K. Knoop, M. Glos, M. Holzhausen, J.G. Peter, T. Penzel, Effect of the first night shift period on sleep in young nurse students, Eur. J. Appl. Physiol. 107 (2009) 707–714, https://doi.org/10.1007/s00421-009-1181-8.